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# **FIRST Robotics Competition**

**WPILib**

**Apr 10, 2020**





## Programming and Electrical Basics

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Welcome to the *FIRST*® Robotics Competition Control System Documentation! An overview of the changes from 2019 to 2020 is available on the [New for 2020](#) document.





## Getting Started

### 1.1 Introduction

Welcome to the official documentation home for the *FIRST*® Robotics Competition Control System and WPILib software packages. This page is the primary resource documenting the use of the FRC® Control System (including wiring, configuration and software) as well as the WPILib libraries and tools.

#### 1.1.1 New to Programming?

These pages cover the specifics of the WPILib libraries and the FRC Control System and do not describe the basics of using the supported programming languages. If you would like resources on learning the supported programming languages check out the recommendations below:

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**Note:** You can continue with this Getting Started section to get a functioning basic robot without knowledge of the programming language. To go beyond that, you will need to be familiar with the language you choose to program in.

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#### C++

- [LearnCPP](#)
- [Programming: Principles and Practice Using C++ 2nd Edition](#) is an introduction to C++ by the creator of the language himself (ISBN-10: 0321992784).
- [C++ Primer Plus 6th Edition](#) (ISBN-10: 0321776402).

#### Java

- [Code Academy](#)
- [Head First Java 2nd Edition](#) is a very beginner friendly introduction to programming in Java (ISBN-10: 0596009208).

### LabVIEW

- [National Instruments Learn LabVIEW](#)

### 1.1.2 0 to Robot

The remaining pages in this Getting Started section are designed to be completed in order to go from 0 to a working basic robot. The documents will walk you through installation of all needed software, wiring and configuration of hardware, and loading a basic example program that should allow your robot to operate. When you complete a page, simply click **Next** to navigate to the next page and continue with the process. When you're done, you can click **Next** to continue to an overview of WPILib in C++/Java or jump back to the home page using the logo at the top left to explore the rest of the content.

## 1.2 FRC Software Component Overview

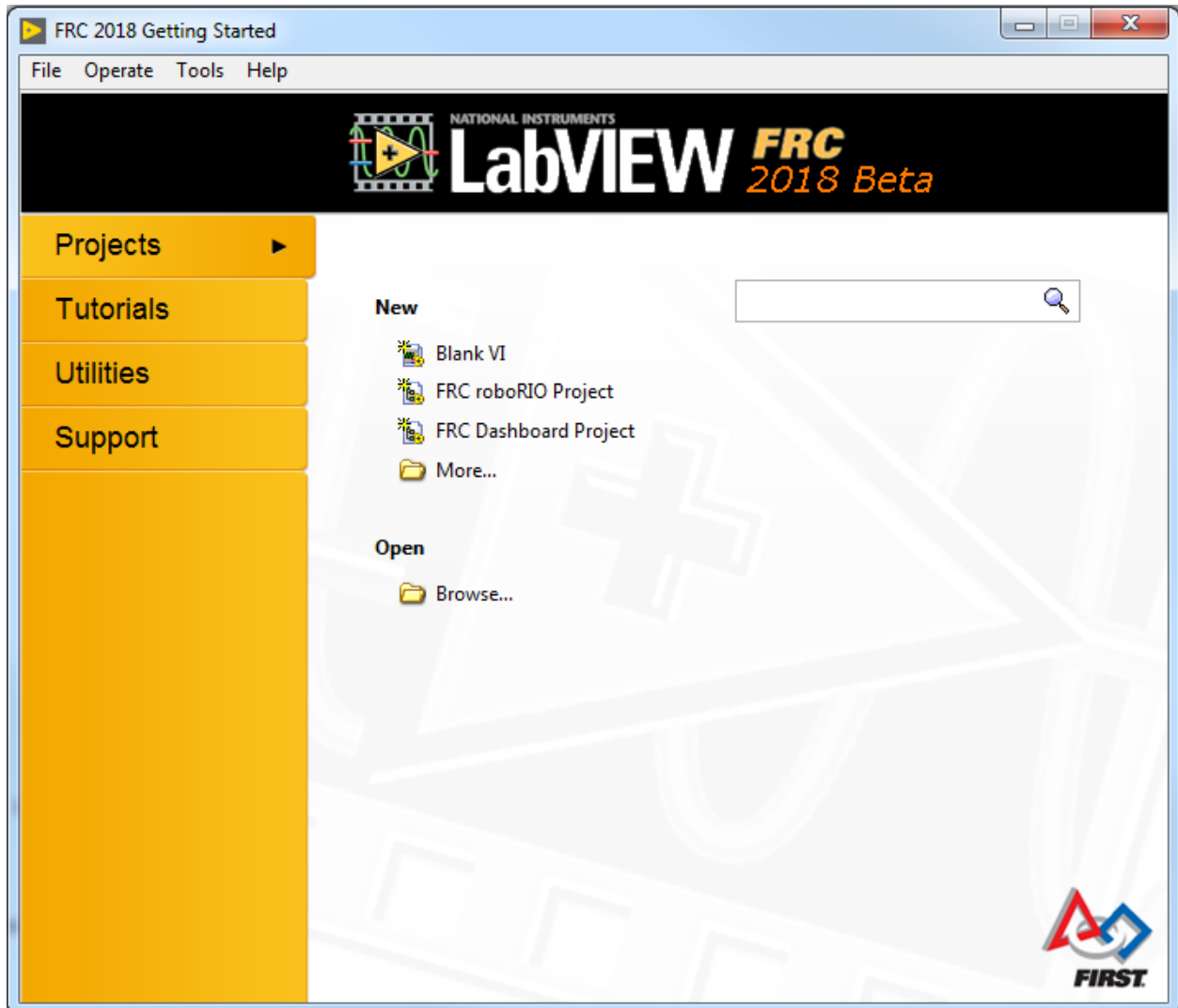
The FRC control system consists of a wide variety of mandatory and optional software components. These elements are designed to assist you in the design, development, and debugging of your robot code as well as assist with control robot operation and to provide feedback when troubleshooting. For each software component this document will provide a brief overview of its purpose, a link to the package download, if appropriate, and a link to further documentation where available.

### 1.2.1 Operating System Compatibility

The primary supported OS for FRC components is Windows. All required FRC software components have been tested on Windows 7, 8, and 10. Windows XP is not supported.

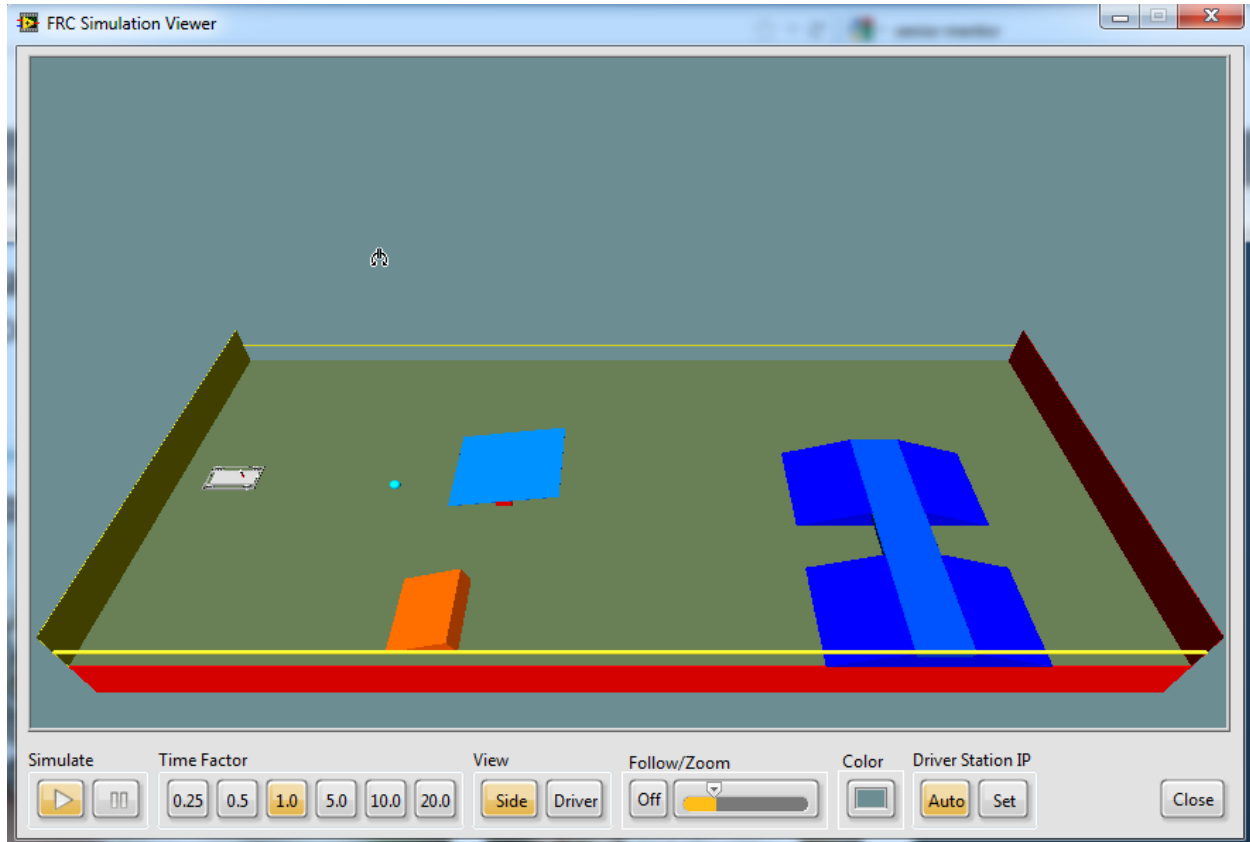
Having said that, many of the tools for C++/Java programming are also supported and tested on macOS and Linux. Teams programming in C++/Java should be able to develop using these systems, using a Windows system for the Windows-only operations such as Driver Station, radio programming, and roboRIO imaging.

### 1.2.2 LabVIEW FRC (Windows Only)



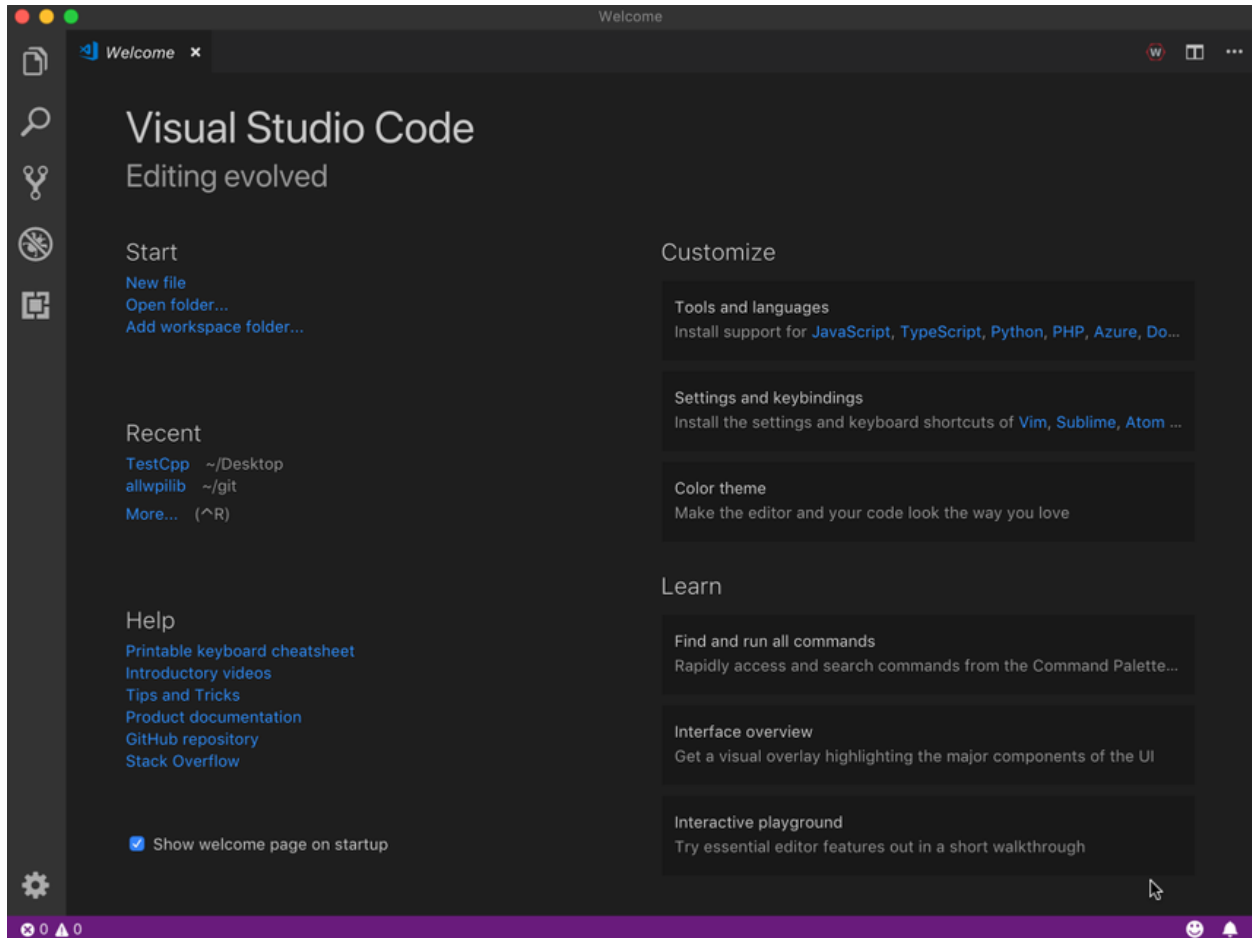
LabVIEW FRC, based on National Instruments' LabVIEW 2019, is the development environment for LabVIEW, one of the three officially supported languages for programming an FRC robot. LabVIEW is a graphical, dataflow-driven language. LabVIEW programs consist of a collection of icons, called VIs, wired together with wires which pass data between the VIs. The LabVIEW FRC installer is distributed on a DVD found in the Kickoff Kit of Parts and is also available for download (see installation instructions page linked below). Instructions for installing the FRC libraries (package also includes Driver Station and Utilities) can be found [here](#). A guide to getting started with the LabVIEW FRC software, including installation instructions can be found [here](#).

### FRC Robot Simulator (Windows Only)



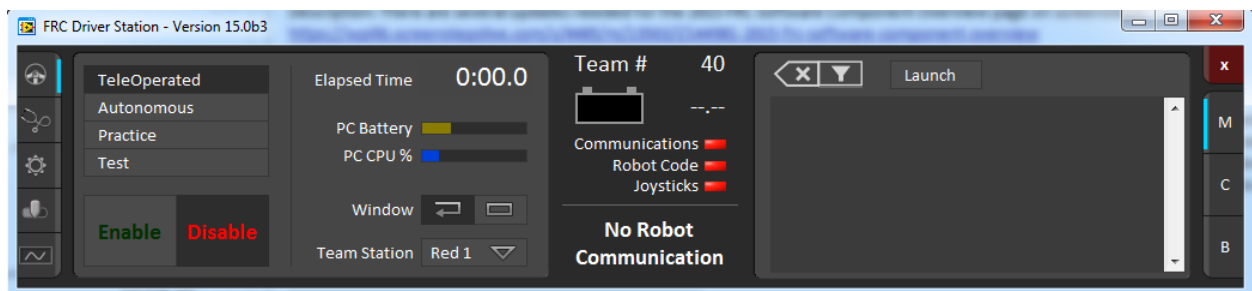
The FRC Robot Simulator is a component of the LabVIEW programming environment that allows you to operate a predefined robot in a simulated environment to test code and/or Driver Station functions. It utilizes a LabVIEW code project as the robot code and communicates with the FRC Driver Station for robot control and the FRC Default Dashboard for robot feedback. The FRC Robot Simulator is installed with the LabVIEW FRC package. Information on using the FRC Robot Simulator can be found by opening the Robot Simulation Readme.html file in the LabVIEW Project Explorer.

### 1.2.3 Visual Studio Code



Visual Studio Code is the supported development environment for C++ and Java, two of the three supported languages used for programming an FRC robot. Both are object-oriented text based programming languages. A program in C++ (for FRC) consists of a number of header (.h) and implementation (.cpp) files where as a program in Java consists of .java files contained in one or more packages. A guide to getting started with C++ for FRC, including the installation and configuration of Visual Studio Code can be found [here](#).

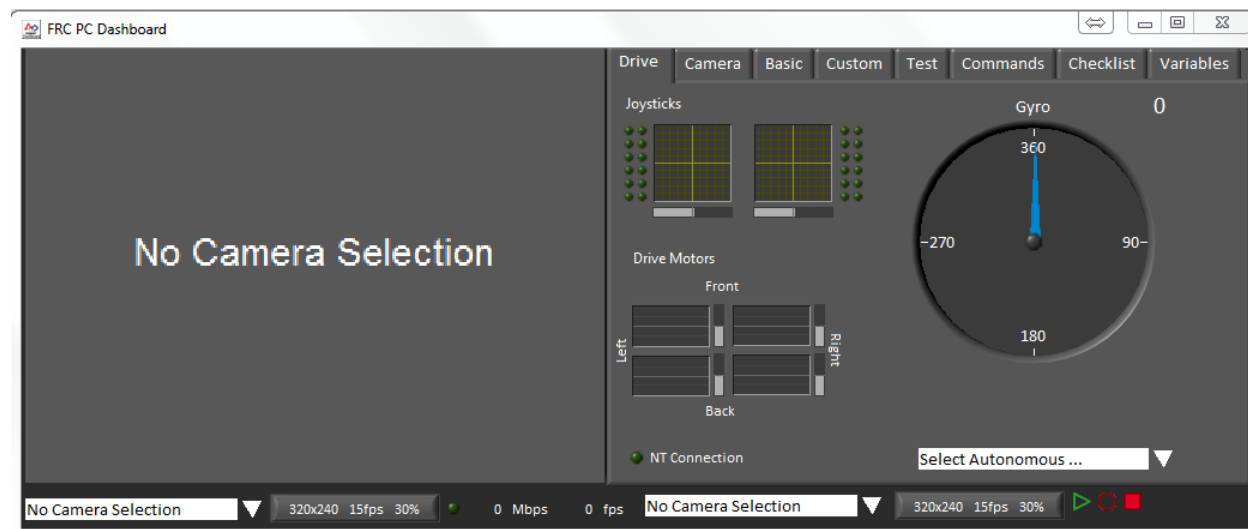
### 1.2.4 FRC Driver Station Powered by NI LabVIEW (Windows Only)



The FRC Driver Station Powered by NI LabVIEW is the only software allowed to be used for

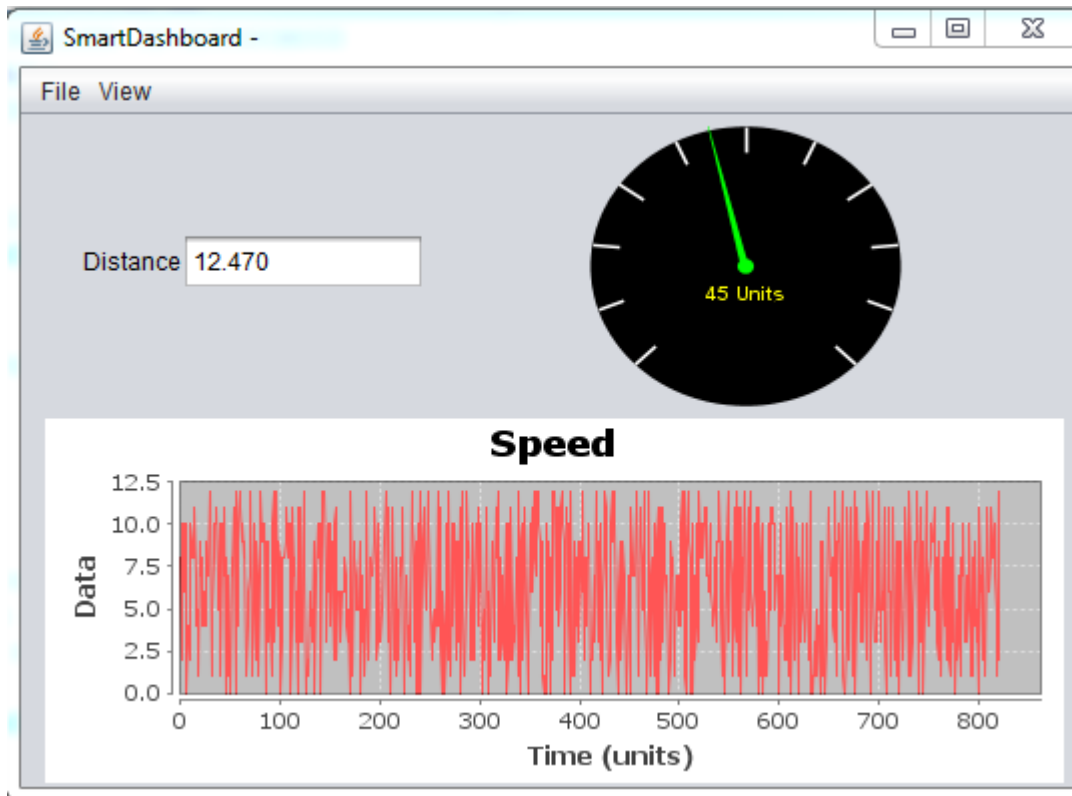
the purpose of controlling the state of the robot during competition. This software contains the code necessary to send data to your robot from a variety of input devices such as joysticks, gamepads, and customizable IO boards. It also contains a number of tools used to help troubleshoot robot issues such as status indicators and log file creation. Instructions for installing the FRC Driver Station Powered by NI LabVIEW (included in the FRC Game Tools) can be found [here](#). More information about the FRC Driver Station Powered by NI LabVIEW can be found [here](#).

### 1.2.5 FRC LabVIEW Dashboard (Windows Only)



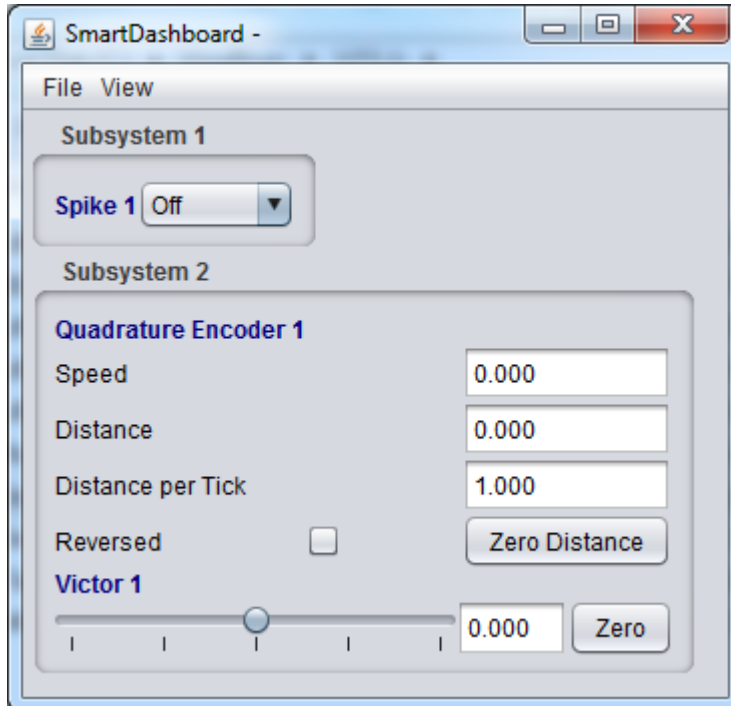
The FRC LabVIEW Dashboard is the default dashboard program installed with, and automatically launched by, the FRC Driver Station. The purpose of the Dashboard is to provide feedback about the operation of the robot. The FRC Default Dashboard serves as an example of the types of feedback teams may want from their robot. It includes a tabbed display that can switch between viewing an image from a camera on the robot or a display of NetworkTables variables, a display of information regarding the joysticks and drive motors, an indicator of the robot IP and battery voltage, and a second tabbed display that can switch between examples of custom indicators and controls, a test tab for use with the Driver Station Test Mode and a Checklist tab that teams can use to enter a custom checklist to complete before each match. The FRC Default Dashboard is included in the FRC Game Tools. Installation instructions can be found [here](#). More information about the FRC Default Dashboard software can be found [here](#).

### 1.2.6 SmartDashboard



SmartDashboard is an alternate dashboard application written in Java. SmartDashboard automatically creates a widget for each variable sent from the Robot sent using the SmartDashboard class or VIs. These widgets can be configured to a number of preset display types, or users can create custom extensions in Java. Vision extensions are available for the SmartDashboard which allow it to display images from the Axis camera on the robot. SmartDashboard is included in the C++ and Java language updates (enabled by clicking the C++ or Java buttons respectively on the Setup tab of the Driver Station). Additional documentation on SmartDashboard can be found [here](#).

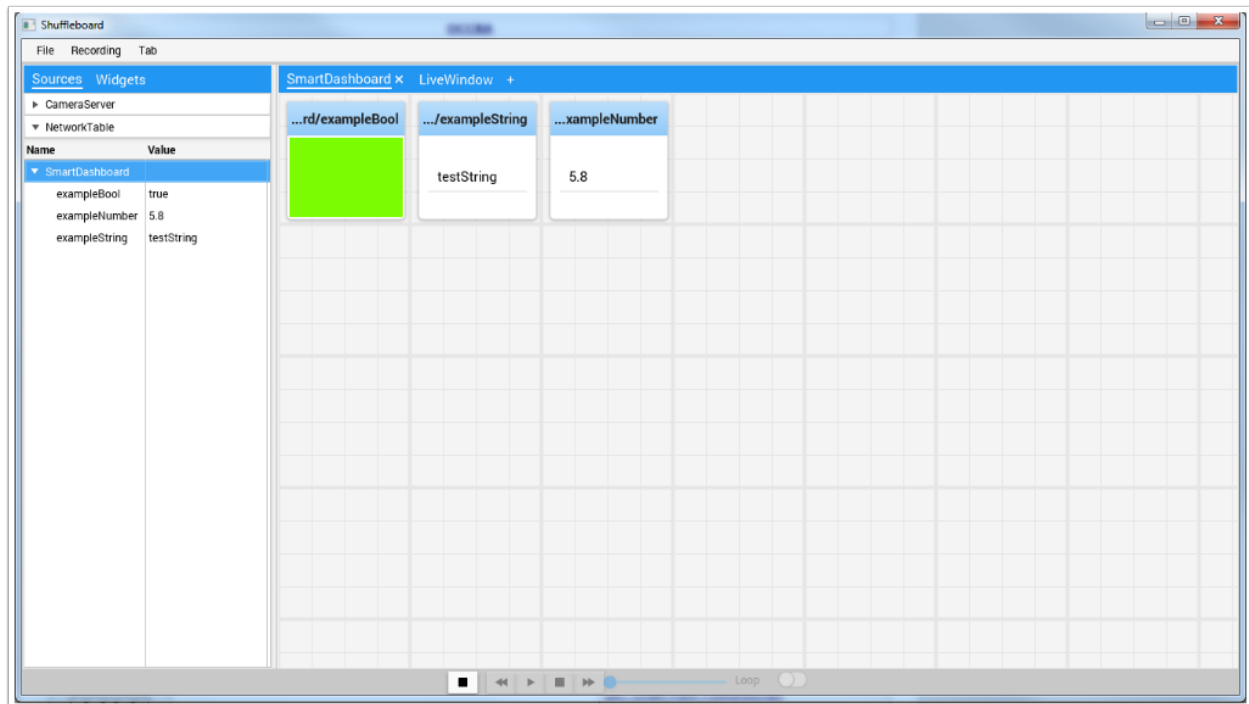
### LiveWindow



LiveWindow is a mode of SmartDashboard , designed for use with the Test Mode of the Driver Station. LiveWindow allows the user to see feedback from sensors on the robot and control actuators independent of the written user code. More information about LiveWindow can be found [here](#).

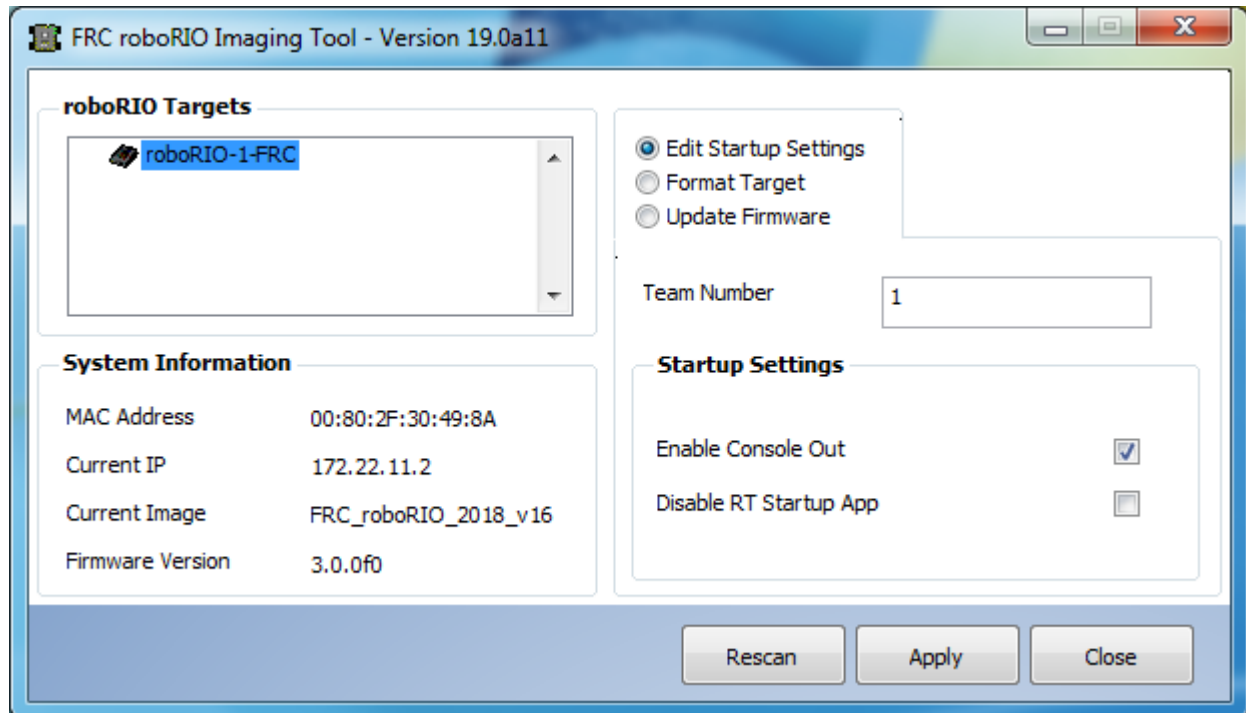


## 1.2.7 Shuffleboard



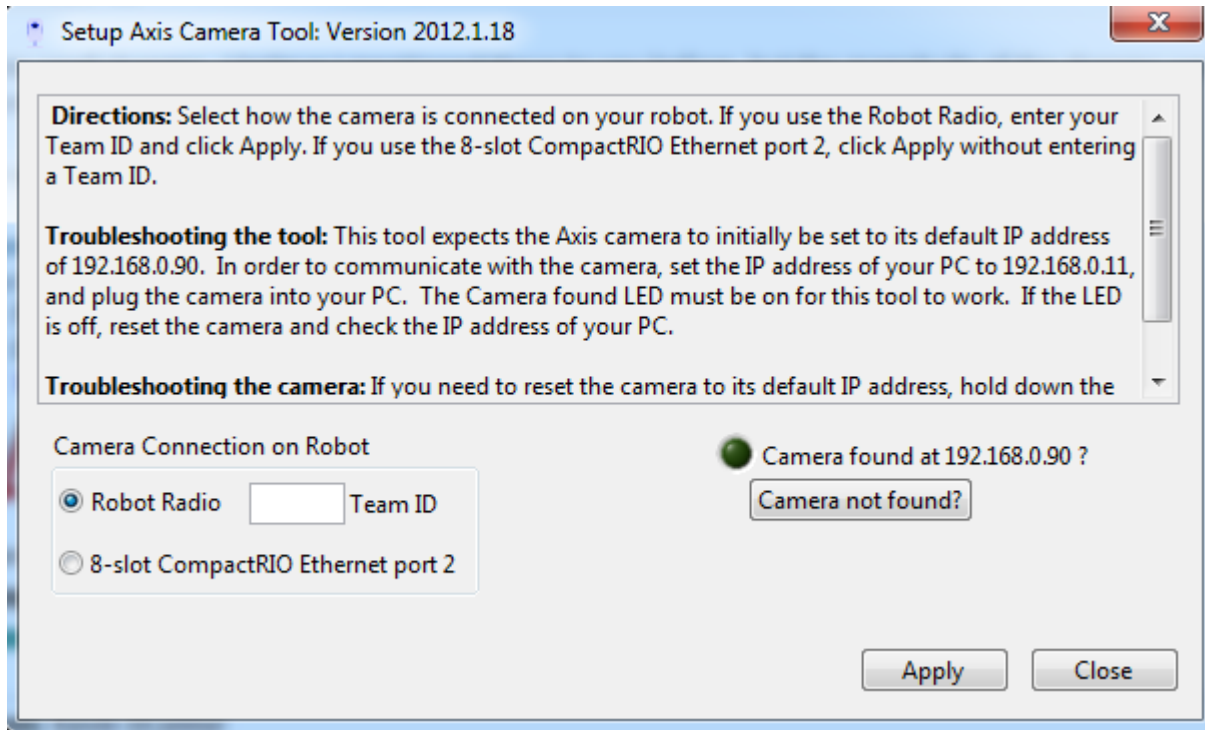
Shuffleboard is an alternative dashboard application written in Java. It takes many of the concepts from SmartDashboard such as automatic adding of widgets and adds new features including better layout control and record/playback functionality. Shuffleboard contains all of the basic widget types found in the SmartDashboard as well as a number of new ones intended to make visualizing specific robot components even easier. It has full integration with WPILib's "cscore" for displaying, recording, and playing back camera streams. Shuffleboard is included in the C++ and Java language updates (enabled by selecting Shuffleboard from the dashboard type on the Setup tab of the Driver Station or by launching it from the WPILib start tool menu in Visual Studio Code). Additional documentation on Shuffleboard can be found [here](#).

### 1.2.8 FRC roboRIO Imaging Tool (Windows Only)



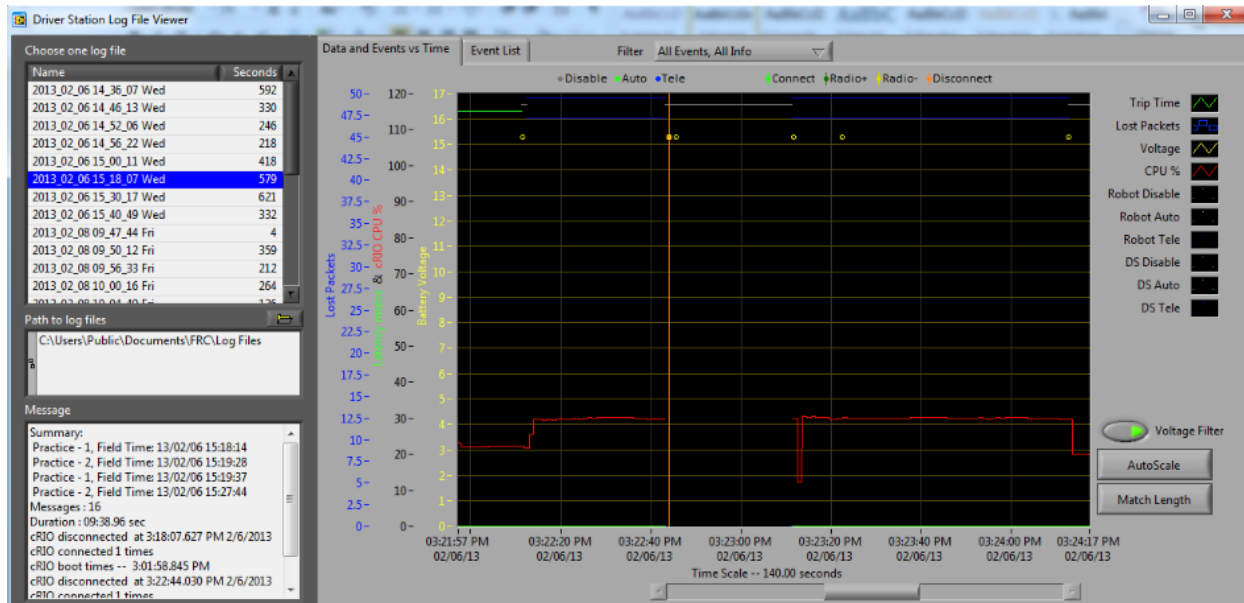
The FRC roboRIO Imaging Tool is a software tool used to format and setup an roboRIO-FRC device for use in FRC. The tool detects any roboRIO device on the network, reports the current MAC, name, IP and Image version. The tool allows the user to configure the team number, set options including Console Out and whether an applications runs on Startup, and install the latest software image on the device. The FRC roboRIO Imaging Tool is installed as part of the FRC Game Tools. Installation instructions can be found [here](#). Additional instructions on imaging your roboRIO using this tool can be found [here](#).

### 1.2.9 Setup Axis Camera (Windows Only)



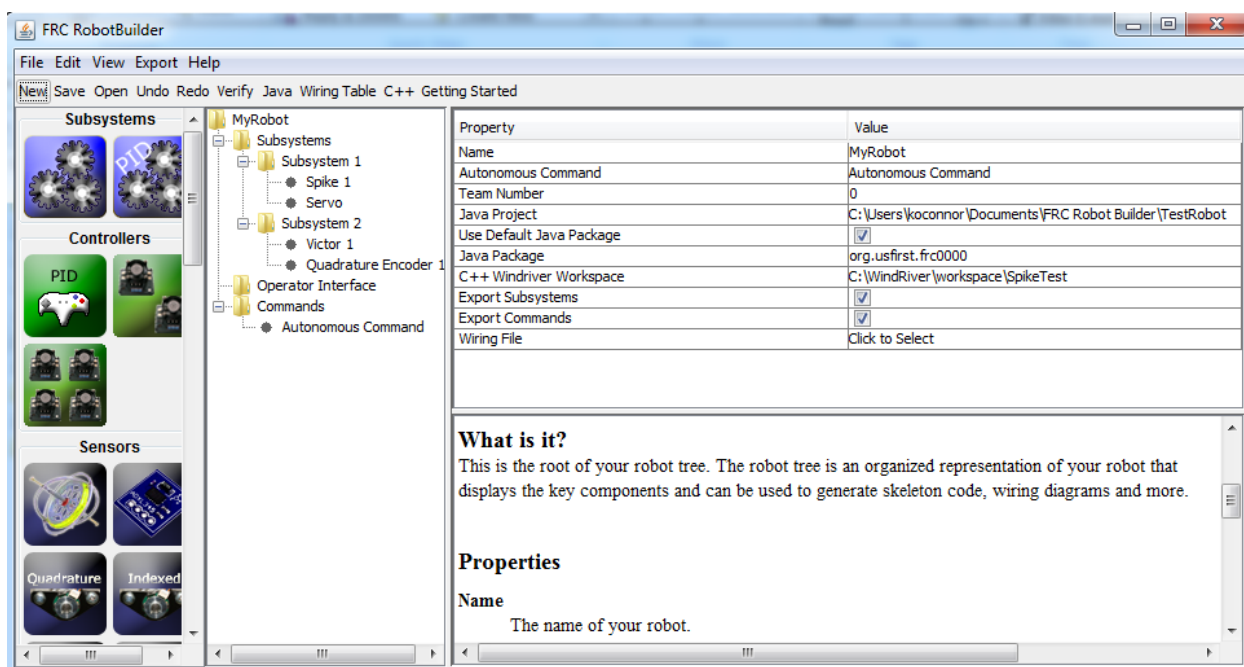
The Setup Axis Camera utility is a LabVIEW program used to configure an Axis 206, M1011 or M1013 camera for use on the robot. The tool takes a factory reset camera connected directly to the computer and configures the IP, username and password, anonymous access, and default framerate and compression (for use with the SmartDashboard or other access methods). The Setup Axis Camera tool is installed as part of the FRC Game Tools. Installation instructions can be found [here](#). Instructions for using the tool to configure the camera are located [here](#).

## 1.2.10 FRC Driver Station Log Viewer (Windows Only)



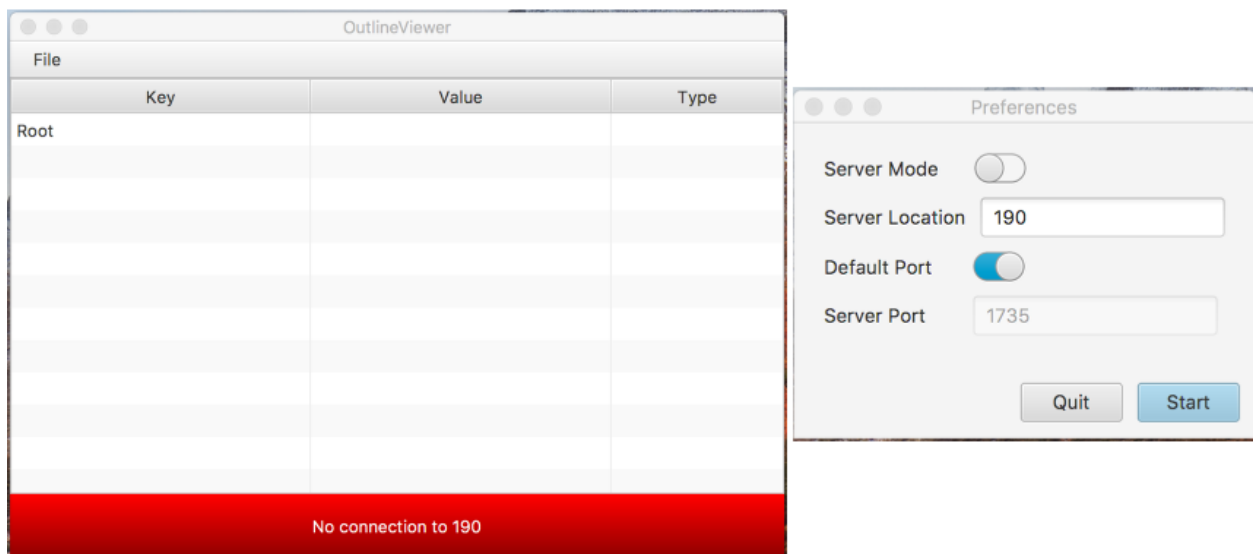
The FRC Driver Station Log Viewer is a LabVIEW program used to view logs created by the FRC Driver Station. These logs contain information such as battery voltage, trip time, CPU% and robot mode, as well as events such as joystick removal. The FRC Driver Station Log Viewer is included in the FRC Game Tools. Installation instructions can be found [here](#). More information about the FRC Driver Station Log Viewer and understanding the logs can be found [here](#).

## 1.2.11 RobotBuilder



RobotBuilder is a tool designed to aid in setup and structuring of a Command Based robot project for C++ or Java. RobotBuilder allows you to enter in the various components of your robot subsystems and operator interface and define what your commands are in a graphical tree structure. RobotBuilder will then verify that you have no port allocation conflicts and can generate a wiring table indicating what is connected to each port as well as C++ or Java code. The code created generates the appropriate files, constructs the appropriate objects and adds LiveWindow code for each sensor and actuator, but does not write any of the actual Subsystem or Command methods. The user must write the appropriate code for these methods for the robot to function. More information about RobotBuilder can be found [here](#). More information about the Command Based programming architecture can be found [here](#).

### 1.2.12 OutlineViewer

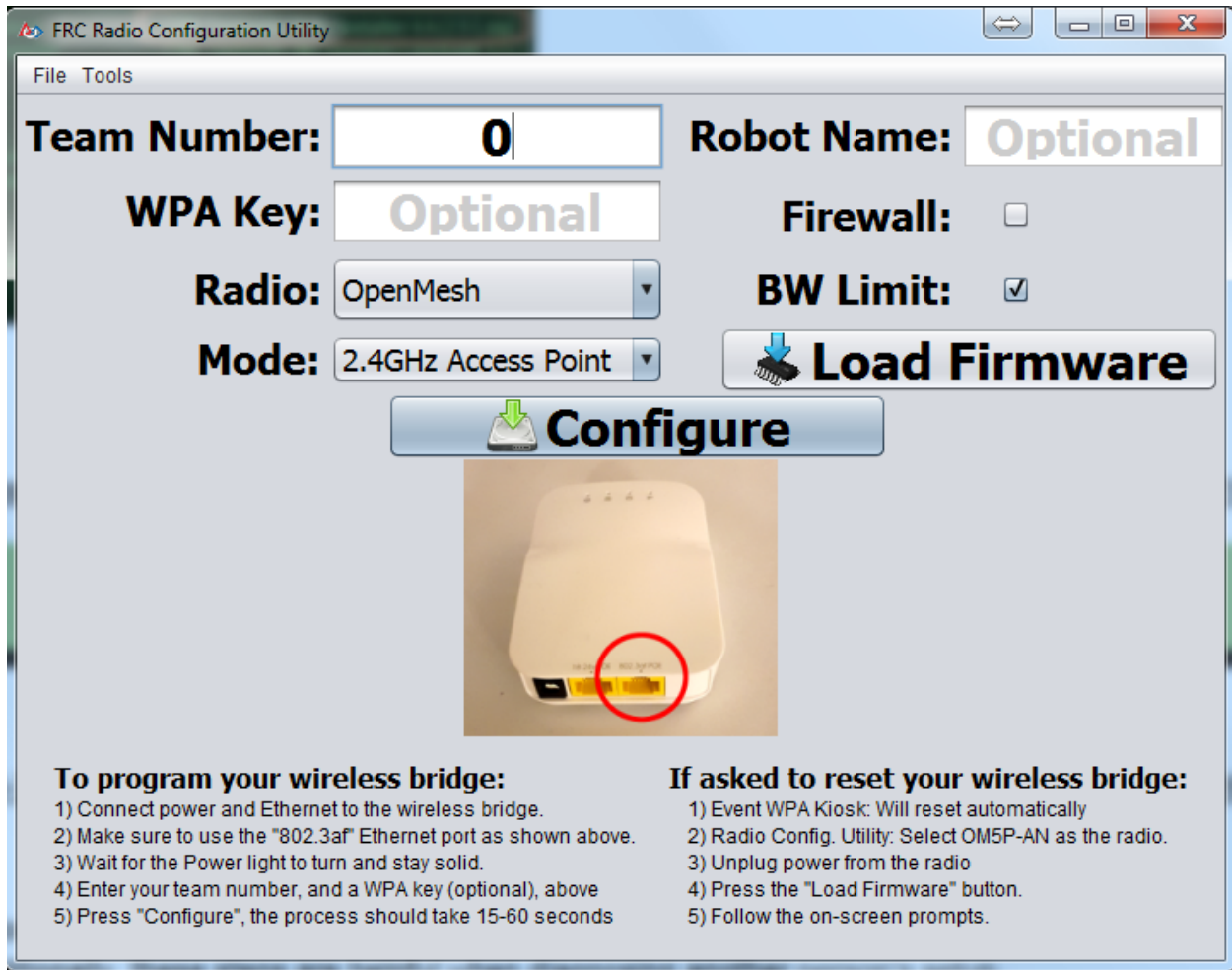


OutlineViewer is a utility used to view, modify and add to the contents of the NetworkTables for debugging purposes. It displays all key value pairs currently in the NetworkTables and can be used to modify the value of existing keys or add new keys to the table. OutlineViewer is included in the C++ and Java language updates (found in \tools\wpilib). Teams may need to install the Java Runtime Environment to use the OutlineViewer on computers not set up for Java programming.

To connect to your robot, open OutlineViewer and set the “Server Location” to be your team number. After you click start, OutlineViewer will connect.

LabVIEW teams can use the Variables tab of the LabVIEW Dashboard to accomplish this functionality.

### 1.2.13 FRC Radio Configuration Utility (Windows Only)



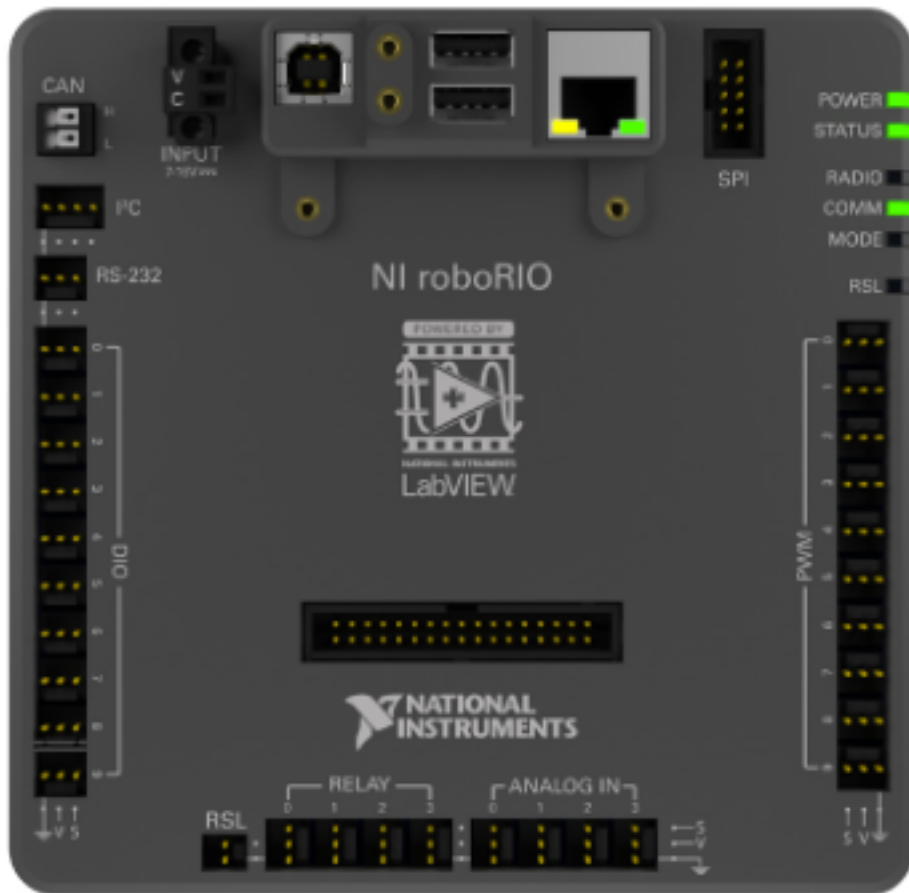
The FRC Radio Configuration Utility is a tool used to configure the the OpenMesh OM5P-AN or OM5P-AC radio for practice use at home. This tool sets the appropriate IP, and network settings for proper network connection, as well as the QOS settings required to mimic the bandwidth limiting and packet prioritization experience on the FRC playing field. The FRC Radio Configuration Utility is installed by a standalone installer; instructions on installing and using the FRC Radio Configuration Utility to configure your radio can be found [here](#).

## 1.3 FRC Control System Hardware Overview

The goal of this document is to provide a brief overview of the hardware components that make up the FRC® Control System. Each component will contain a brief description of the component function, a brief listing of critical connections, and a link to more documentation if available.

**Note:** For complete wiring instructions/diagrams, please see the [Wiring the FRC Control System](#) document.

### 1.3.1 National Instruments roboRIO



The NI-roboRIO is the main robot controller used for FRC. The roboRIO includes a dual-core ARM Cortex™-A9 processor and FPGA which runs both trusted elements for control and safety as well as team-generated code. Integrated controller I/O includes a variety of communication protocols (Ethernet, USB, CAN, SPI, I2C, and serial) as well as PWM, servo, digital I/O, and analog I/O channels used to connect to robot peripherals for sensing and control. The roboRIO should connect to the dedicated 12V port on the Power Distribution Panel for power. Wired communication is available via USB or Ethernet. Detailed information on the roboRIO can be found in the [roboRIO User Manual](#).



### 1.3.2 Power Distribution Panel





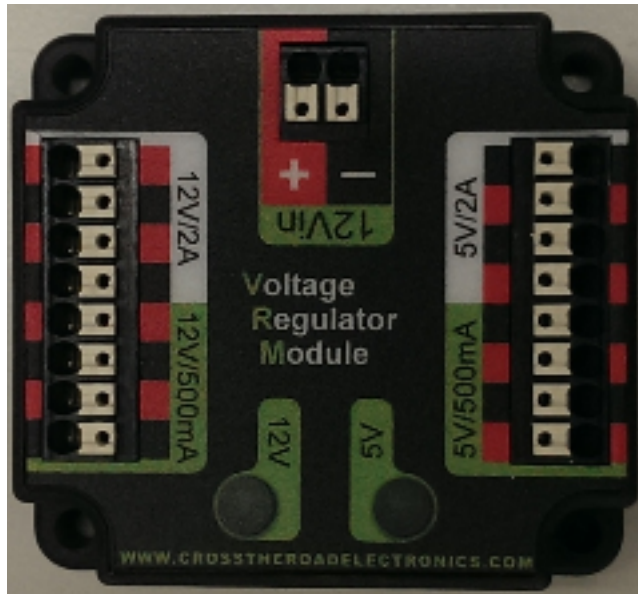
The Power Distribution Panel (PDP) is designed to distribute power from a 12VDC battery to various robot components through auto-resetting circuit breakers and a small number of special function fused connections. The PDP provides 8 output pairs rated for 40A continuous current and 8 pairs rated for 30A continuous current. The PDP provides dedicated 12V connectors for the roboRIO, as well as connectors for the Voltage Regulator Module and Pneumatics Control Module. It also includes a CAN interface for logging current, temperature, and battery voltage. For more detailed information, see the [PDP User Manual](#).

### 1.3.3 Pneumatics Control Module



The PCM is a device that contains all of the inputs and outputs required to operate 12V or 24V pneumatic solenoids and the on board compressor. The PCM is enabled/disabled by the roboRIO over the CAN interface. The PCM contains an input for the pressure sensor and will control the compressor automatically when the robot is enabled and a solenoid has been created in the code. The device also collects diagnostic information such as solenoid states, pressure switch state, and compressor state. The module includes diagnostic LED's for both CAN and the individual solenoid channels. For more information see the [PCM User Manual](#).

### 1.3.4 Voltage Regulator Module



The VRM is an independent module that is powered by 12 volts. The device is wired to a dedicated connector on the PDP. The module has multiple regulated 12V and 5V outputs. The purpose of the VRM is to provide regulated power for the robot radio, custom circuits, and IP vision cameras. The two connector pairs associated with each label have a combined rating of what the label indicates (e.g. 5V/500mA total for both pairs not for each pair). The 12V/2A limit is a peak rating, the supply should not be loaded with more than 1.5A continuous current draw. For more information, see the [VRM User Manual](#).

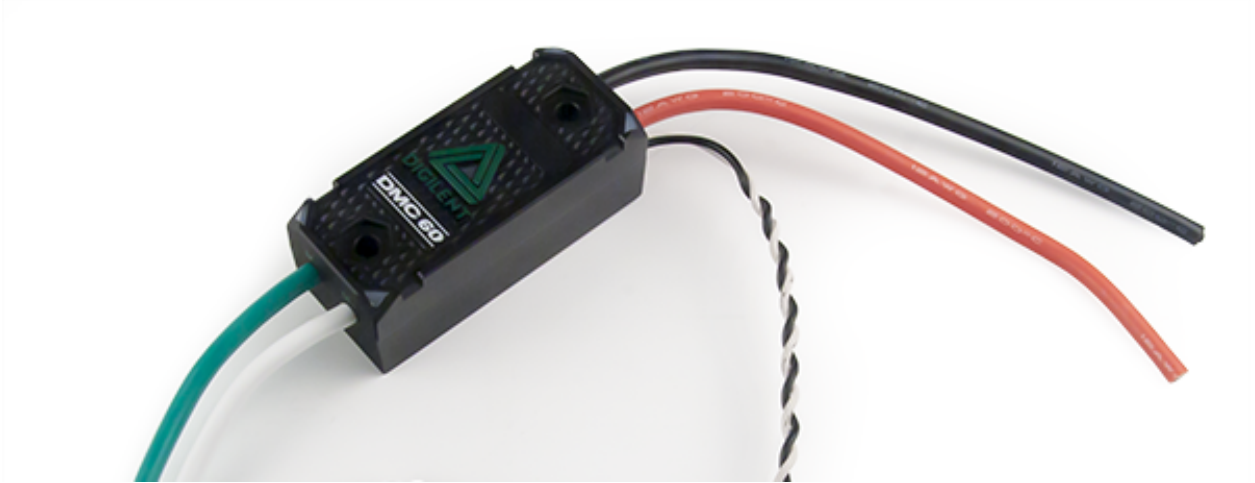
### 1.3.5 Motor Controllers

There are a variety of different motor controllers which work with the FRC Control System and are approved for use. These devices are used to provide variable voltage control of the brushed DC motors used in FRC. They are listed here in alphabetical order.

---

## DMC-60 and DMC-60C Motor Controller

---



The DMC-60 is a PWM motor controller from Digilent. The DMC-60 features integrated thermal sensing and protection including current-foldback to prevent overheating and damage, and four multi-color LEDs to indicate speed, direction, and status for easier debugging. For more information, see the [DMC-60 reference manual](#)

The DMC-60C adds CAN smart controller capabilities to the DMC-60 controller. This enables closed loop control features and other intelligent control options. For more information see the [DMC-60C Product Page](#)

### Jaguar Motor Controller



The Jaguar Motor Controller from VEX Robotics (formerly made by Luminary Micro and Texas Instruments) is a variable speed motor controller for use in FRC. For FRC, the Jaguar may only be controlled using the PWM interface.

## SD540B and SD540C Motor Controllers



The SD540 Motor Controller from Mindsensors is a variable speed motor controller for use in FRC. The SD540B is controlled using the PWM interface. The SD540C is controllable over CAN. Limit switches may be wired directly to the SD540 to limit motor travel in one or both directions. Switches on the device are used to flip the direction of motor travel, configure the wiring polarity of limit switches, set Brake or Coast mode, and put the device in calibration mode. For more information see the [Mindsensors FRC page](#)

### SPARK Motor Controller



The SPARK Motor Controller from REV Robotics is a variable speed motor controller for use in FRC. The SPARK is controlled using the PWM interface. Limit switches may be wired directly to the SPARK to limit motor travel in one or both directions. The RGB status LED displays the current state of the device including whether the device is currently in Brake mode or Coast mode. For more information, see the [REV Robotics SPARK product page](#)

### SPARK MAX Motor Controller



The SPARK MAX Motor Controller from REV Robotics is a variable speed motor controller for use in FRC. The SPARK MAX is capable of controlling either the traditional brushed DC motors commonly used in FRC or the new brushless REV Robotics NEO Brushless Motor. The SPARK MAX can be controlled over PWM, CAN or USB (for configuration/testing only). The controller has a data port for sensor input and is capable of closed loop control modes when controlled over CAN or USB. For more information see the [REV Robotics SPARK MAX product page](#).



### Talon Motor Controller



The Talon Motor Controller from Cross the Road Electronics is a variable speed motor controller for use in FRC. The Talon is controlled over the PWM interface. The Talon should be connected to a PWM output of the roboRIO and powered from the Power Distribution Panel. For more information see the [Talon User Manual](#).



## Talon SRX



The Talon SRX motor controller is a CAN-enabled “smart motor controller” from Cross The Road Electronics/VEX Robotics. The Talon SRX has an electrically isolated metal housing for heat dissipation, making the use of a fan optional. The Talon SRX can be controlled over the CAN bus or PWM interface. When using the CAN bus control, this device can take inputs from limit switches and potentiometers, encoders, or similar sensors in order to perform advanced control such as limiting or PID(F) closed loop control on the device. For more information see the [Talon SRX User Manual](#).

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**Note:** CAN Talon SRX has been removed from WPILib. See this [blog](#) for more info and find the CTRE Toolsuite installer [here](#).

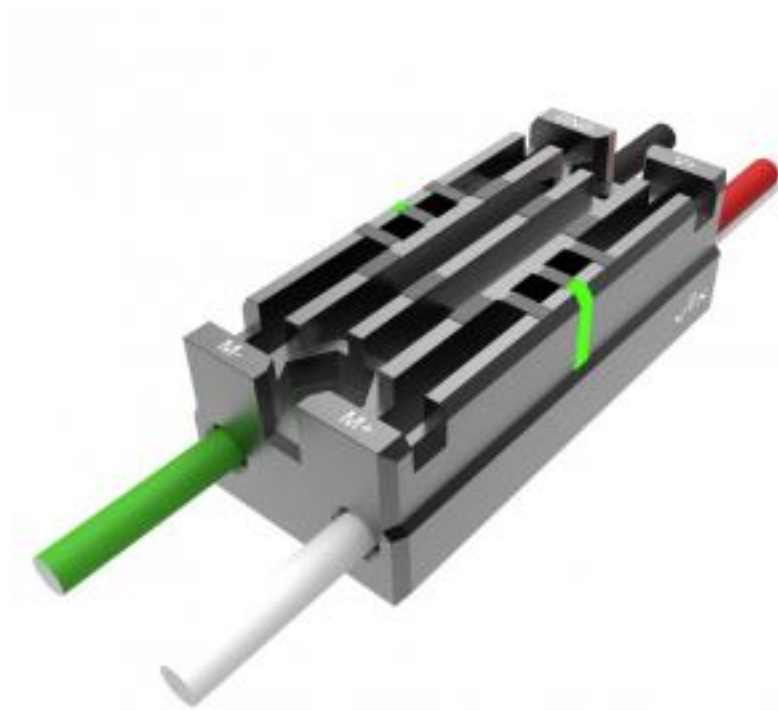
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### Victor 888 Motor Controller / Victor 884 Motor Controller



The Victor 888 Motor Controller from VEX Robotics is a variable speed motor controller for use in FRC. The Victor 888 replaces the Victor 884, which is also usable in FRC. The Victor is controlled over the PWM interface. The Victor should be connected to a PWM output of the roboRIO and powered from the Power Distribution Panel. For more information, see the [Victor 884 User Manual](#) and [Victor 888 User Manual](#).

## Victor SP



The Victor SP motor controller is a PWM motor controller from Cross The Road Electronics/VEX Robotics. The Victor SP has an electrically isolated metal housing for heat dissipation, making the use of the fan optional. The case is sealed to prevent debris from entering the controller. The controller is approximately half the size of previous models.

### Victor SPX



The Victor SPX motor controller is a CAN or PWM controlled motor controller from Cross The Road Electronics/VEX Robotics. The device is connectorized to allow easy connection to the roboRIO PWM connectors or a CAN bus chain. When controlled over the CAN bus, the device has a number of the closed loop features also present in the Talon SRX. The case is sealed to prevent debris from entering the controller. For more information, see the [Victor SPX Webpage](#).

---

**Note:** Victor SPX CAN control is not supported from WPILib. See [this blog](#) for more info and find the CTRE Toolsuite installer [here](#).

---

### 1.3.6 Spike H-Bridge Relay



The Spike H-Bridge Relay from VEX Robotics is a device used for controlling power to motors or other custom robot electronics. When connected to a motor, the Spike provides On/Off control in both the forward and reverse directions. The Spike outputs are independently controlled so it can also be used to provide power to up to 2 custom electronic circuits. The Spike H-Bridge Relay should be connected to a relay output of the roboRIO and powered from the Power Distribution Panel. For more information, see the [Spike User's Guide](#).

### 1.3.7 Servo Power Module



The Servo Power Module from Rev Robotics is capable of expanding the power available to servos beyond what the roboRIO integrated power supply is capable of. The Servo Power Module provides up to 90W of 6V power across 6 channels. All control signals are passed through directly from the roboRIO. For more information, see the [Servo Power Module web-page](#).

### 1.3.8 Axis M1013/M1011/206 Ethernet Camera



The Axis M1013, M1011 and Axis 206 Ethernet cameras are used for capturing images/control-system-hardware for vision processing and/or sending video back to the Driver Station laptop. The camera should be wired to a 5V power output on the Voltage Regulator Module and an open ethernet port on the robot radio. For more information, see [Configuring an Axis Camera](#) and the [Axis 206](#), [Axis M1011](#), [Axis M1013](#) pages.

### 1.3.9 Microsoft Lifecam HD3000



The Microsoft Lifecam HD3000 is a USB webcam that can be plugged directly into the roboRIO. The camera is capable of capturing up to 1280x720 video at 30 FPS. For more information about the camera, see the [Microsoft product page](#). For more information about using the camera with the roboRIO, see the [Vision Processing](#) section of this documentation.

### 1.3.10 OpenMesh OM5P-AN or OM5P-AC Radio



Either the OpenMesh OM5P-AN or OpenMesh OM5P-AC wireless radio is used as the robot radio to provide wireless communication functionality to the robot. The device can be con-



figured as an Access Point for direct connection of a laptop for use at home. It can also be configured as a bridge for use on the field. The robot radio should be powered by one of the 12V/2A outputs on the VRM and connected to the roboRIO controller over Ethernet. For more information, see [Programming your Radio](#).

The OM5P-AN is [no longer available for purchase](#). The OM5P-AC is slightly heavier, has more cooling grates, and has a rough surface texture compared to the OM5P-AN.

### 1.3.11 120A Circuit Breaker



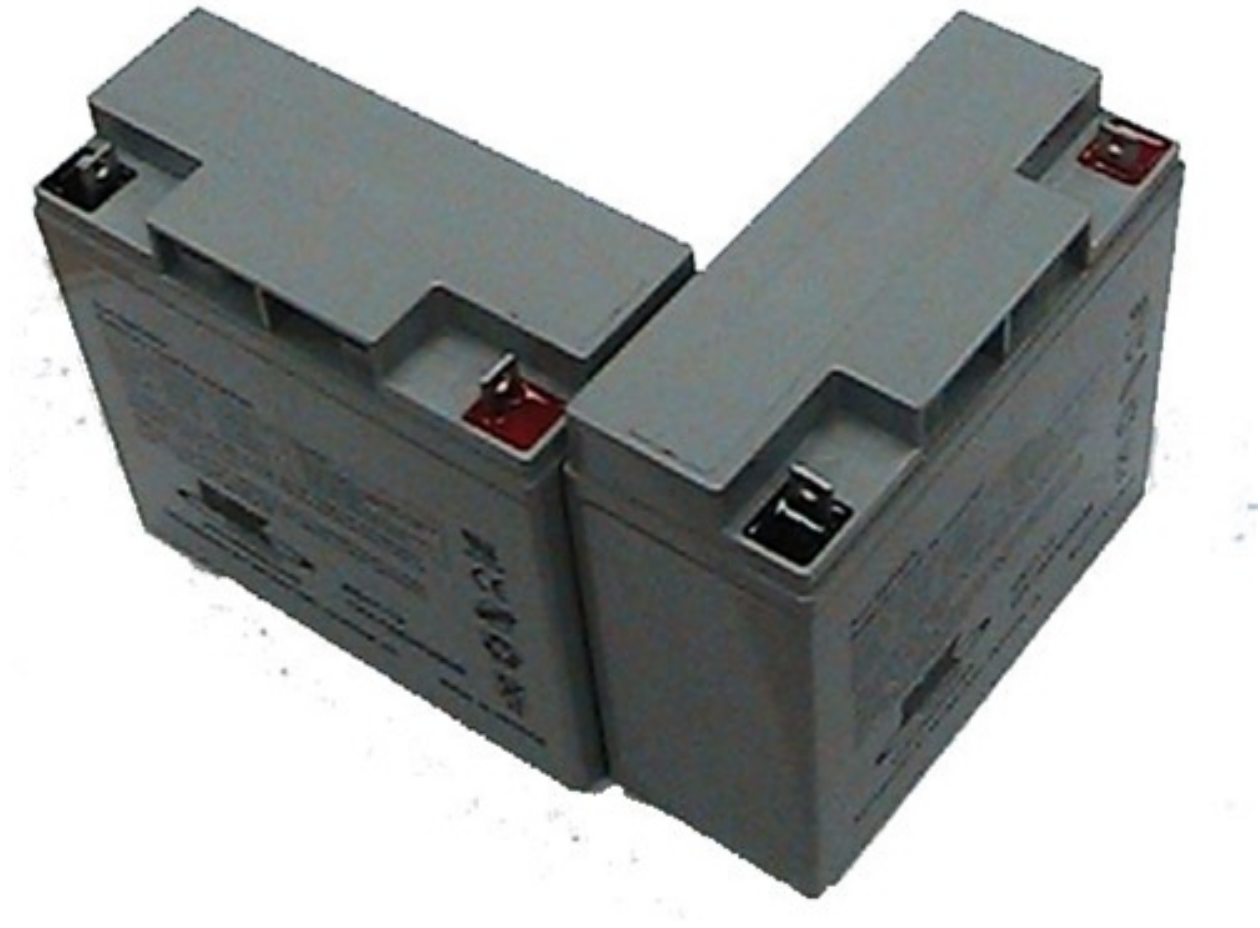
The 120A Main Circuit Breaker serves two roles on the robot: the main robot power switch and a protection device for downstream robot wiring and components. The 120A circuit breaker is wired to the positive terminals of the robot battery and Power Distribution boards. For more information, please see the [Cooper Bussmann 18X Series Datasheet \(PN: 185120F\)](#)

### 1.3.12 Snap Action Circuit Breakers



The Snap Action circuit breakers, MX5-A40 and VB3 series, are used with the Power Distribution Panel to limit current to branch circuits. The MX5-A40 40A MAXI style circuit breaker is used with the larger channels on the Power Distribution Panel to power loads which draw current up to 40A continuous. The VB3 series are used with the smaller channels on the PDP to power circuits drawing current of 30A or less continuous. For more information, see the Datasheets for the [MX5 series](#) and [VB3 Series](#).

### 1.3.13 Robot Battery



The power supply for an FRC robot is a single 12V 18Ah battery. The batteries used for FRC are sealed lead acid batteries capable of meeting the high current demands of an FRC robot. For more information, see the Datasheets for the [MK ES17-12](#) and [nersys NP18-12](#).

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**Note:** Other battery part numbers may be legal, consult the [FRC Manual](#) for a complete list.

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### 1.3.14 Image Credits

Image of roboRIO courtesy of National Instruments. Image of DMC-60 courtesy of Digilent. Image of SD540 courtesy of Mindsensors. Images of Jaguar Motor Controller, Talon SRX, Victor 888, Victor SP, Victor SPX, and Spike H-Bridge Relay courtesy of VEX Robotics, Inc. Image of SPARK MAX courtesy of REV Robotics. Lifecam, PDP, PCM, SPARK, and VRM photos courtesy of *FIRST*®. All other photos courtesy of AndyMark Inc.

# 1.4 Offline Installation Preparation

This article contains instructions/links to components you will want to gather if you need to do offline installation of the FRC® Control System software.

## 1.4.1 Documentation

This documentation can be downloaded for offline viewing. The link to download the PDF can be found [here](#).

## 1.4.2 Installers

### All Teams

- [2020 FRC Game Tools](#) (Note: Click on link for “Individual Offline Installers”)
- [2020 FRC Radio Configuration Utility](#) or [2020 FRC Radio Configuration Utility Israel Version](#)
- (Optional - Veterans Only!) [Classmate/Acer PC Image](#)

### LabVIEW Teams

- LabVIEW USB (from *FIRST*® Choice) or [Download](#) (Note: Click on link for “Individual Offline Installers”)

### C++/Java Teams

- [C++/Java WPILib Installer](#)
- Visual Studio Code (if using Windows, run the installer and use it to download the appropriate VS Code file. If using macOS/Linux, download Visual Studio Code from [here](#))

## 1.4.3 3rd Party Libraries/Software

A number of software components were broken out of WPILib in 2017 and are now maintained by third parties. See [this blog](#) for more details.

A directory of available 3rd party software that plugs in to WPILib can be found on [3rd Party Libraries](#).

# 1.5 WPILib Installation Guide

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**Note:** This setup is for C++/Java teams. LabVIEW teams should proceed to [Installing LabVIEW for FRC](#).

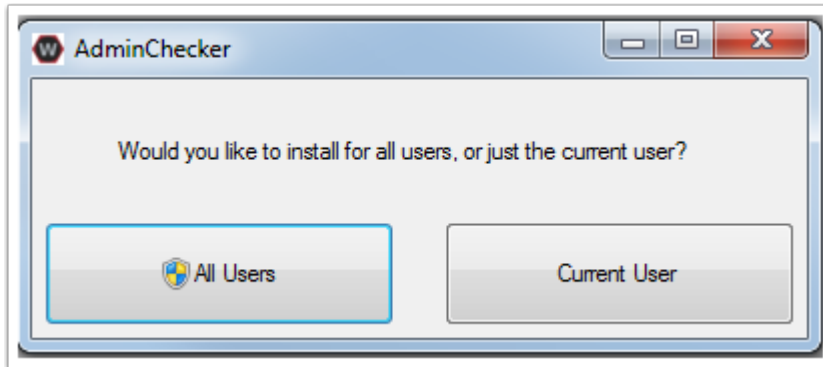
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## Windows

### Offline Installer

Download the appropriate installer for your Windows installation (32 bit or 64 bit) from [GitHub](#). If you're not sure, open Control Panel -> System to check. After the zip file is downloaded, ensure that the installer is extracted before attempting to run it. Running it while the installer is inside the zip will cause the installation process to fail.

Double click on the installer to run it. If you see any Security warnings, click *Run* (Windows 7) or *More Info -> Run Anyway* (Windows 8+).



Choose whether to install for *All Users* on the machine or the *Current User*. The *All Users* option requires administrator privileges, but installs in a way that is accessible to all user accounts, the *Current User* install is only accessible from the account it is installed from.

If you select *All Users*, you will need to accept the security prompt that appears to allow administrator access.

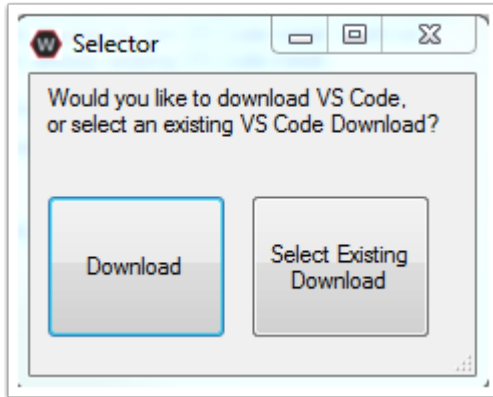
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**Note:** Regardless of whether *All Users* or *Current User* is chosen, the software is installed to C:\Users\Public\wpilib\YYYY where YYYY is the current FRC year. If you choose *All Users*, then shortcuts are installed to all users desktop and start menu and system environment variables are set. If *Current User* is chosen, then shortcuts and environment variables are set for only the current user.

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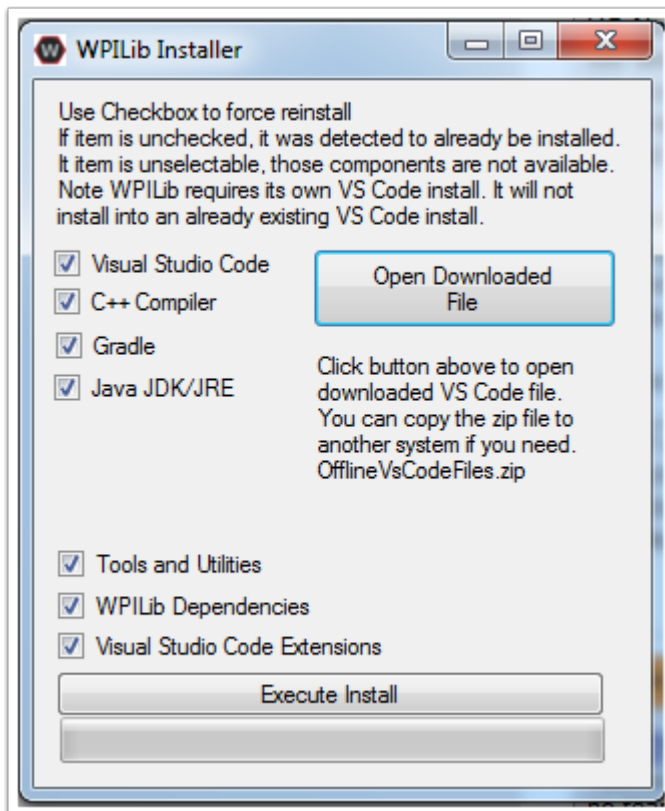
### Download Visual Studio Code

For licensing reasons, the installer cannot contain the VS Code installer bundled in. Click *Select/Download VS Code* to either download the VS Code installer or select a pre-downloaded copy. If you intend to install on other machines without internet connections, after the download completes, you can click *Open Downloaded File* to be taken to the zip file on the file system to copy along with the Offline Installer.



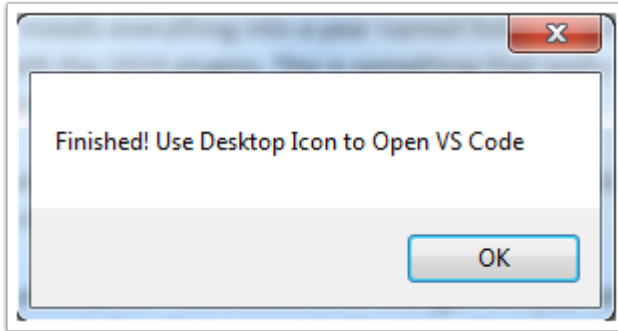
### Execute Install

Make sure all checkboxes are checked (unless you have already installed 2020 WPILib software on this machine and the software unchecked them automatically), then click *Execute Install*.



### Finished

When the installer completes, you will now be able to open and use the WPILib version of VS Code. If you are using any 3rd party libraries, you will still need to install those separately before using them in robot code.



### What's installed?

The Offline Installer installs the following components:

- *Visual Studio Code* - The supported IDE for 2019 and later robot code development. The offline installer sets up a separate copy of VS Code for WPILib development, even if you already have VS Code on your machine. This is done because some of the settings that make the WPILib setup work may break existing workflows if you use VS Code for other projects.
- *C++ Compiler* - The toolchains for building C++ code for the roboRIO
- *Gradle* - The specific version of Gradle used for building/deploying C++ or Java robot code
- *Java JDK/JRE* - A specific version of the Java JDK/JRE that is used to build Java robot code and to run any of the Java based Tools (Dashboards, etc.). This exists side by side with any existing JDK installs and does not overwrite the `JAVA_HOME` variable
- *WPILib Tools* - SmartDashboard, Shuffleboard, Robot Builder, Outline Viewer, Pathweaver
- *WPILib Dependencies* - OpenCV, etc.
- *VS Code Extensions* - WPILib extensions for robot code development in VS Code

### What's Installed - Continued

The Offline Installer also installs a Desktop Shortcut to the WPILib copy of VS Code and sets up a command shortcut so this copy of VS Code can be opened from the command line using the command `frccode2020`.



Both of these reference the specific year as the WPILib C++ tools will now support side-by-side installs of multiple environments from different seasons.

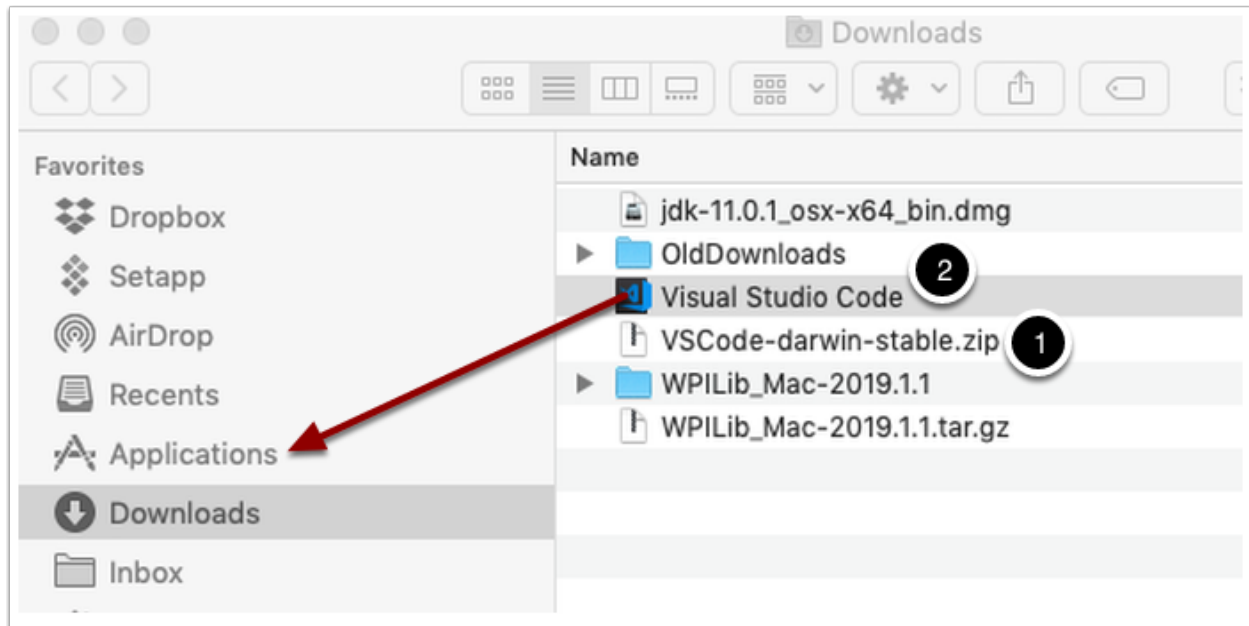
macOS

### Getting Visual Studio Code

VS Code is the IDE (Integrated Development Environment) that is used for 2019 and beyond. It needs to be installed on any development computer. It can be downloaded here: [code.visualstudio.com](https://code.visualstudio.com). For 2020, the recommended version is 1.41.1 which can be directly downloaded here: <https://update.code.visualstudio.com/1.41.1/darwin/stable>

The downloaded file will be “VSCode-darwin-stable.zip” (1)

Once downloaded, double-click on the zip file to expand it and copy the new file: “Visual Studio Code” to the Applications folder (2).



### Download the WPILib release and move the directory

Download the software release by navigating to this page: <https://github.com/wpilibsuite/allwpilib/releases> and downloading the macOS release.

Unzip and untar the file by looking at the file in the explorer and double-clicking on it, once or twice to unzip (remove the .gz extension) and again to untar it (remove the .tar extension). When finished it should look like the folder shown below.

Using Finder (or command line) copy the contents of the folder to a new folder in your home directory, ~/wpilib/2020 as shown below.

### Run the ToolsUpdater.py script

To update all the additional tools WPILib tools, open a terminal window and change directory to ~/wpilib/2020/tools and run the script ToolsUpdater.py with the commands:

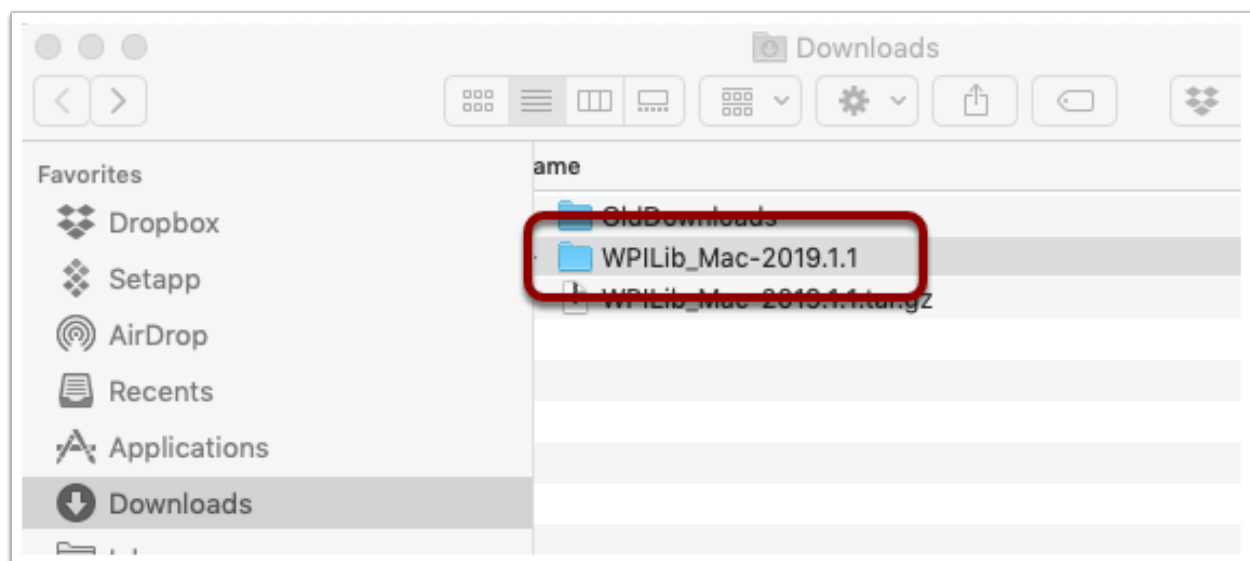
```
cd ~/wpilib/2020/tools
python ToolsUpdater.py
```

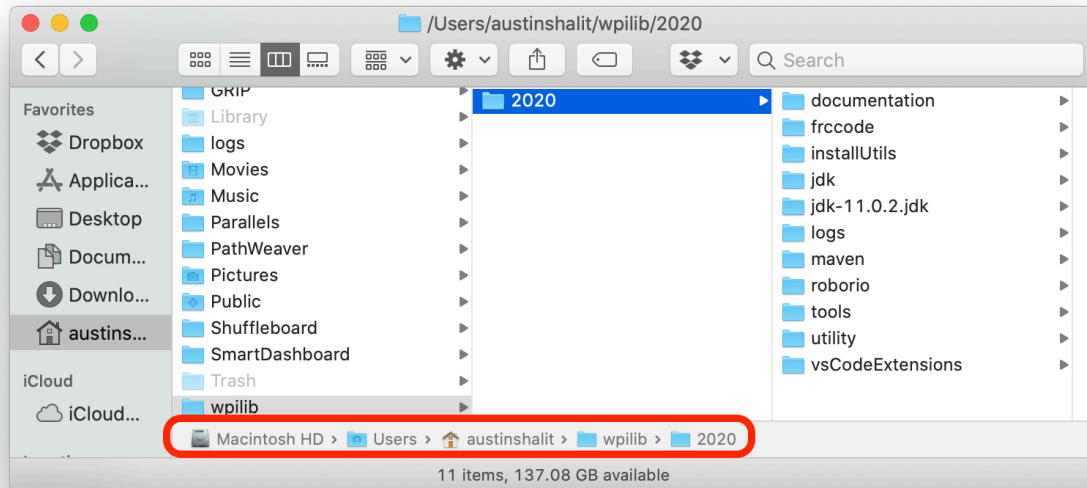
This should populate the tools directory with all of the WPILib tools (Shuffleboard, Robot Builder, PathWeaver, etc.)

### Installing the extensions for WPILib development



The screenshot shows the GitHub repository page for `wpi/suite / allwpi`. The `Releases` tab is selected, displaying the `WPILib 2019.1.1 Kickoff Release`. The release was made by `JacisNonsense` 11 hours ago. Under the `Assets` section, four files are listed: `WPILibInstaller_Windows32-2019.1.1.zip` (1.06 GB), `WPILibInstaller_Windows64-2019.1.1.zip` (1.1 GB), `WPILib_Linux-2019.1.1.tar.gz` (1.15 GB), and `WPILib_Mac-2019.1.1.tar.gz` (1.08 GB). The `WPILib_Mac-2019.1.1.tar.gz` file is highlighted with a red box. Below the assets, there are links for `Source code (zip)` and `Source code (tar.gz)`. The release description states: "This is the kickoff release of WPILib for the 2019 season." It also provides instructions for Windows and Mac/Linux users, with links to `https://wpilib.screenstepslive.com/s/currentCS/m/getting_started/l/999999-installing-c-and-java-development-tools-for-frc#windows` and `https://wpilib.screenstepslive.com/s/currentCS/m/getting_started/l/999999-`.

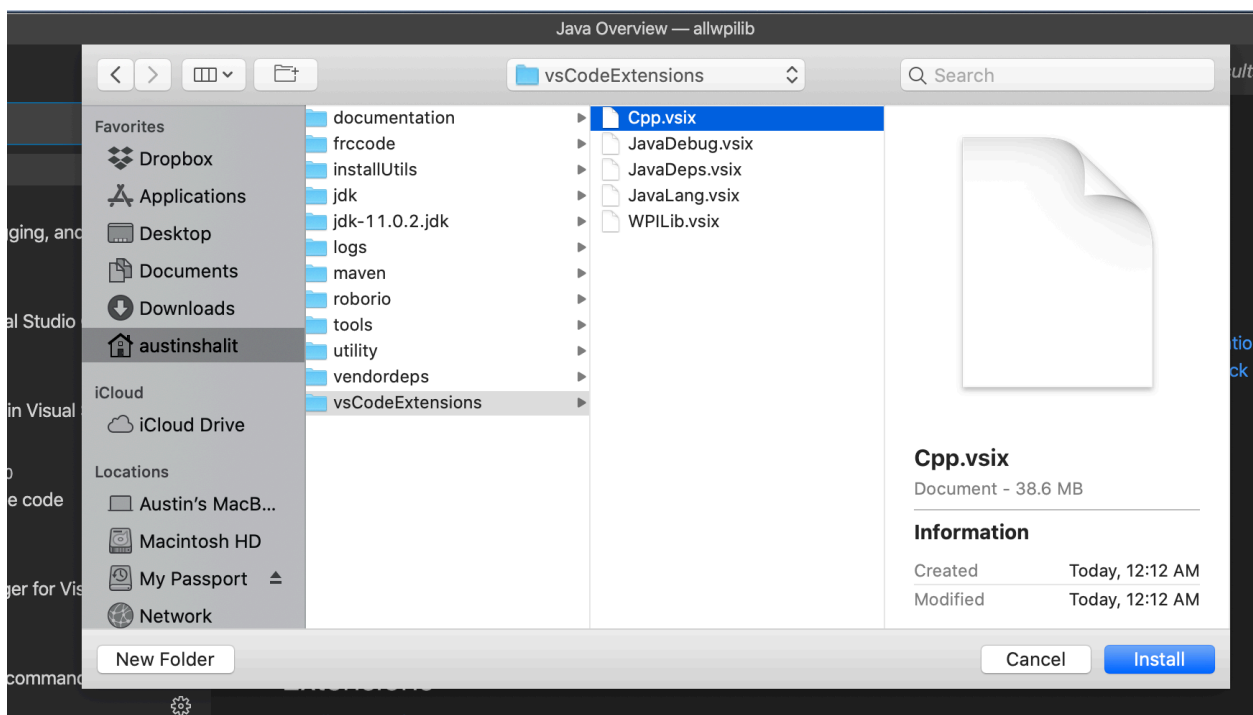
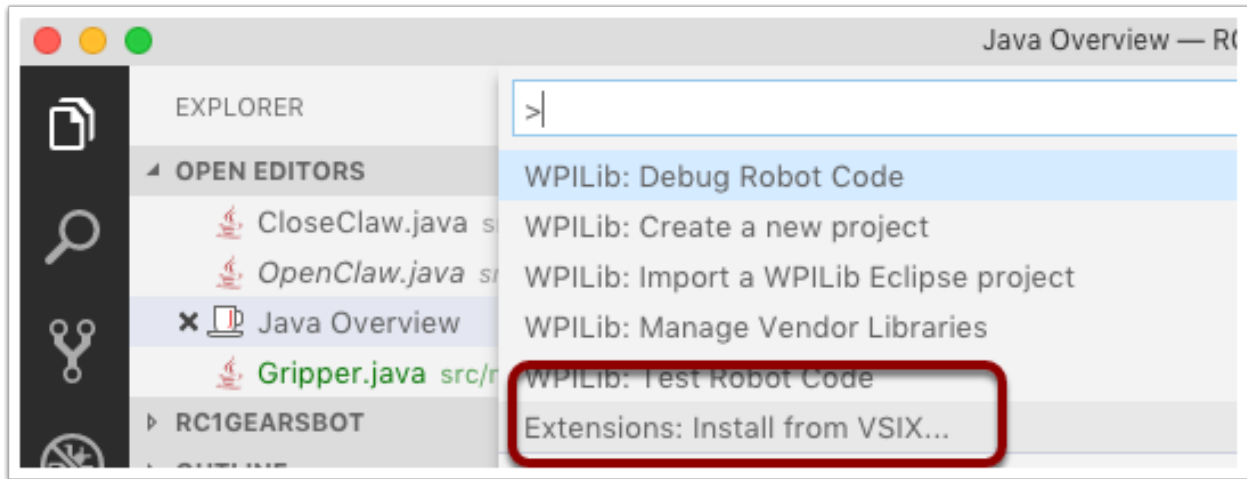




```
tools — austinshalit@austin-en0 — ..ib/2020/tools — -zsh — 69x9
[~ [ cd ~/wpilib/2020/tools ] 7:42 PM ]
[2020/tools [ python ToolsUpdater.py ] 7:42 PM ]

2020/tools [ █ ] 7:43 PM
```

Before using VS Code for WPILib development there are a number of extensions that need to be installed. Start up VS Code and type the shortcut Cmd-Shift-P to bring up the list of commands available. Start typing "Install from VSIX into the search box. Choose that command. In the file selection box select Cpp.vsix.



You should see a message confirming the install and asking to reload VS Code. Click the reload button then repeat the vsix installation for the rest of the vsix files in this order:

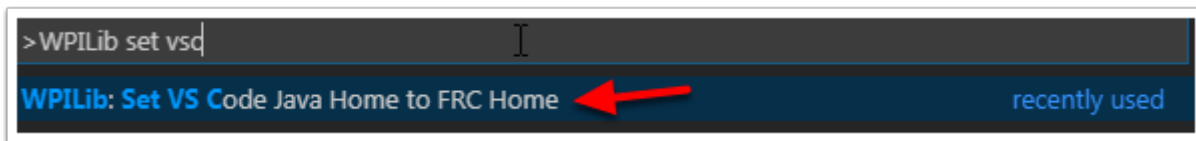
1. Cpp.vsix
2. JavaLang.vsix
3. JavaDeps.vsix
4. JavaDebug.vsix

### 5. WPILib.vsix

#### Setting up Visual Studio Code to use Java 11

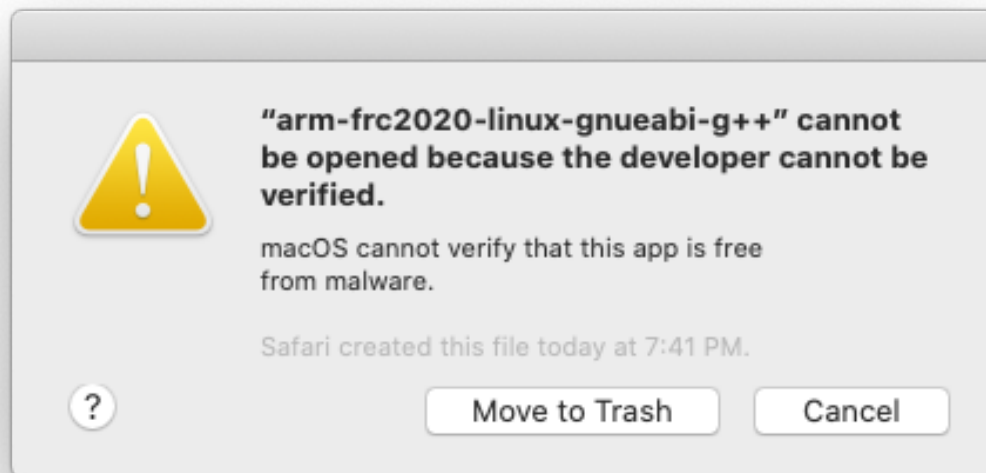
The WPILib installation includes a JDK, however you need to point VS Code at where it is. To do this:

- 1) Open VS Code
- 2) Press *Ctrl + Shift + P* and type *WPILib* or click on the WPILib icon in the top right to open the WPILib Command Palette
- 3) Begin typing *Set VS Code Java Home to FRC Home* and select that item from the dropdown



#### Allow toolchain to bypass Gatekeeper

In order to build certain components, you may be prompted with a Gatekeeper dialog that says: "cannot be opened because the developer cannot be verified".



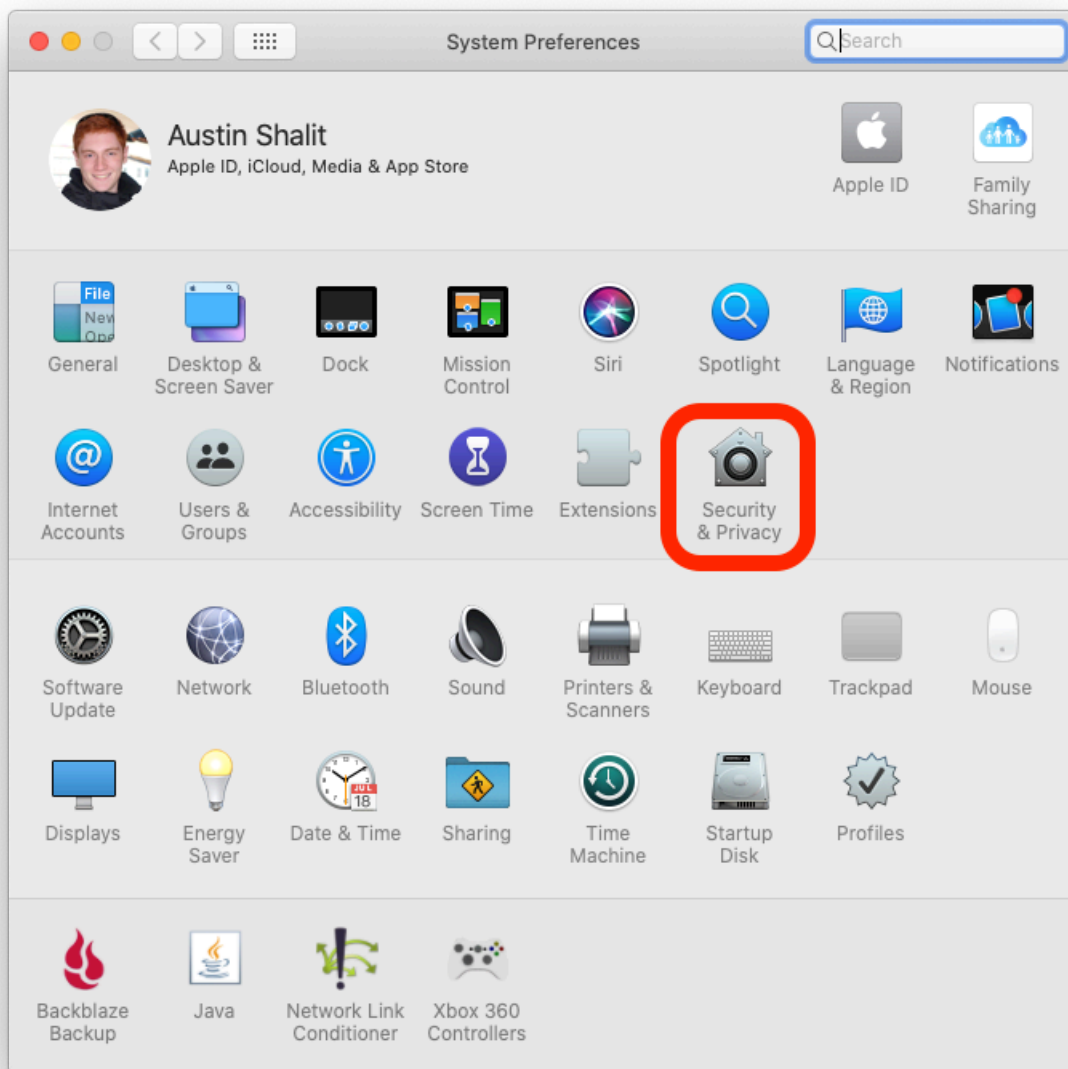
The name of the programs that will cause this are named:

- arm-frc2020-linux-gnueabi-g++
- ccl
- arm-frc2020-linux-gnueabi-gcc
- cclplus

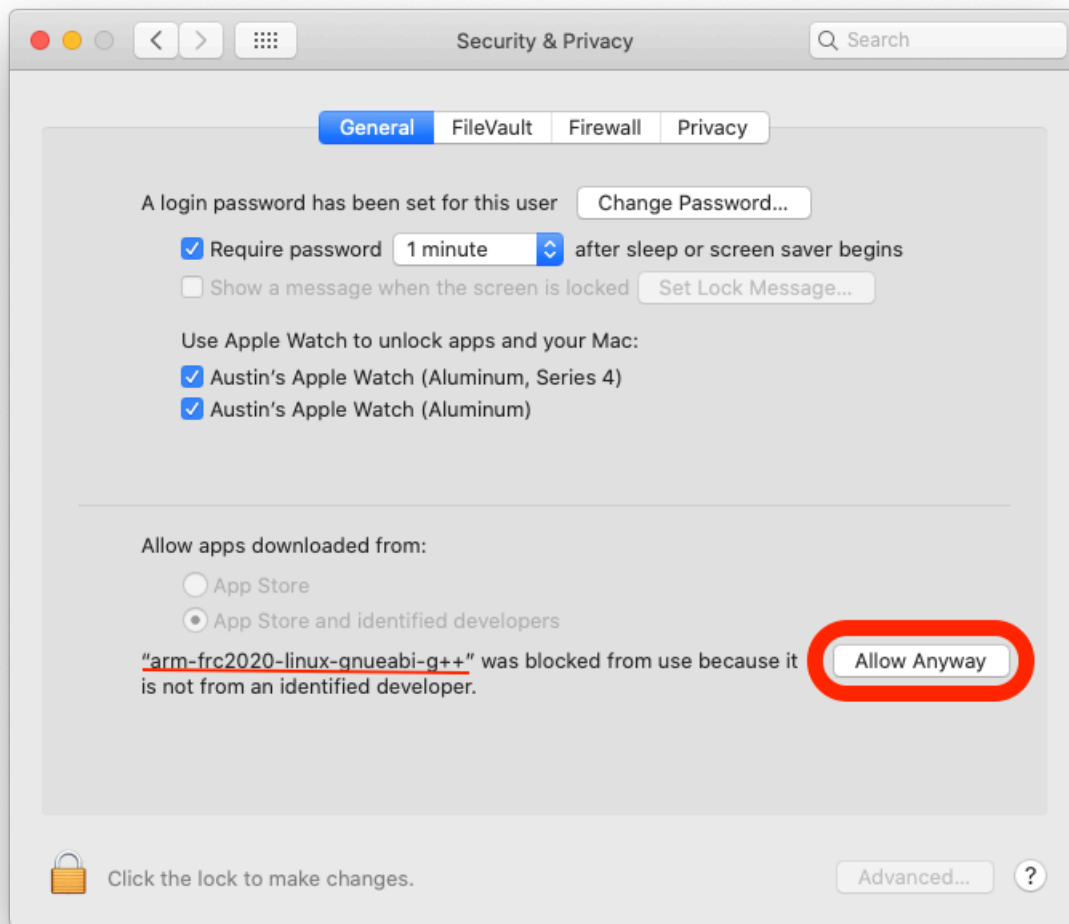
- as
- collect2
- ld
- liblto\_plugin.so
- arm-frc2020-linux-gnueabi-objcopy
- arm-frc2020-linux-gnueabi-strip

Builds will fail when this dialog appears. Follow the steps below and try to rerun the build.

- 1) Press the *Cancel* button on the dialog.
- 2) Open System Preferences to the “Security and Privacy” pane



3) On the “General” tab, press *Allow Anyway*



4) Rerun the build that caused the initial dialog to appear

5) A similar dialog will appear but will have an *Open* button. Press the *Open* button

You may need to repeat this process multiple times for each of the programs listed above but once each program has been whitelisted, it should stay whitelisted and not prompt you again.

Linux

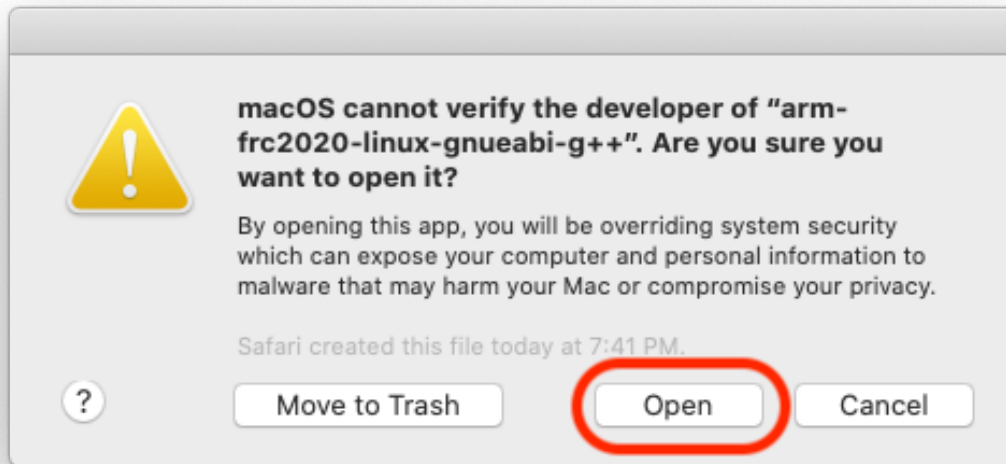
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**Note:** These instructions are based on Ubuntu 18.04, but would be similar for other Debian based Linux distributions.

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### Installing Visual Studio Code

1. Download the Linux .deb file from [code.visualstudio.com](https://code.visualstudio.com). For 2020, the recommended version is 1.41.1 which can be directly downloaded here: <https://update.code.visualstudio.com/1.41.1/linux-deb-x64/stable>



2. Double-click on the .deb file in the file explorer
3. Click the “Install” button to install VS Code

### Download the most recent WPILib release

Download the latest Linux release from <https://github.com/wpilibsuite/allwpilib/releases> Right-click on the downloaded archive, click “Extract Here”

### Moving to wpilib/2020

1. Create a directory structure in your home directory called wpilib/2020 - either from the file manager or with `$ mkdir -p ~/wpilib/2020`
2. Drag the contents of WPILib\_Linux-VERSIONUM directory to ~/wpilib/2020 or run `$ mv -v WPILib_Linux-VERSIONUM/* ~/wpilib/2020`

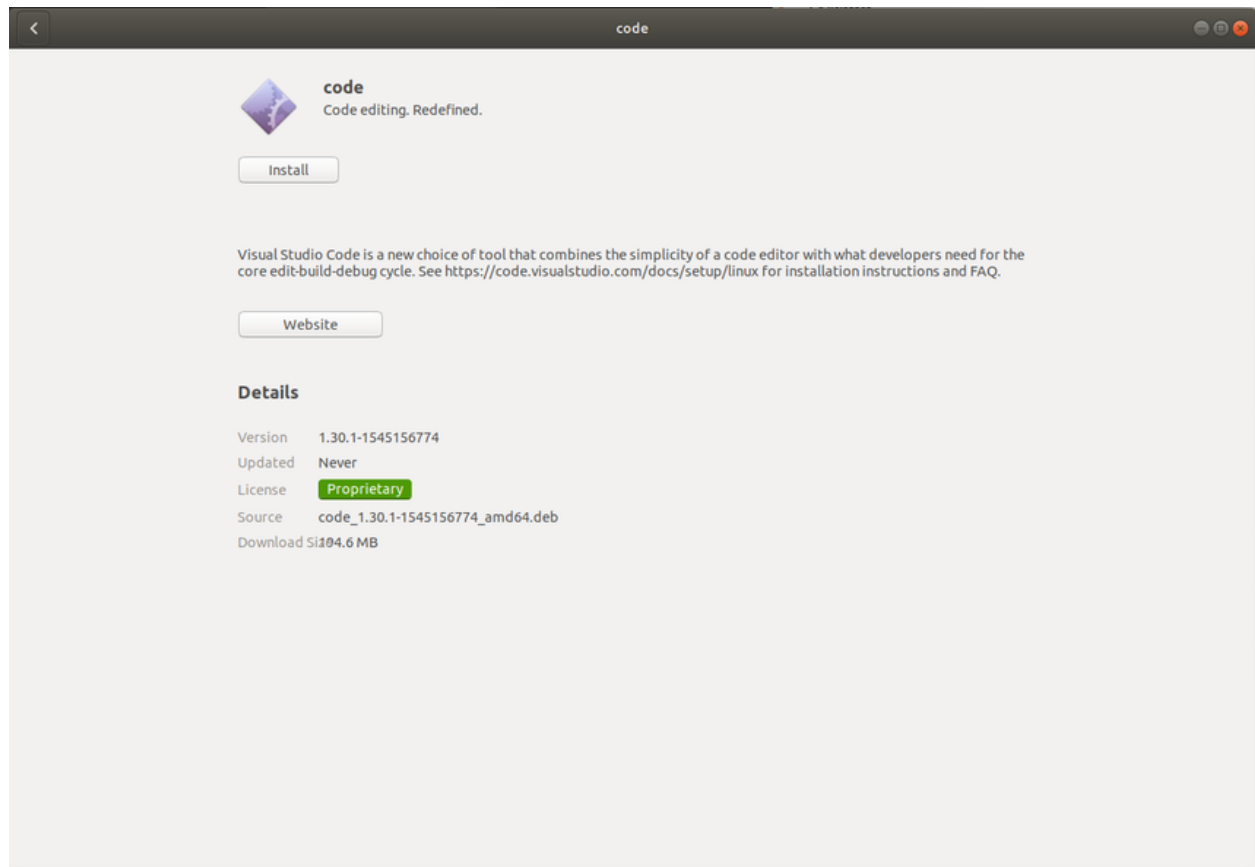
### Running Tools Updater

To update or extract the WPILib tools (Dashboards, Robot Builder, etc.), run:

```
$ example@pc:~/Downloads$ cd ~/wpilib/2020/tools
$ example@pc:~/wpilib/2020/tools$ python3 ToolsUpdater.py
```

### Installing the extensions for WPILib Visual Studio Code

1. Start VS Code (`$ code` or search “Visual Studio Code” in your application launcher)
2. *Control-Shift-P* to bring up the command palette, type “Install from VSIX”
3. Select “Extensions: Install from VSIX”
4. Navigate to ~/wpilib/2020/vsCodeExtensions and select Cpp.vsix
5. Repeat for JavaLang.vsix, JavaDeps.vsix, JavaDebug.vsix, and WPILib.vsix in that order



Latest release

35eb90c

Compare

## WPILib Release


 PeterJohnson released this on Jan 3

### Getting Started

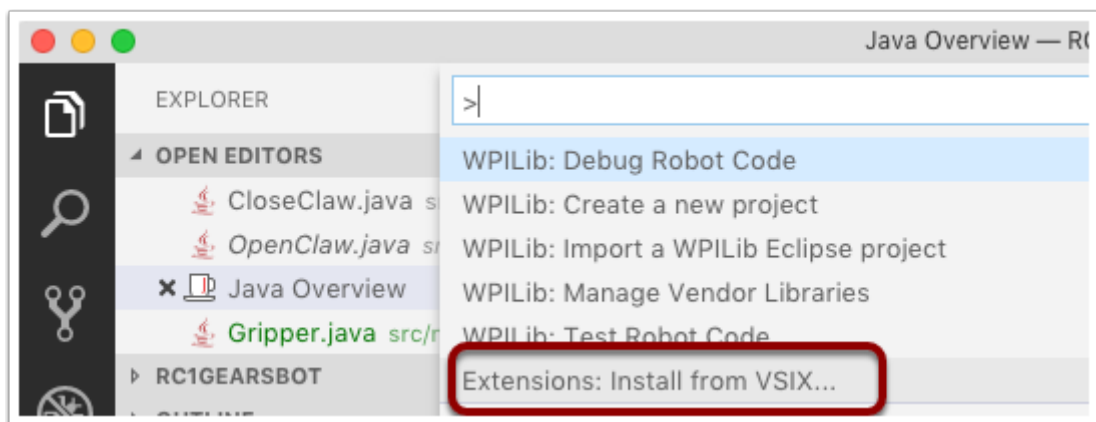
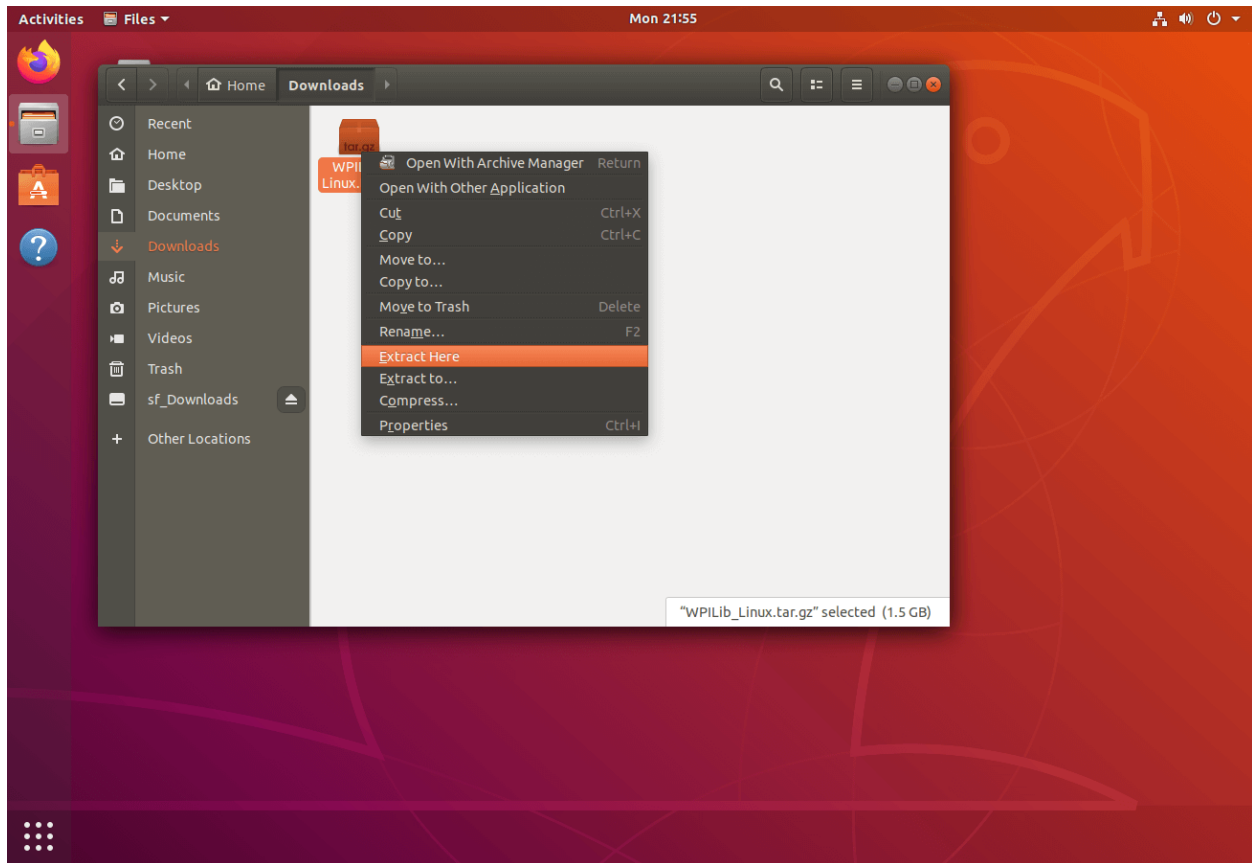
Download the appropriate file for your platform and see the installation instructions at [Getting started](#).

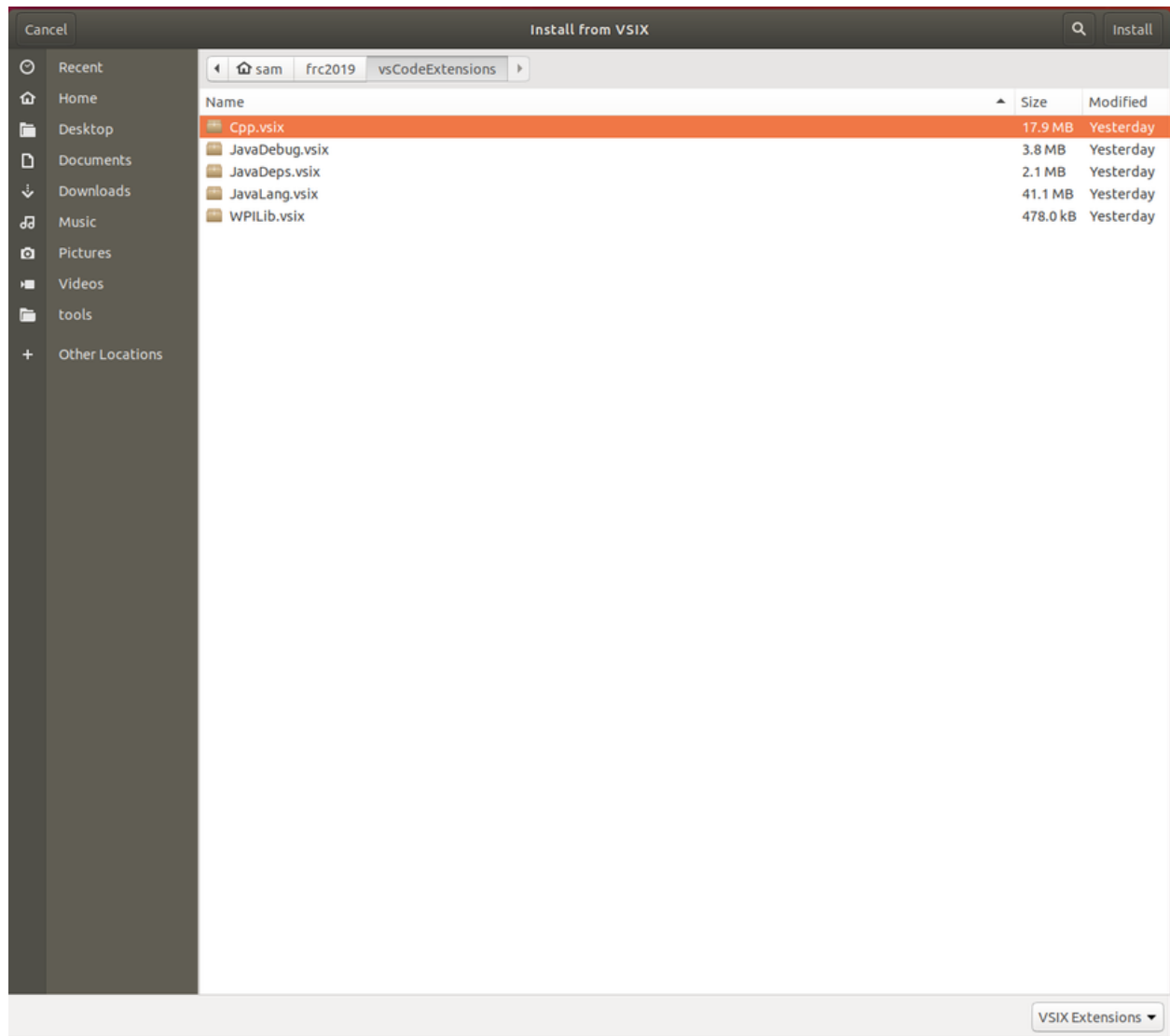
For this release, it's okay to skip reinstalling Visual Studio Code, JDK, and the compiler if you already installed them with a previous release.

#### Assets 6

 <a href="#">WPILibInstaller_Windows32.zip</a>	1.19 GB
 <a href="#">WPILibInstaller_Windows64.zip</a>	1.23 GB
 <a href="#">WPILib_Linux.tar.gz</a>	1.37 GB
 <a href="#">WPILib_Mac.tar.gz</a>	1.19 GB
 <a href="#">Source code (zip)</a>	
 <a href="#">Source code (tar.gz)</a>	



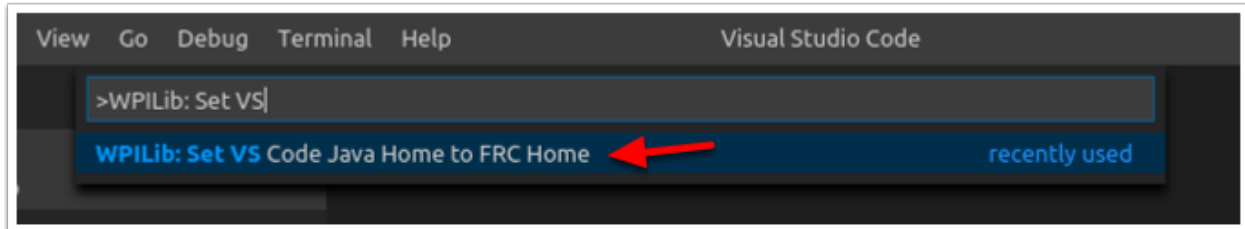




## Setting up Visual Studio Code to use Java 11

The WPILib installation includes a JDK, however you need to point VS Code at where it is. To do this:

1. Open VS Code
2. Press *Ctrl-Shift-P* and type *WPILib* or click on the WPILib icon in the top right to open the WPILib Command Palette
3. Begin typing *Set VS Code Java Home to FRC Home* and select that item from the dropdown.



## Install libvulkan for simulation GUI

To install libvulkan in order to run the simulation GUI run:

```
$ example@pc:~$ sudo apt-get install libvulkan1
```

**Note:** The installation directory has changed for 2020. In 2019 the software was installed to `~\frcYYYY` where `~` is `C:\Users\Public` on Windows and `YYYY` is the FRC year. In 2020 and later it is installed to `~\wpilib\YYYY`. This lessens clutter when multiple years software are installed.

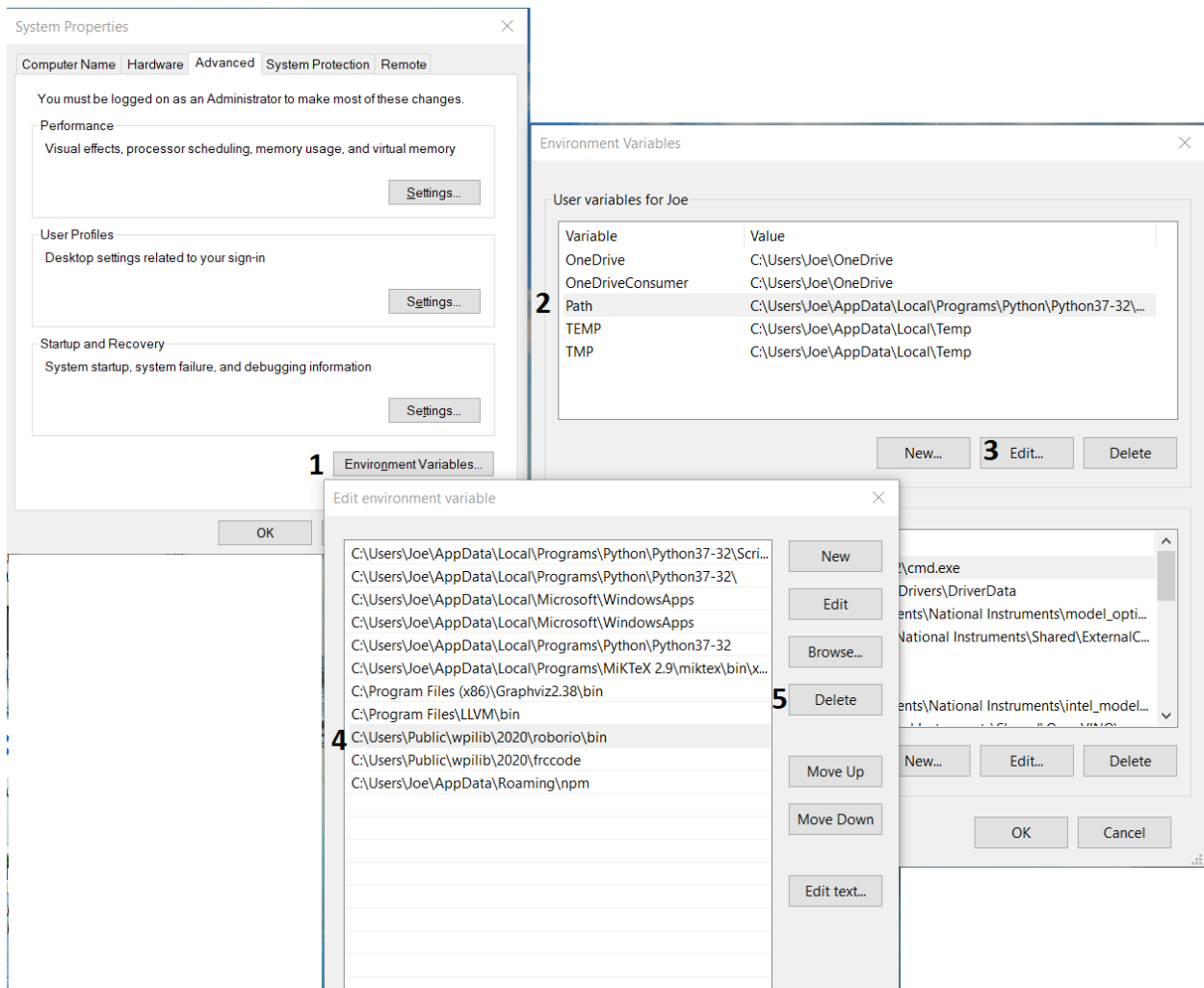
### 1.5.1 Uninstall Instructions

WPILib is designed to install to different folders for different years, so that it is not necessary to uninstall a previous version before installing this year's WPILib. However, the following instructions can be used to uninstall WPILib if desired.

Windows

1. Delete the appropriate wpilib folder (2019: `c:\Users\Public\frc2019`, 2020 and later: `c:\Users\Public\wpilib\YYYY` where `YYYY` is the year to uninstall)
2. Delete the desktop icons at `C:\Users\Public\Public Desktop`
3. Delete the path environment variables.
  1. In the start menu, type environment and select "edit the system environment variables"
  2. Click on the environment variables button (1).
  3. In the user variables, select path (2) and then click on edit (3).
  4. Select the path with `roborio\bin` (4) and click on delete (5).
  5. Select the path with `frccode` and click on delete (5).

6. Repeat steps 3-6 in the Systems Variable pane.



## macOS

1. Delete Visual Studio Code from the Applications folder. Alternately, the extensions can be **uninstalled**
2. Delete the appropriate wpilib folder (2019: ~/frc2019, 2020 and later: ~/wpilib/YYYY where YYYY is the year to uninstall)

## Linux

1. Delete the appropriate wpilib folder (2019: ~/frc2019, 2020 and later: ~/wpilib/YYYY where YYYY is the year to uninstall). eg `rm -rf ~/frc2019`
2. Uninstall Visual Studio Code `sudo dpkg -r code`. Alternately, the extensions can be **uninstalled**

## 1.6 Installing LabVIEW for FRC (LabVIEW only)



---

**Note:** This installation is for teams programming in LabVIEW or using NI Vision Assistant only. C++ and Java teams not using these features do not need to install from the DVD and should proceed to *Installing the FRC Game Tools*.

---

Download and installation times will vary widely with computer and internet connection specifications, however note that this process involves a large file download and installation and will likely take at least an hour to complete.

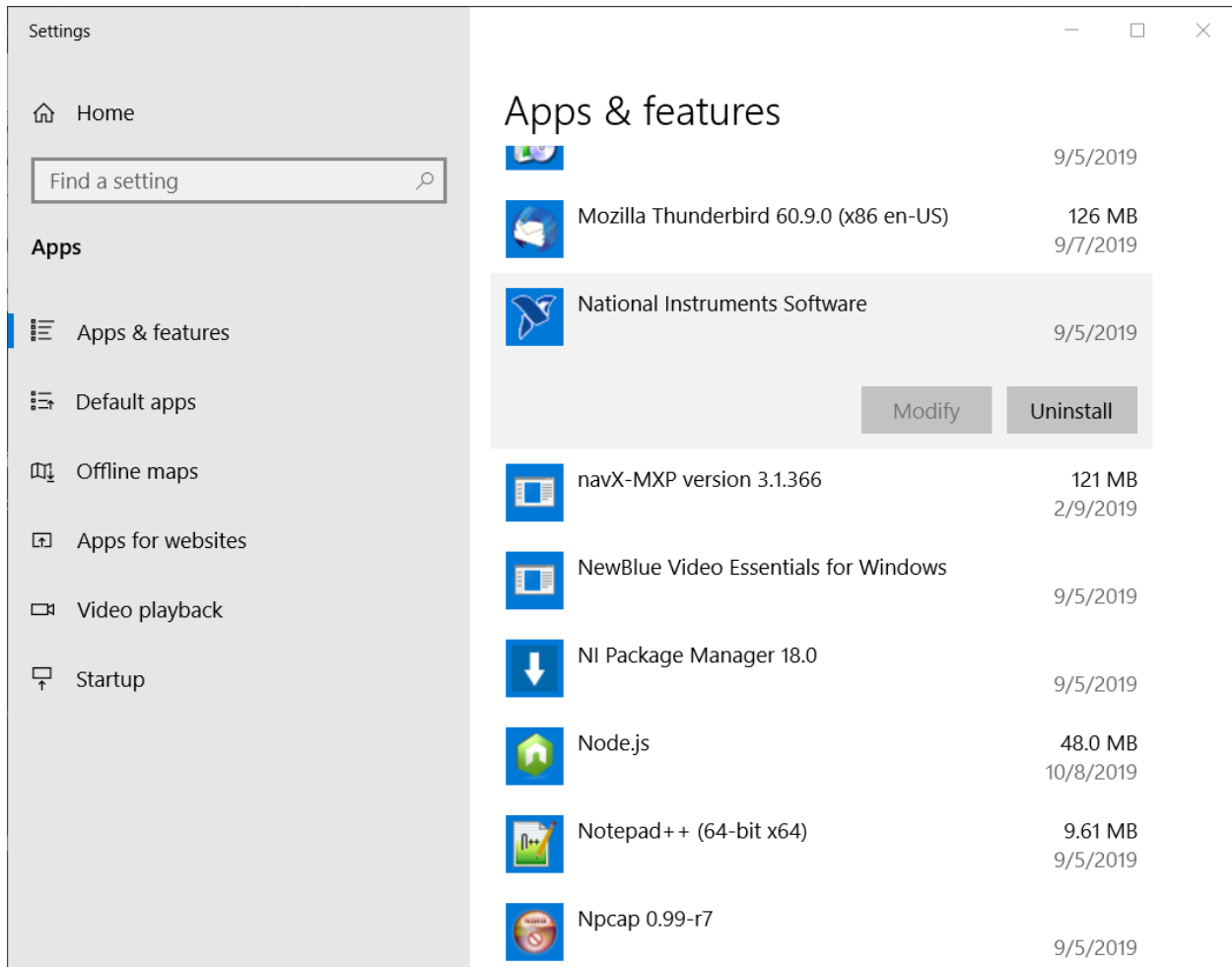
### 1.6.1 Uninstall Old Versions (Recommended)

---

**Note:** If you wish to keep programming cRIOs you will need to maintain an install of LabVIEW for FRC 2014. The LabVIEW for FRC 2014 license has been extended. While these versions should be able to co-exist on a single computer, this is not a configuration that has been extensively tested.

---

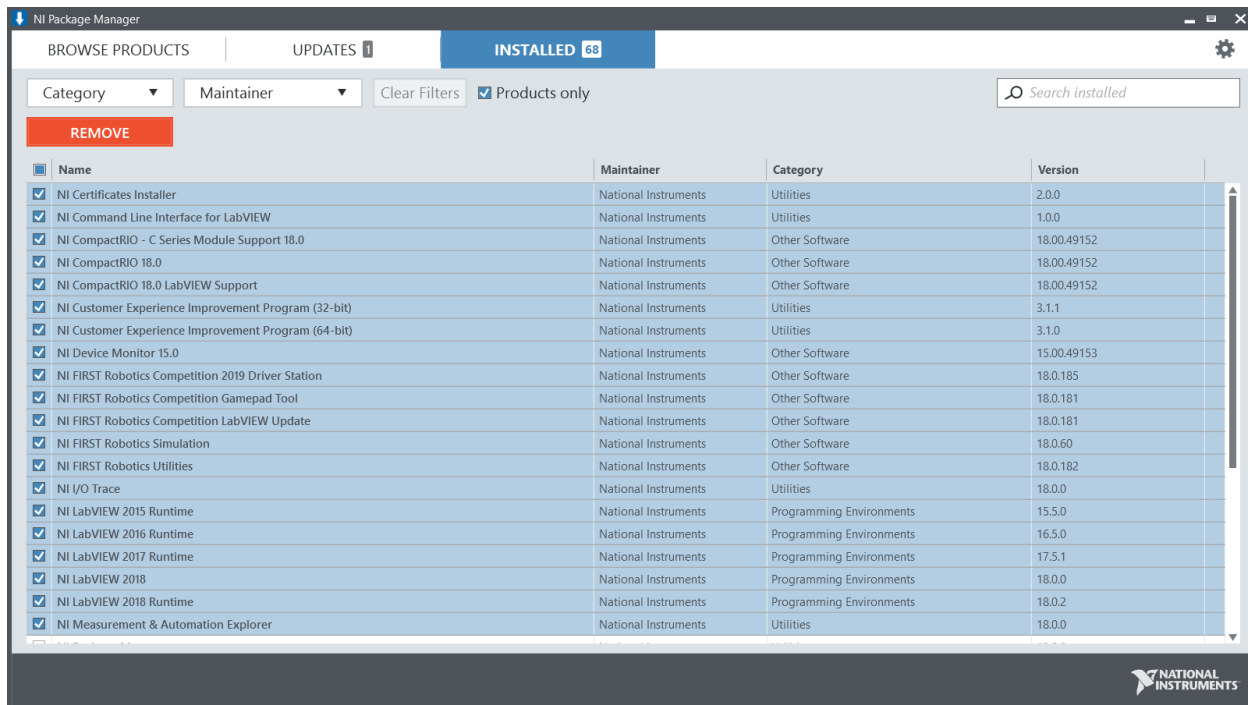
Before installing the new version of LabVIEW it is recommended to remove any old versions. The new version will likely co-exist with the old version, but all testing has been done with FRC 2020 only. Make sure to back up any team code located in the "User\LabVIEW Data" directory before un-installing. Then click Start >> Add or Remove Programs. Locate the entry labeled "National Instruments Software", and select Uninstall.



### Select Components to Uninstall

In the dialog box that appears, select all entries. The easiest way to do this is to de-select the “Products Only” check-box and select the check-box to the left of “Name”. Click Remove. Wait for the uninstaller to complete and reboot if prompted.

**Warning:** These instructions assume that no other National Instruments software is installed. If you have other National Instruments software installed, it is necessary to uncheck the software that should not be uninstalled.



## 1.6.2 Getting LabVIEW installer

Either locate and insert the LabVIEW USB Drive or download the LabVIEW 2020 installer from [https://www.ni.com/en-us/support/downloads/drivers/download\\_labview-software-for-frc.html](https://www.ni.com/en-us/support/downloads/drivers/download_labview-software-for-frc.html)

DOWNLOAD

Online installer

**File Size**

5.37 MB

i **Note:** If you need to download individual versions or patches, you can select from Individual Offline Installers

Offline Installer

If you wish to install on other machines offline, do not click the Download button, click **Individual Offline Installers** and then click Download, to download the full installer.

**Note:** This is a large download (~8GB). It is recommended to use a fast internet connection and to use the NI Downloader to allow the download to resume if interrupted.

### 1.6.3 Installing LabVIEW

National Instruments LabVIEW requires a license. Each season's license is active until January 31st of the following year (e.g. the license for the 2020 season expires on January 31, 2021)

Teams are permitted to install the software on as many team computers as needed, subject to the restrictions and license terms that accompany the applicable software, and provided that only team members or mentors use the software, and solely for FRC. Rights to use LabVIEW are governed solely by the terms of the license agreements that are shown during the installation of the applicable software.

#### Welcome

#### Starting Install

##### Online Installer

Run the downloaded exe file to start the install process. Click "Yes" if a Windows Security prompt

##### Offline Installer (Windows 10)

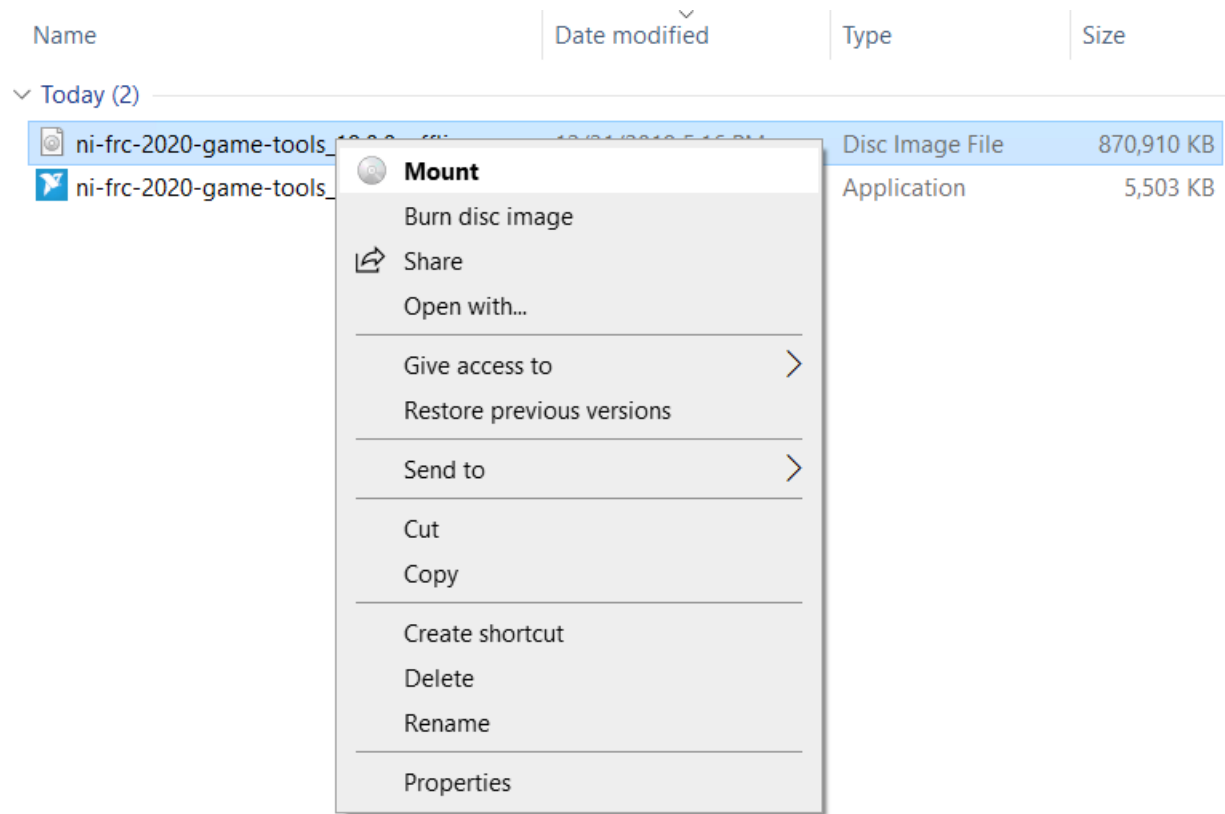
Right click on the downloaded iso file and select mount. Run install.exe from the mounted iso. Click "Yes" if a Windows Security prompt

---

**Note:** other installed programs may associate with iso files and the mount option may not appear. If that software does not give the option to mount or extract the iso file, then follow the directions in the "Offline Installer (Windows 7, 8, & 8.1)" tab.

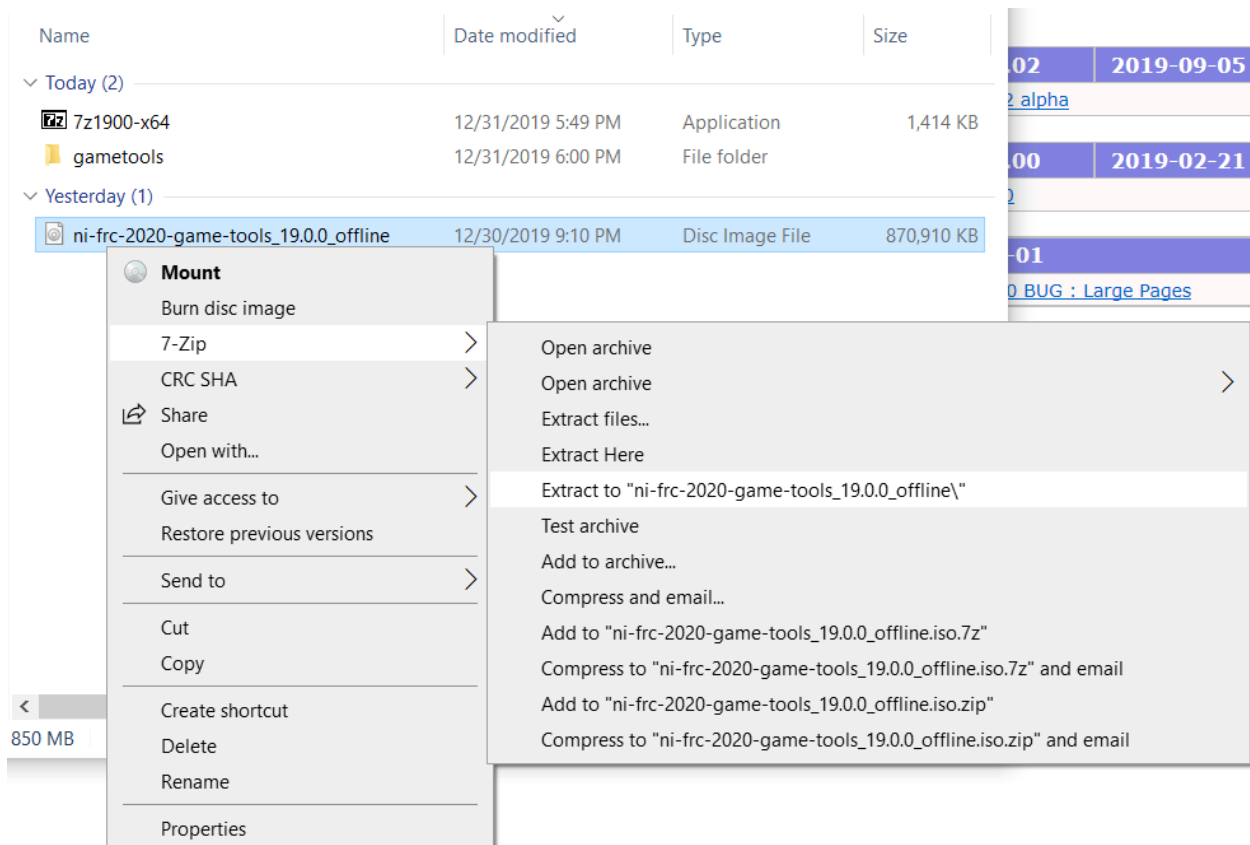
---



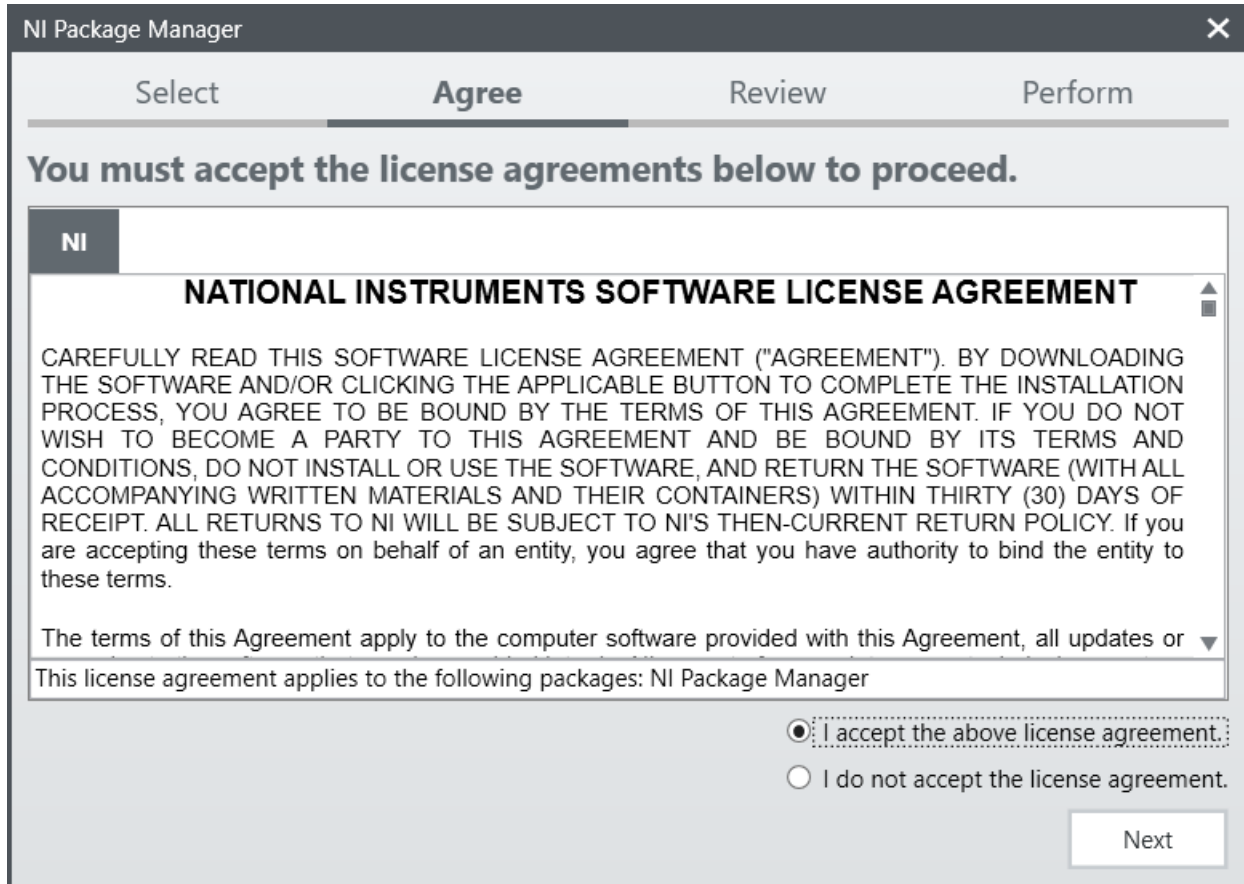


Offline Installer (Windows 7, 8, & 8.1)

Install 7-Zip (download [here](#)). As of the writing of this document, the current released version is 19.00 (2019-02-21). Right click on the downloaded iso file and select Extract to.



Run install.exe from the extracted folder. Click “Yes” if a Windows Security prompt appears. Click “Yes” if a Windows Security prompt appears.

**NI Package Manager License**

The image shows a screenshot of the 'NI Package Manager' window. At the top, there is a title bar with the text 'NI Package Manager' and a close button. Below the title bar is a navigation bar with four tabs: 'Select', 'Agree', 'Review', and 'Perform'. The 'Agree' tab is currently selected. The main content area has a heading 'You must accept the license agreements below to proceed.' followed by a list of license agreements. The first agreement is 'NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT'. The text of the agreement is displayed in a scrollable area. At the bottom of the window, there are two radio buttons: 'I accept the above license agreement.' (which is selected) and 'I do not accept the license agreement.'. A 'Next' button is located at the bottom right of the window.

NI Package Manager

Select Agree Review Perform

**You must accept the license agreements below to proceed.**

**NI**

**NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT**

CAREFULLY READ THIS SOFTWARE LICENSE AGREEMENT ("AGREEMENT"). BY DOWNLOADING THE SOFTWARE AND/OR CLICKING THE APPLICABLE BUTTON TO COMPLETE THE INSTALLATION PROCESS, YOU AGREE TO BE BOUND BY THE TERMS OF THIS AGREEMENT. IF YOU DO NOT WISH TO BECOME A PARTY TO THIS AGREEMENT AND BE BOUND BY ITS TERMS AND CONDITIONS, DO NOT INSTALL OR USE THE SOFTWARE, AND RETURN THE SOFTWARE (WITH ALL ACCOMPANYING WRITTEN MATERIALS AND THEIR CONTAINERS) WITHIN THIRTY (30) DAYS OF RECEIPT. ALL RETURNS TO NI WILL BE SUBJECT TO NI'S THEN-CURRENT RETURN POLICY. If you are accepting these terms on behalf of an entity, you agree that you have authority to bind the entity to these terms.

The terms of this Agreement apply to the computer software provided with this Agreement, all updates or

This license agreement applies to the following packages: NI Package Manager

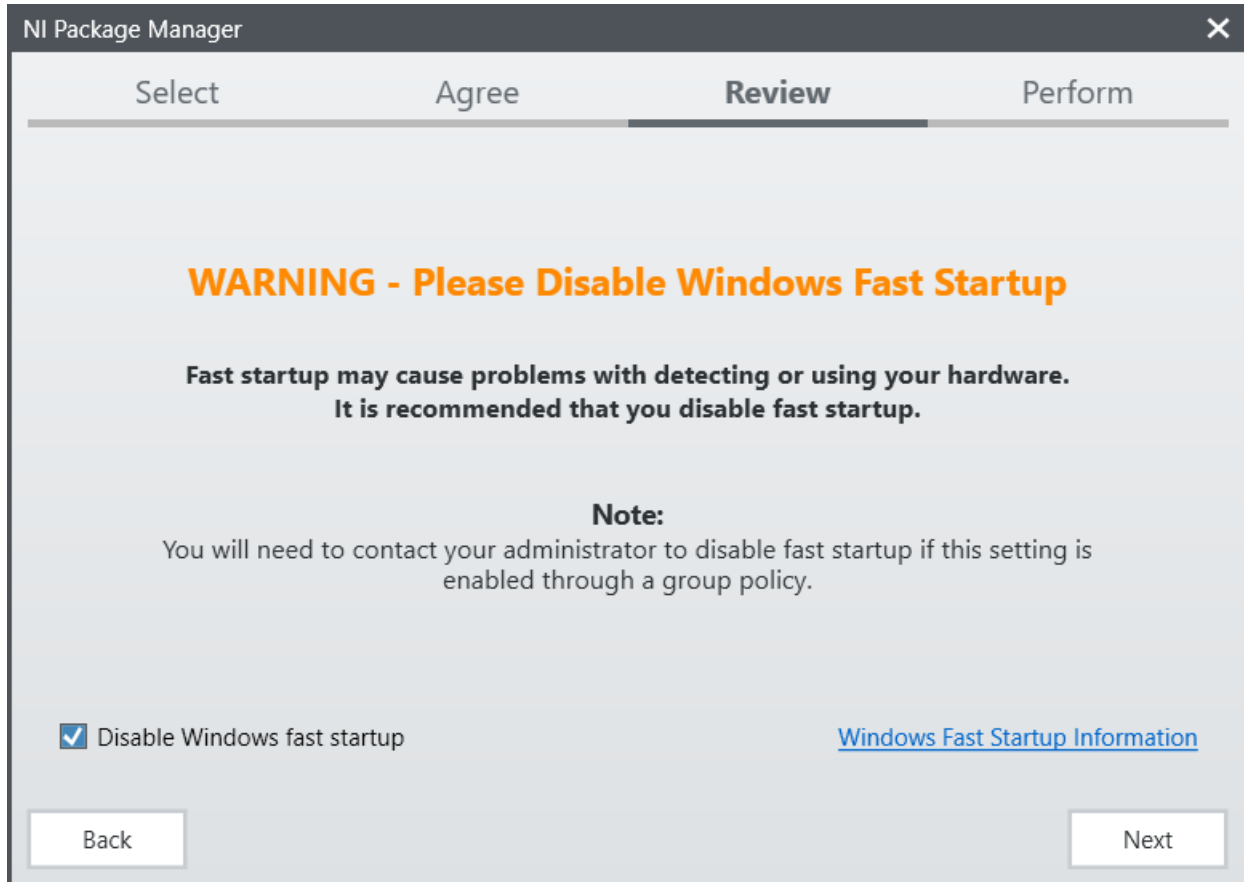
☒ I accept the above license agreement.

☐ I do not accept the license agreement.

Next

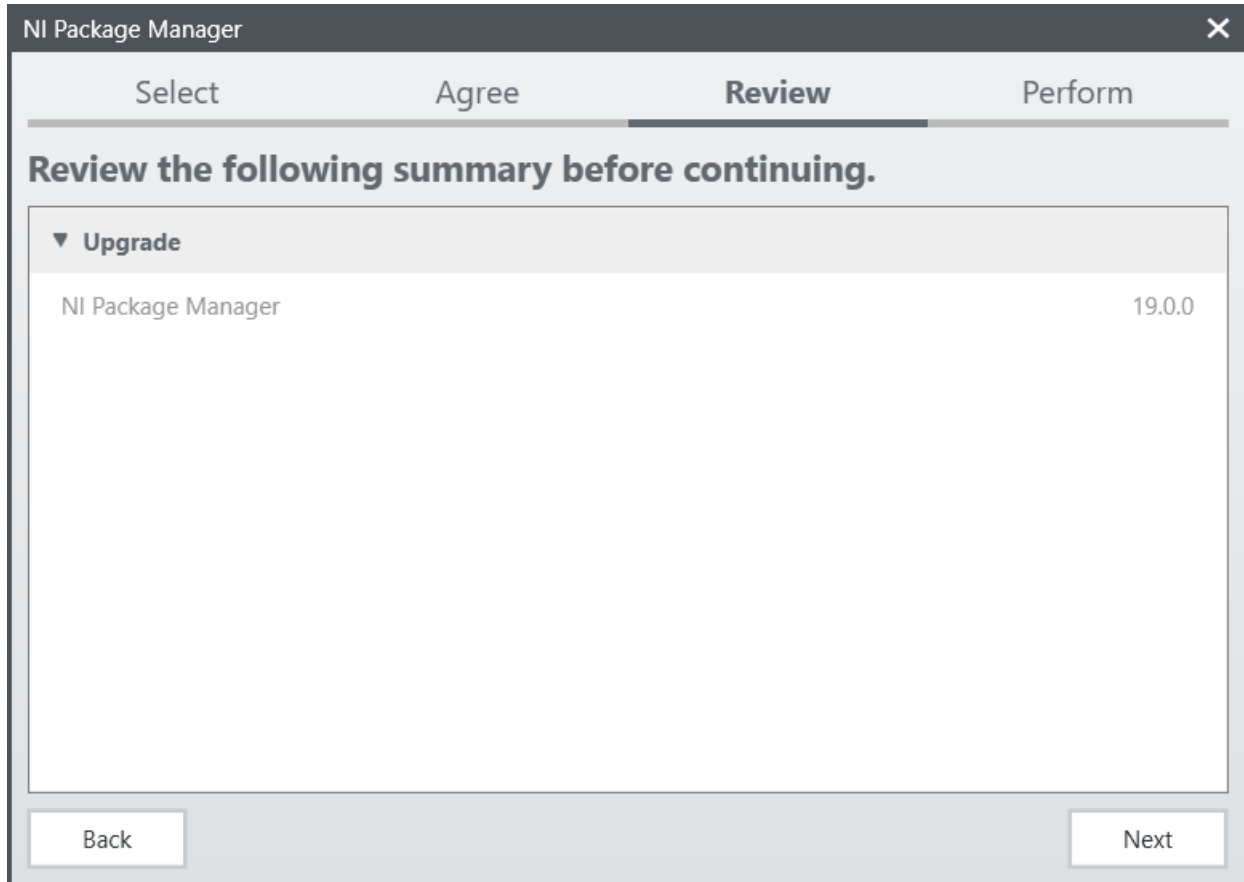
If you see this screen, click "Next"

### Disable Windows Fast Startup



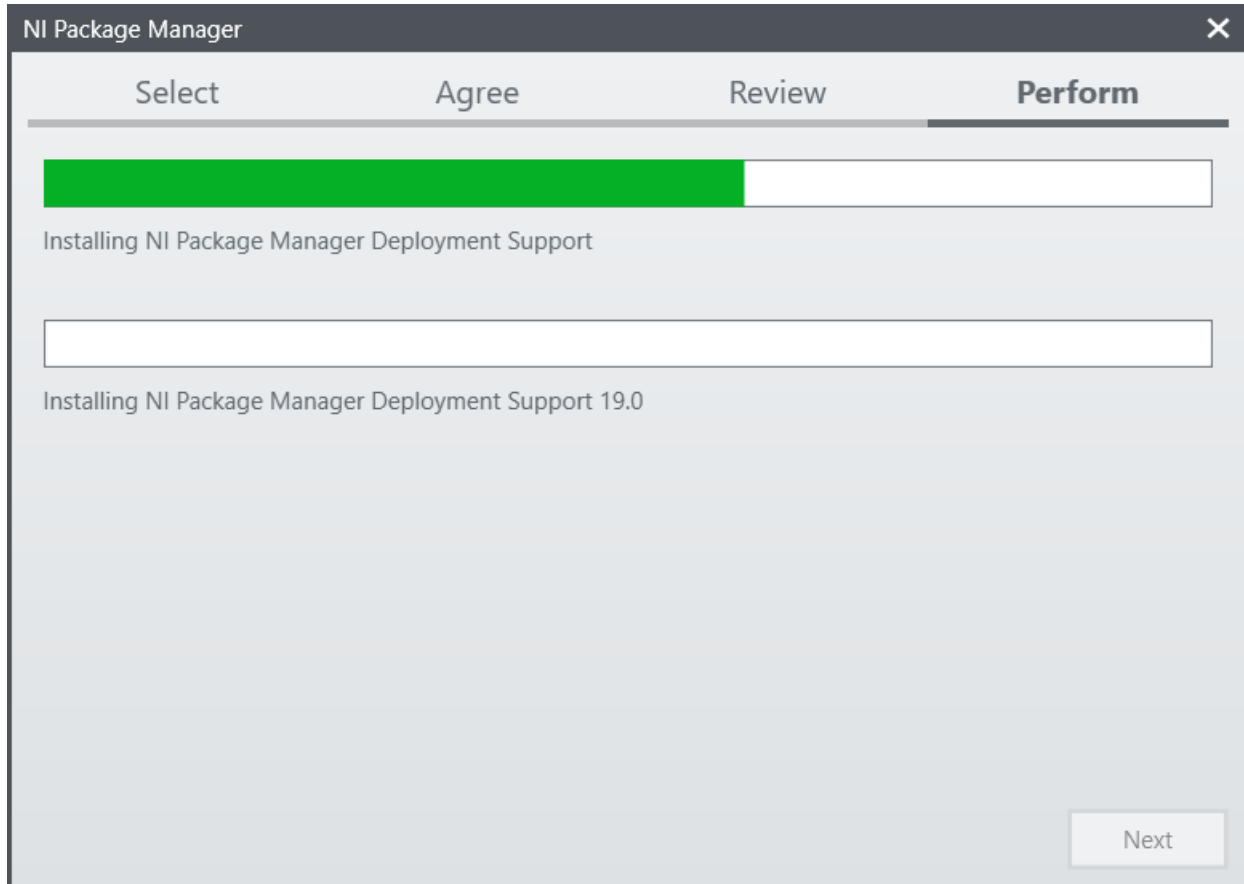
If you see this screen, click "Next"

## NI Package Manager Review

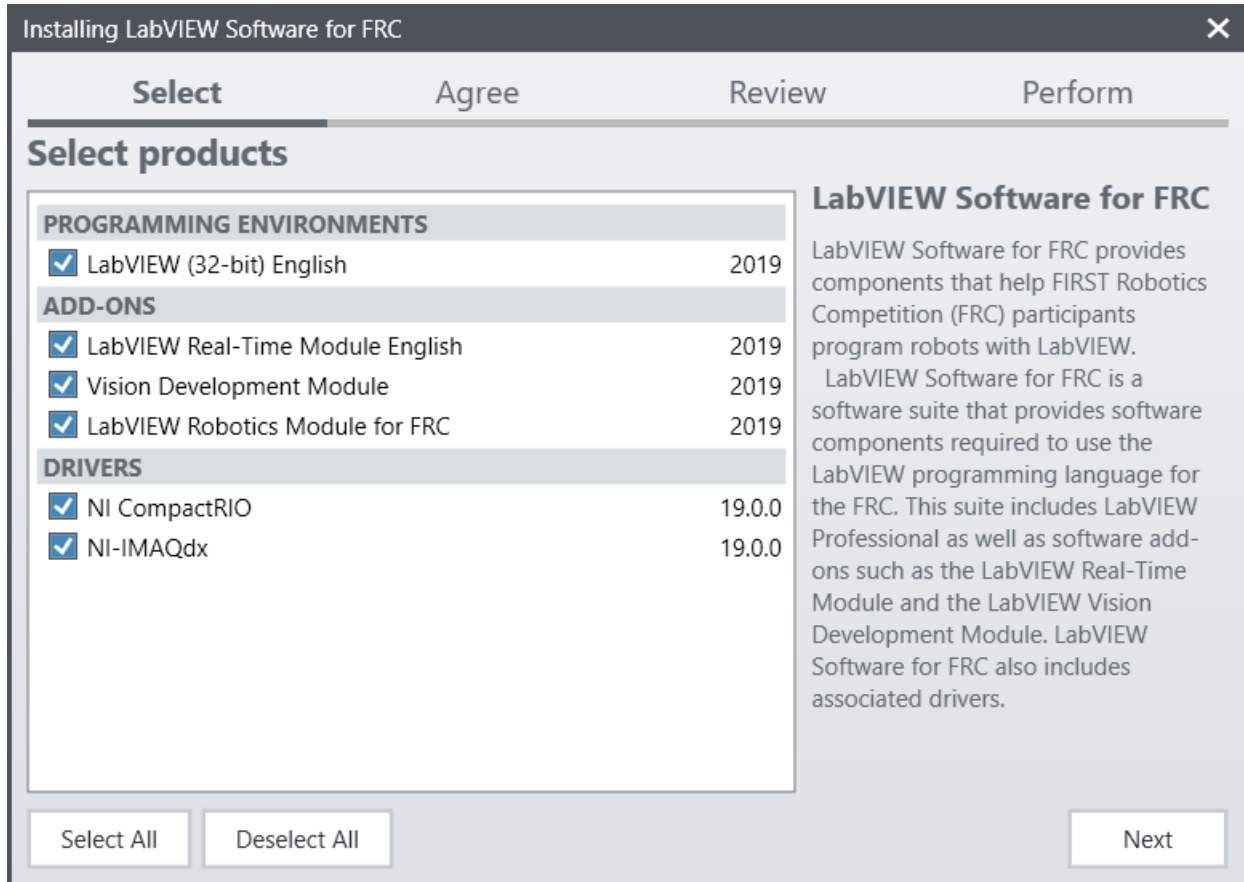


If you see this screen, click “Next”

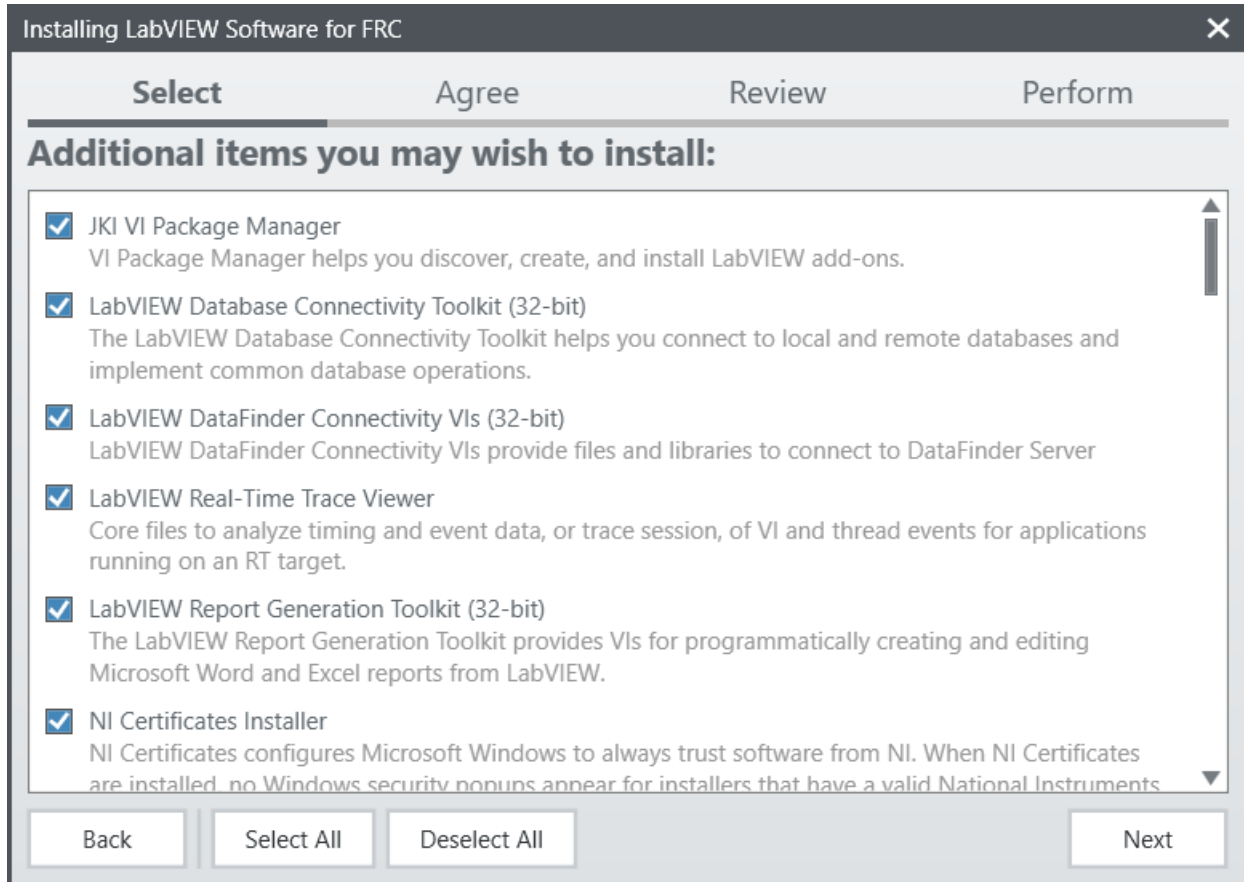
## **NI Package Manager Installation**



Installation progress of the NI Package Manager will be tracked in this window

**Product List**

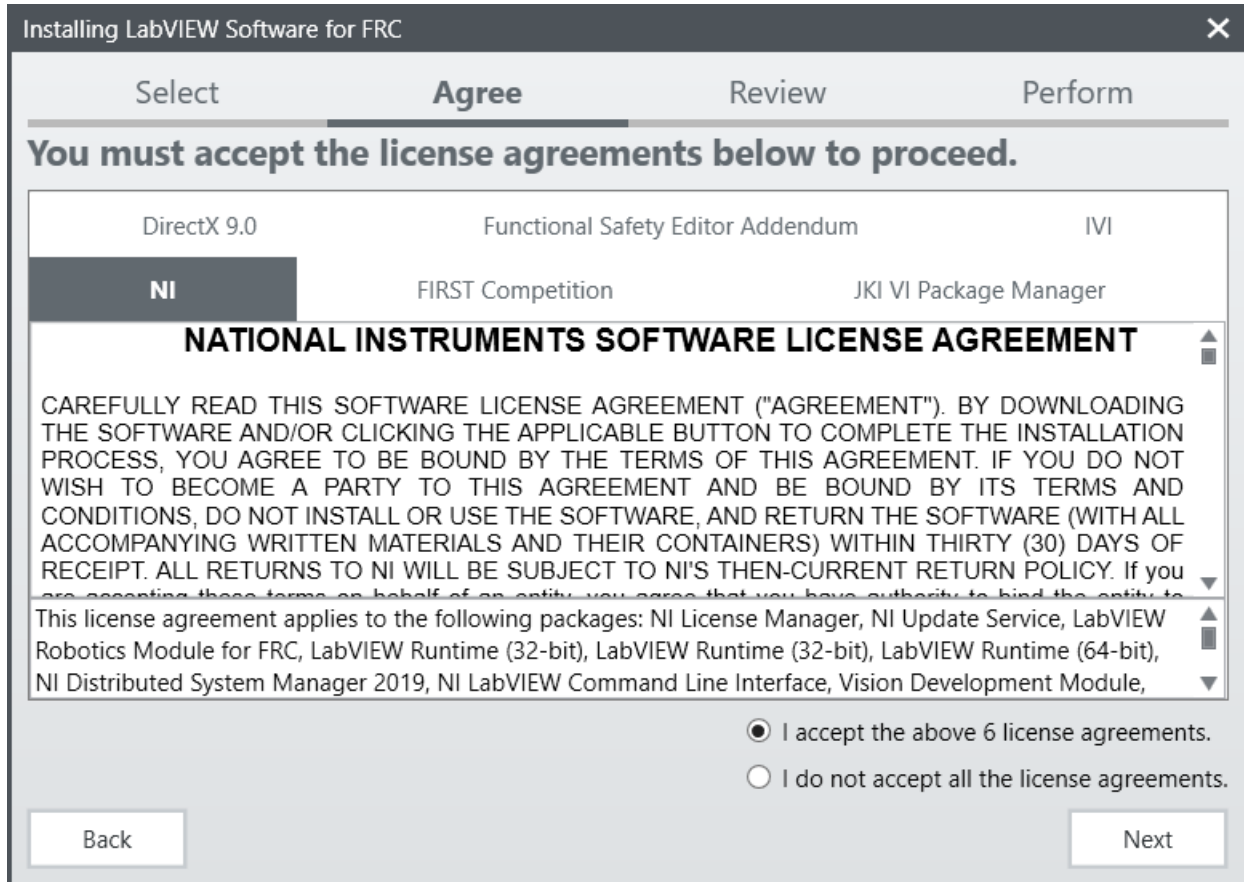
Click "Next"

**Additional Packages**

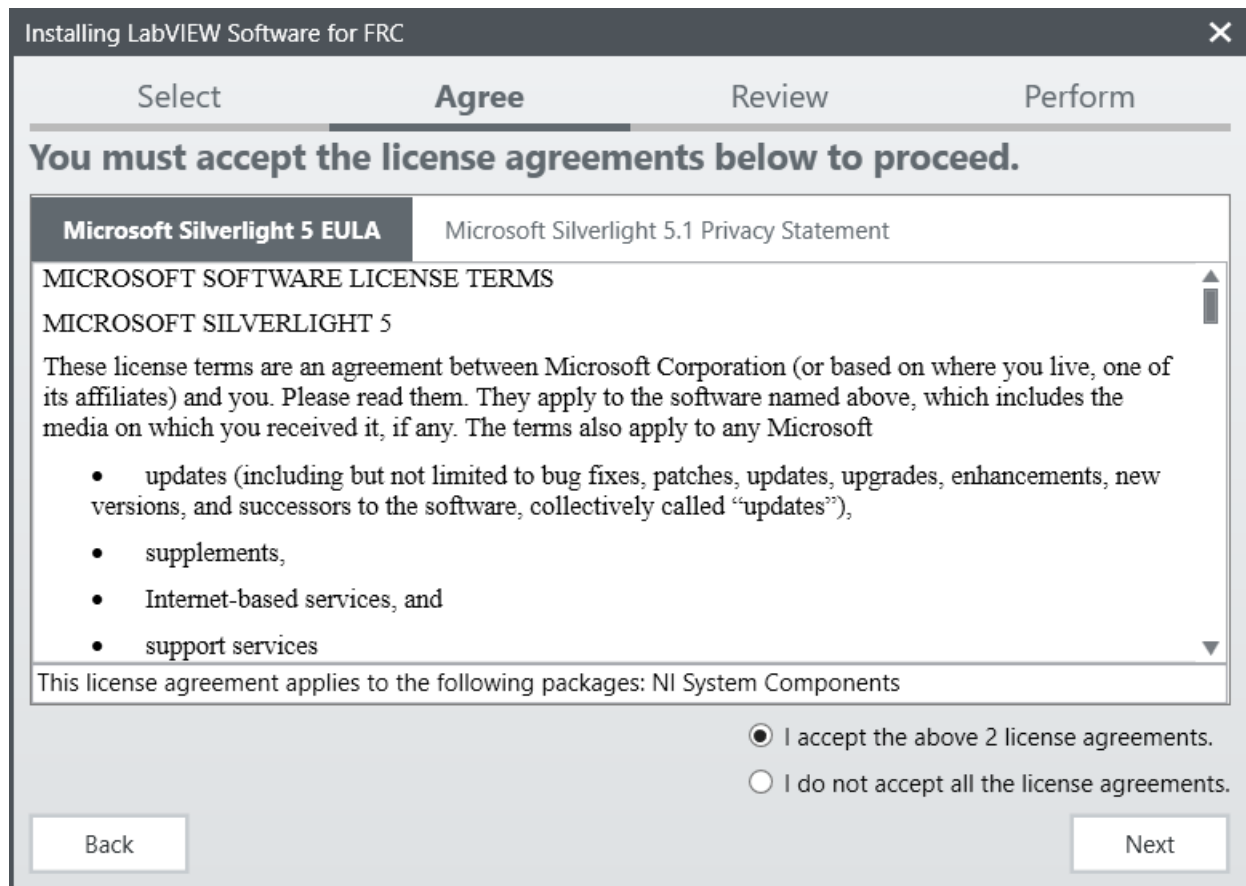
Click "Next"



## License agreements

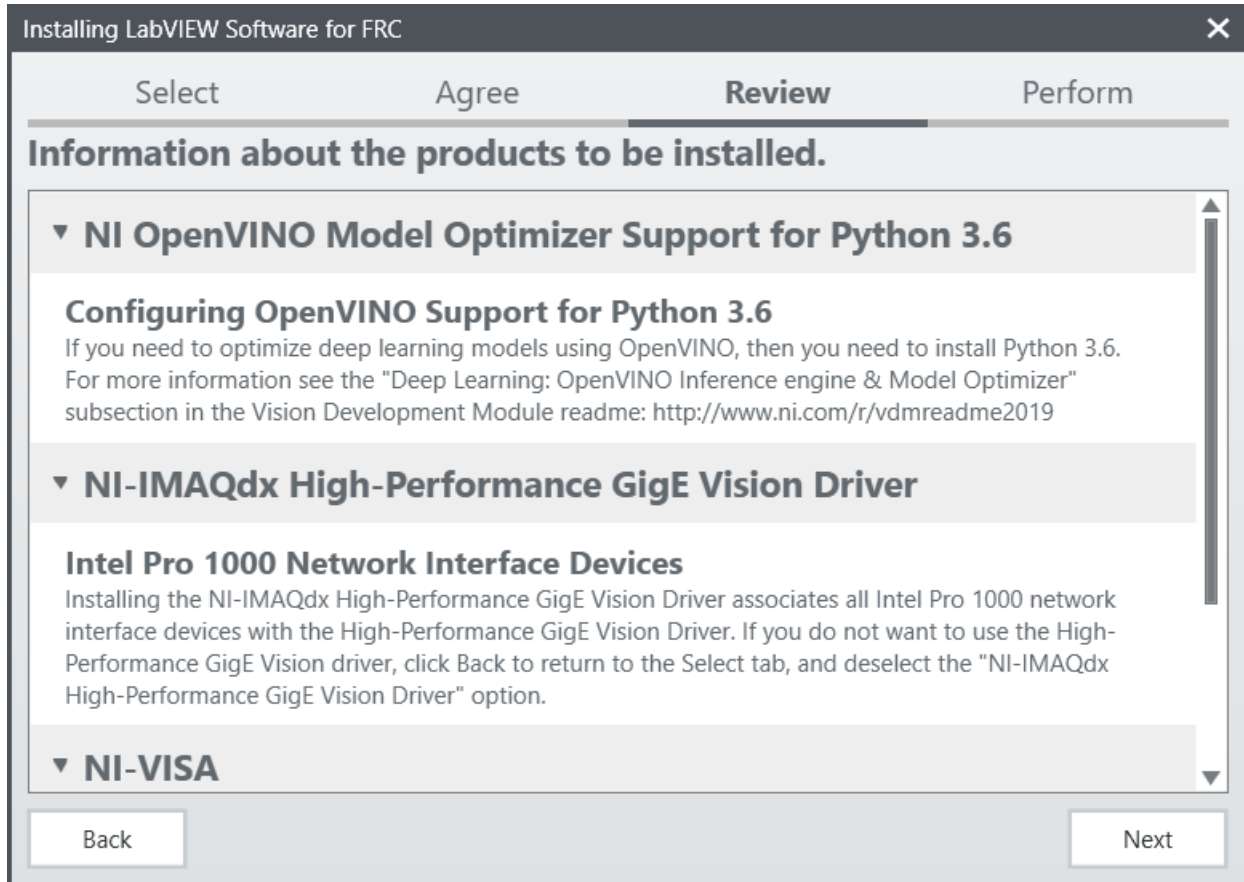


Check "I accept..." then Click "Next"



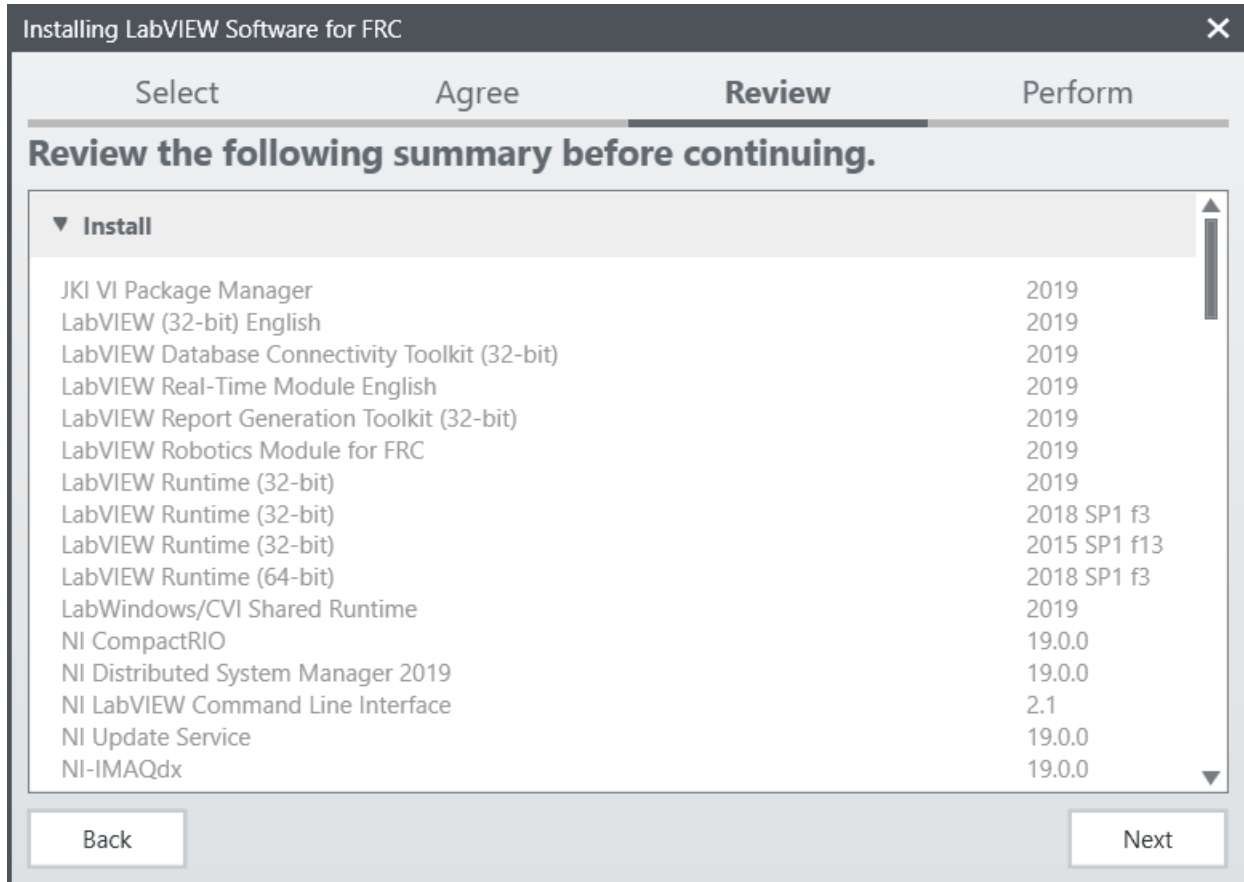
Check “I accept...” then Click “Next”

## Product Information



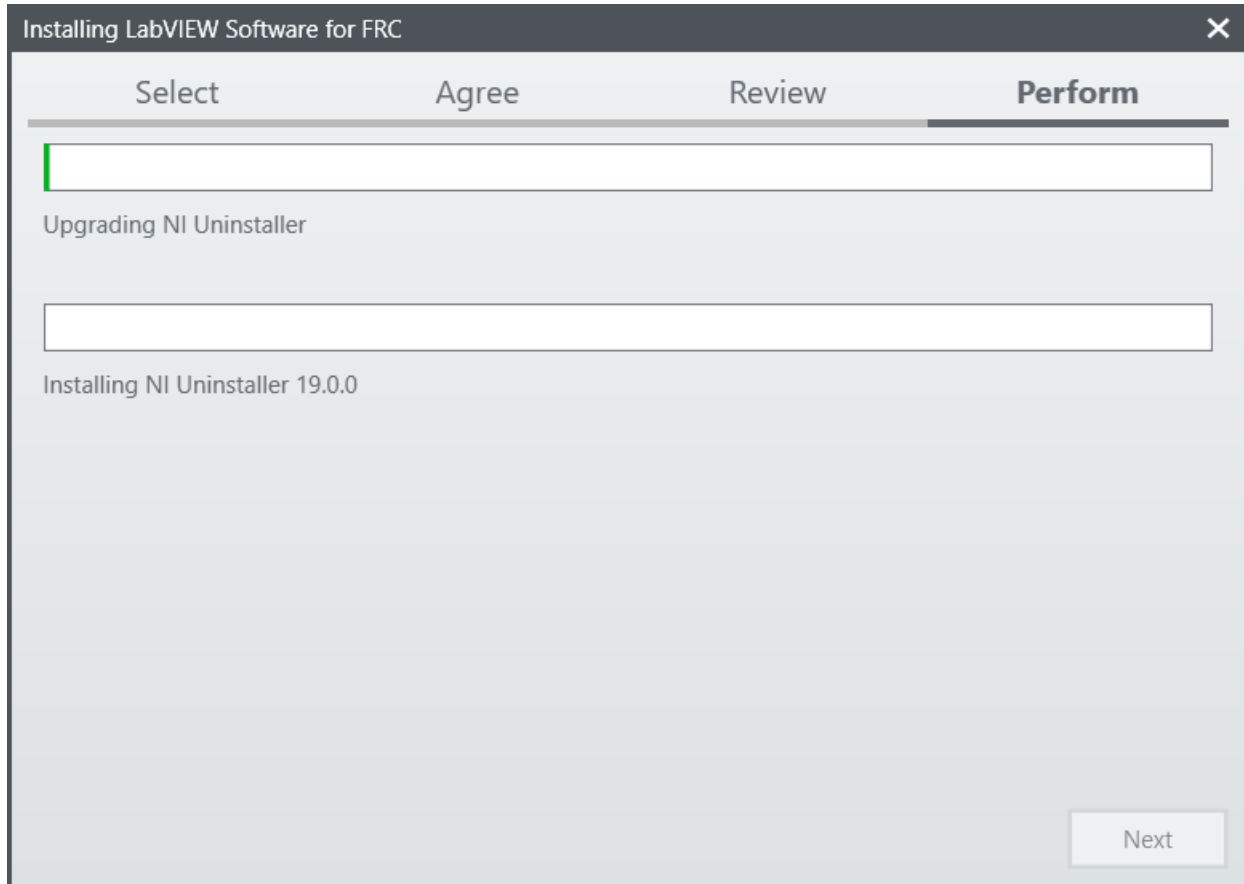
Click "Next"

## Start Installation



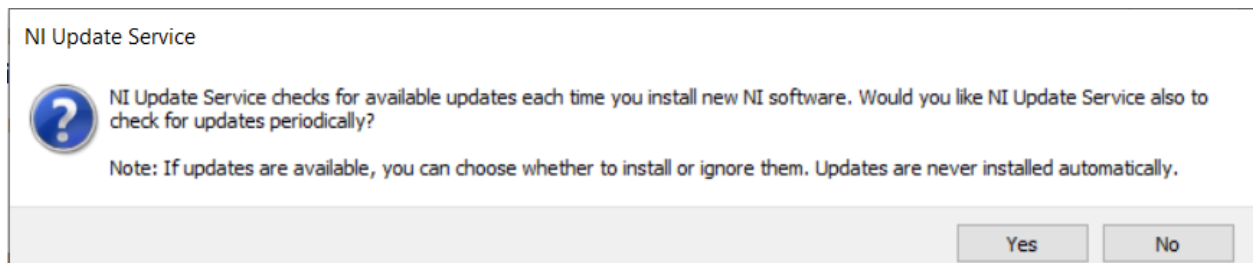
Click "Next"

## Overall Progress



Overall installation progress will be tracked in this window

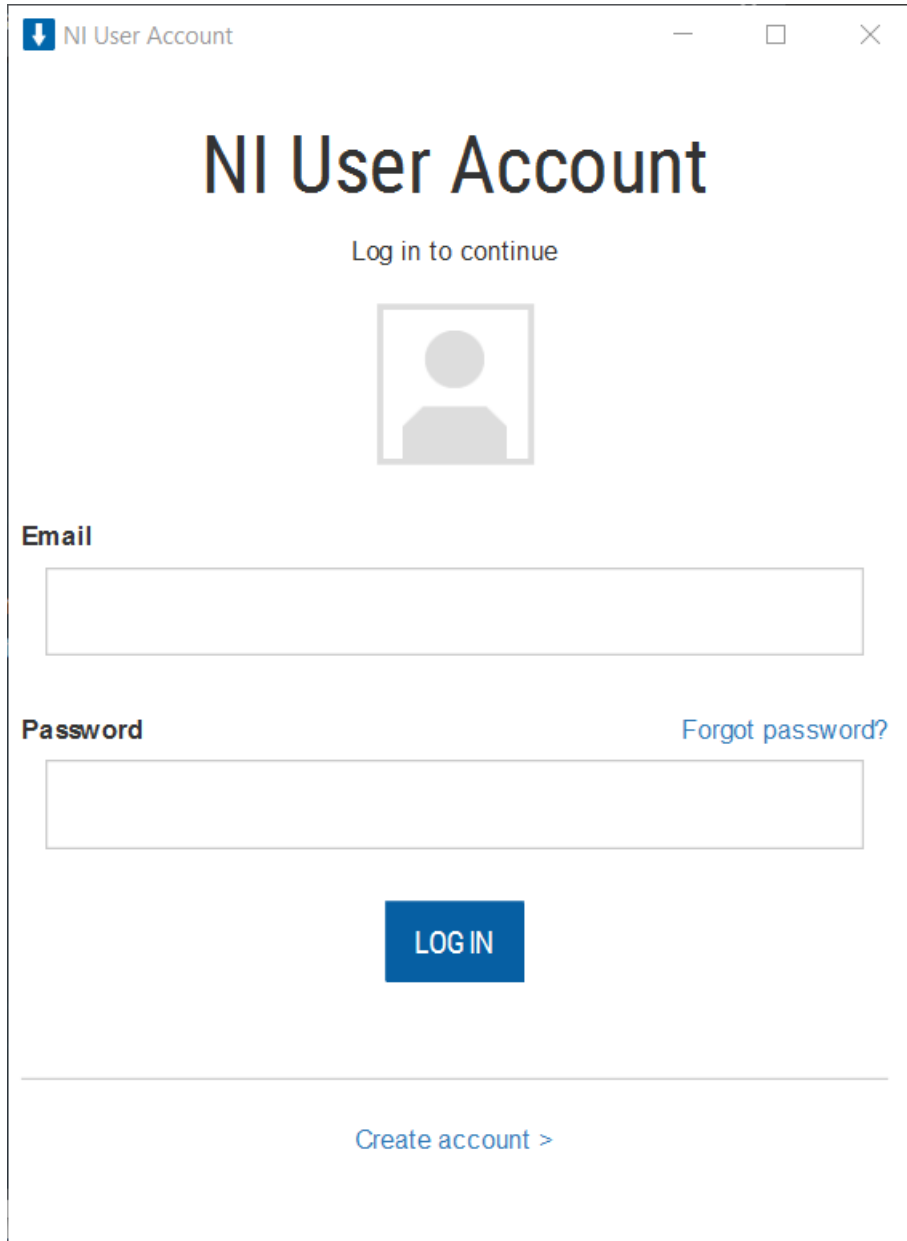
### 1.6.4 NI Update Service



You will be prompted whether to enable the NI update service. You can choose to not enable the update service.

**Warning:** It is not recommended to install these updates unless directed by FRC through our usual communication channels (FRC Blog, Team Updates or E-mail Blasts).

## NI Activation Wizard



The screenshot shows a window titled "NI User Account" with standard Windows window controls (minimize, maximize, close). The main heading is "NI User Account" in a large, bold font. Below it is the text "Log in to continue". There is a placeholder for a user profile picture, represented by a gray circle and rectangle. Below the profile picture are two input fields: "Email" and "Password". To the right of the "Password" field is a link that says "Forgot password?". Below the input fields is a blue button with the text "LOGIN". At the bottom of the window, there is a link that says "Create account >".

Log into your ni.com account. If you don't have an account, select 'Create account' to create a free account.

The screenshot shows the 'NI Licensing Wizard' window. At the top, a message states: 'A valid license for the following software product(s) was not found for your acc'. Below this, it says 'Enter serial numbers to activate'. A table lists ten software products, each with a corresponding 'Serial Number' text box containing 'XXXXXXXXXX'. At the bottom, there is a section for 'Enter Activation Codes', a 'Refresh' button, and an 'Activate' button.

	Serial Number
LabVIEW 2019 Application Builder	XXXXXXXXXX
LabVIEW 2019 Base Development System	XXXXXXXXXX
LabVIEW 2019 Continuous Integration System	XXXXXXXXXX
LabVIEW 2019 Database Connectivity Toolkit	XXXXXXXXXX
LabVIEW 2019 Debug Deployment System	XXXXXXXXXX
LabVIEW 2019 Full Development System	XXXXXXXXXX
LabVIEW 2019 LabVIEW Robotics FRC Simulation	XXXXXXXXXX
LabVIEW 2019 Professional Development System	XXXXXXXXXX
LabVIEW 2019 Real-Time Debug Deployment	XXXXXXXXXX

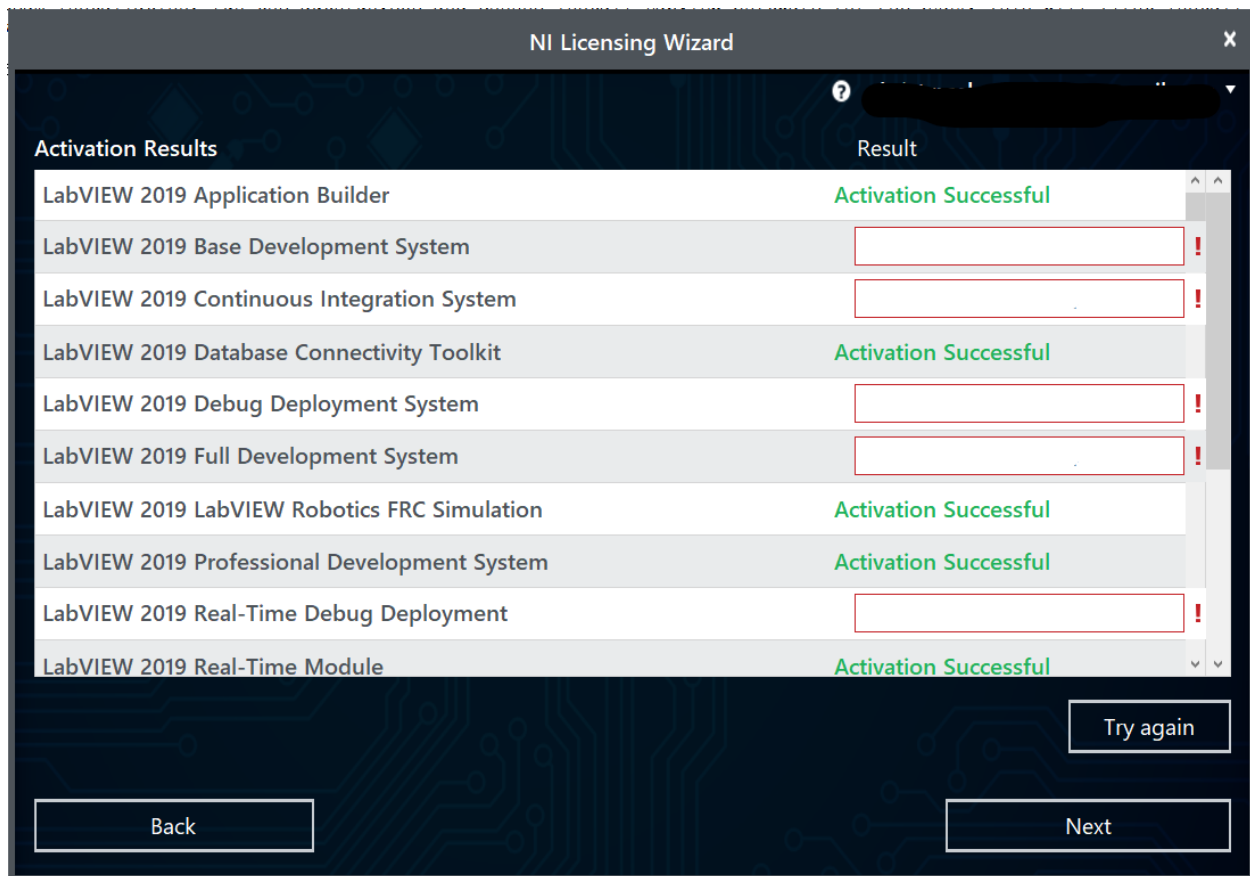
Enter Activation Codes

Refresh

Activate

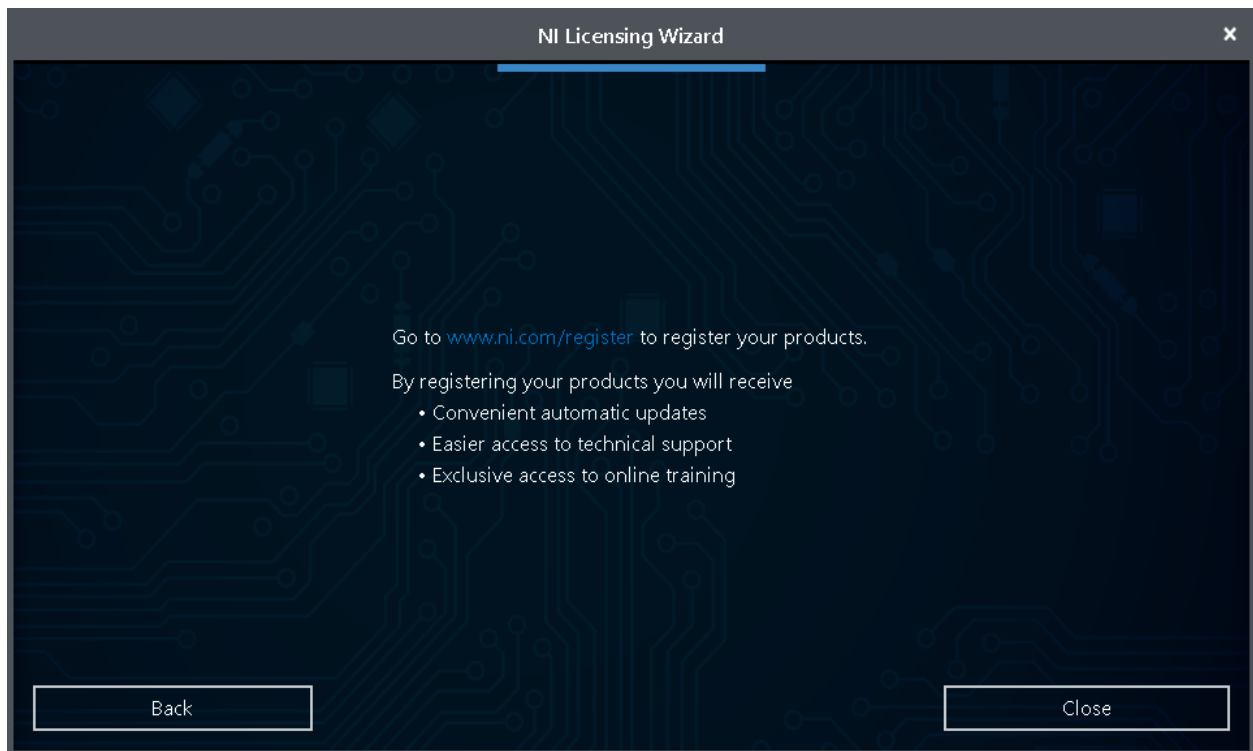
The serial number you entered at the “User Information” screen should appear in all of the text boxes, if it doesn’t, enter it now. Click “Activate”.

**Note:** If this is the first time activating the 2020 software on this account, you will see the message shown above about a valid license not being found. You can ignore this.



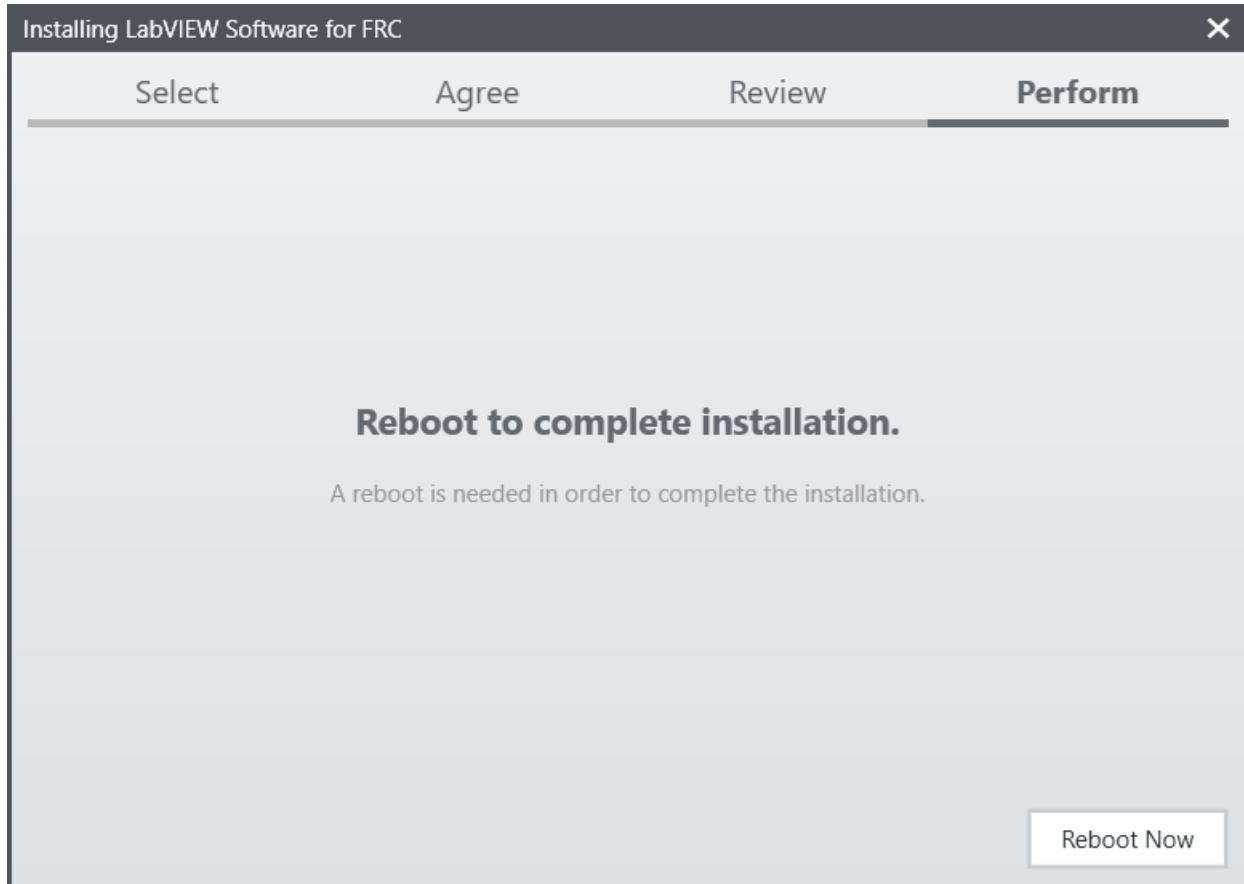
If your products activate successfully, an “Activation Successful” message will appear. If the serial number was incorrect, it will give you a text box and you can re-enter the number and select “Try Again”. The items shown above are not expected to activate. If everything activated successfully, click “Next”.





Click "Close".

### Restart



Select "Reboot Now" after closing any open programs.

## 1.7 Installing the FRC Game Tools

The FRC Game Tools contains the following software components: LabVIEW Update, FRC Driver Station, and FRC Utilities. The LabVIEW runtime components required for the Driver Station and Utilities are included in this package. **No components from the LabVIEW Software for FRC package are required for running either the Driver Station or Utilities.**

---

**Note:** The Driver Station will only work on Windows 7, Windows 8, Windows 8.1, and Windows 10. It will not work on Windows XP.

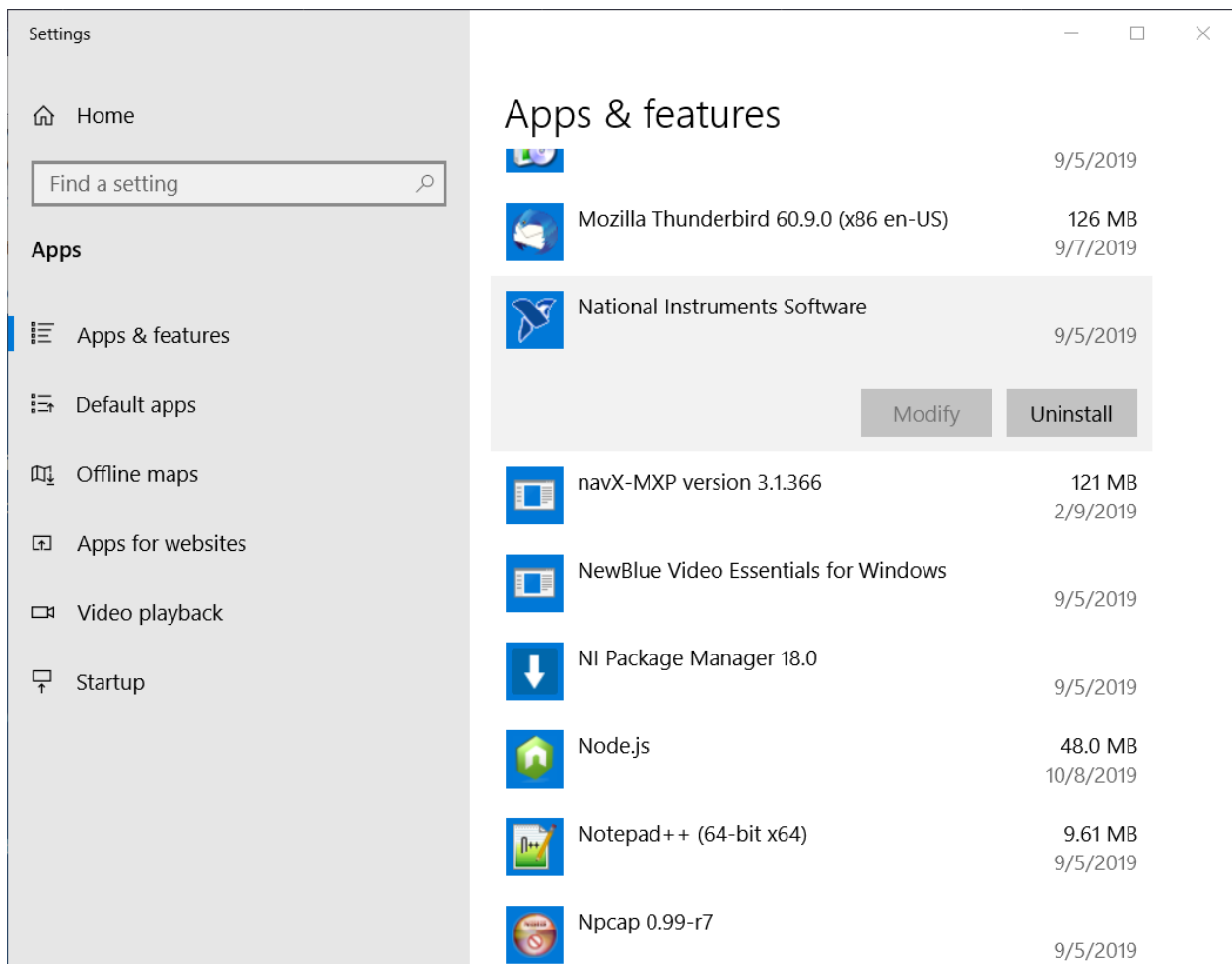
---

### 1.7.1 Uninstall Old Versions (Recommended)

**Warning:** LabVIEW teams have already completed this step, do not repeat it.

**Note:** It is only necessary to uninstall previous versions when installing a new year's tools. For example, uninstall the 2019 tools before installing the 2020 tools. It is not necessary to uninstall before upgrading to a new update of the 2020 game tools.

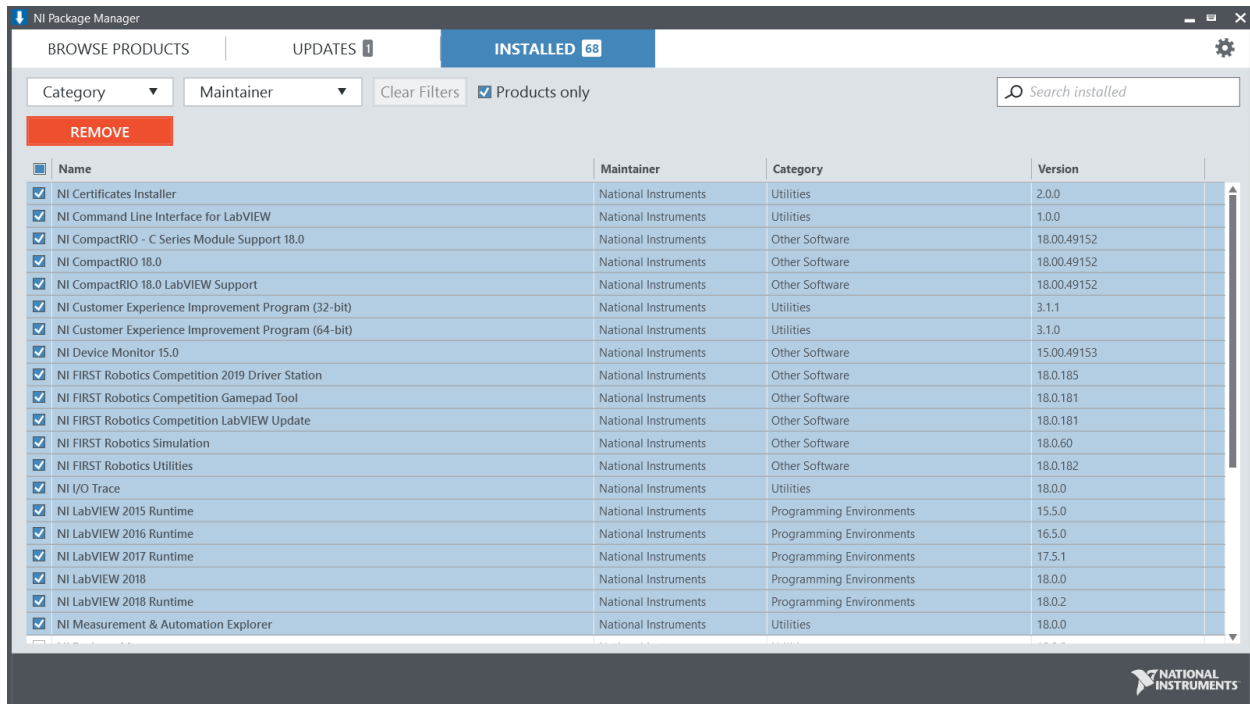
Before installing the new version of the FRC Game Tools it is recommended to remove any old versions. The new version will likely co-exist with the old version (note that the DS will overwrite old versions), but all testing has been done with FRC 2020 only. Then click Start >> Add or Remove Programs. Locate the entry labeled "National Instruments Software", and select Uninstall.



#### Select Components to Uninstall

In the dialog box that appears, select all entries. The easiest way to do this is to de-select the "Products Only" check-box and select the check-box to the left of "Name". Click Remove.

Wait for the uninstaller to complete and reboot if prompted.



### 1.7.2 Downloading the Update

Download the update from <https://www.ni.com/en-us/support/downloads/drivers/download.frc-game-tools.html>

[DOWNLOAD](#) Online installer

File Size  
5.37 MB

**Note:** If you need to download individual versions or patches, you can select from [Individual Offline Installers](#) [Offline Installer](#)

If you wish to install on other machines offline, do not click the Download button, click **Individual Offline Installers** and then click Download, to download the full installer.

### 1.7.3 .NET Framework 4.6.2

The Game Tools installer may prompt that .NET Framework 4.6.2 needs to be updated or installed. Follow prompts on-screen to complete the installation, including rebooting if re-

quested. Then resume the installation of the FRC Game Tools, restarting the installer if necessary.

## 1.7.4 Welcome

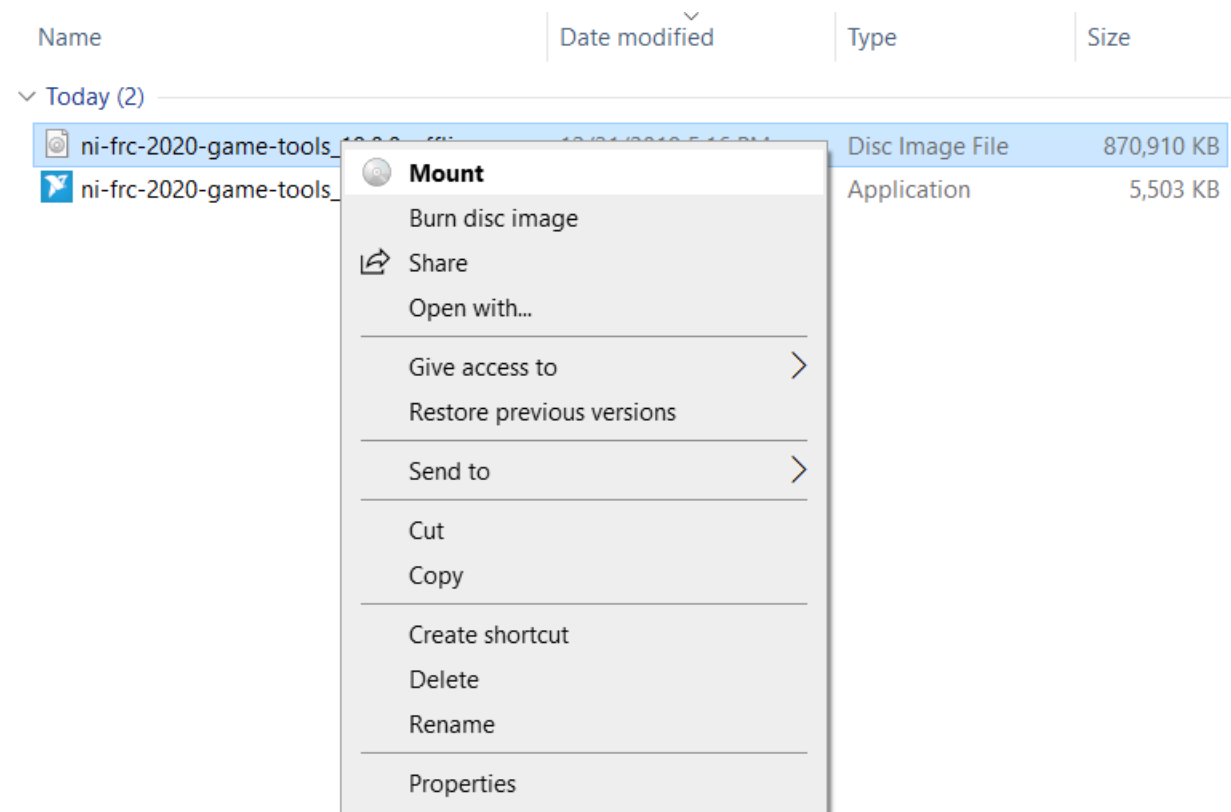
### Starting Install

#### Online Installer

Run the downloaded exe file to start the install process. Click “Yes” if a Windows Security prompt

#### Offline Installer (Windows 10)

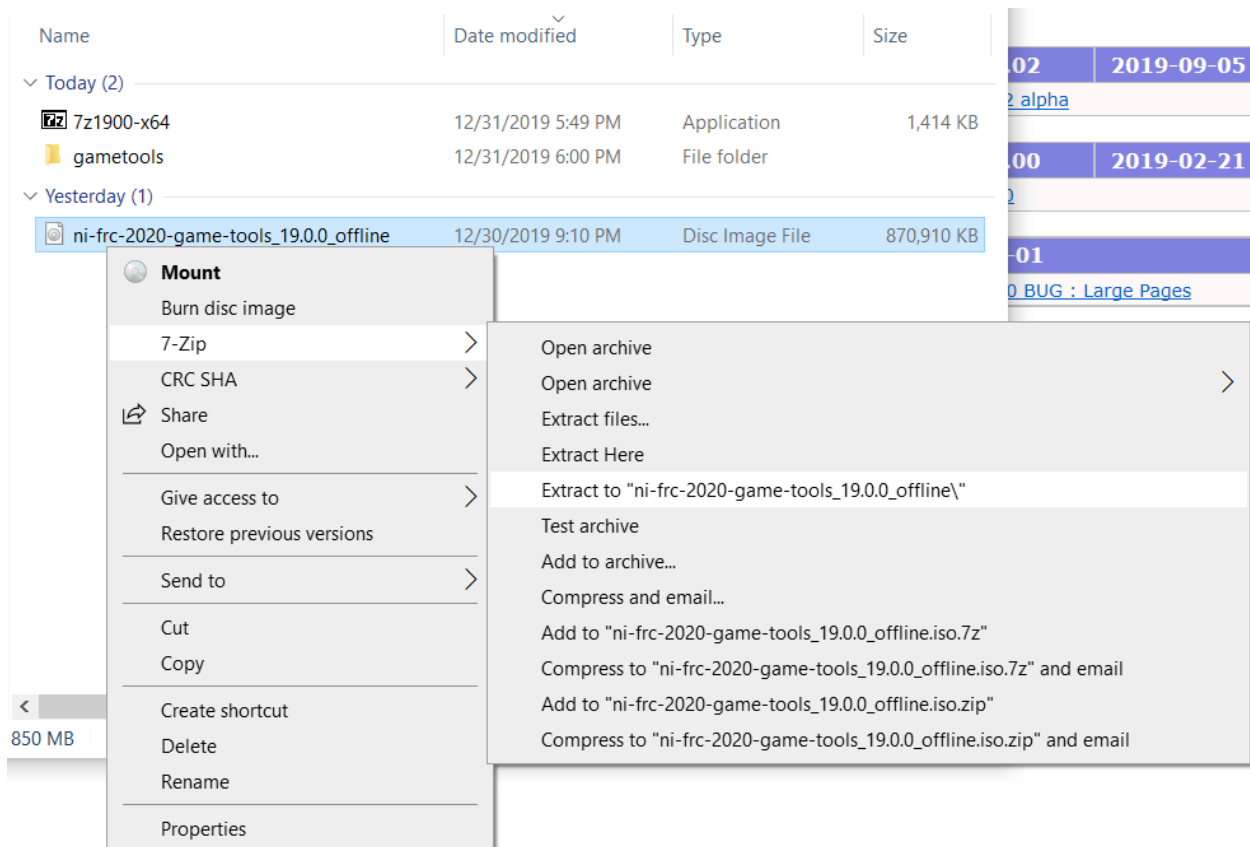
Right click on the downloaded iso file and select mount. Run install.exe from the mounted iso. Click “Yes” if a Windows Security prompt



**Note:** other installed programs may associate with iso files and the mount option may not appear. If that software does not give the option to mount or extract the iso file, then follow the directions in the “Offline Installer (Windows 7, 8, & 8.1)” tab.

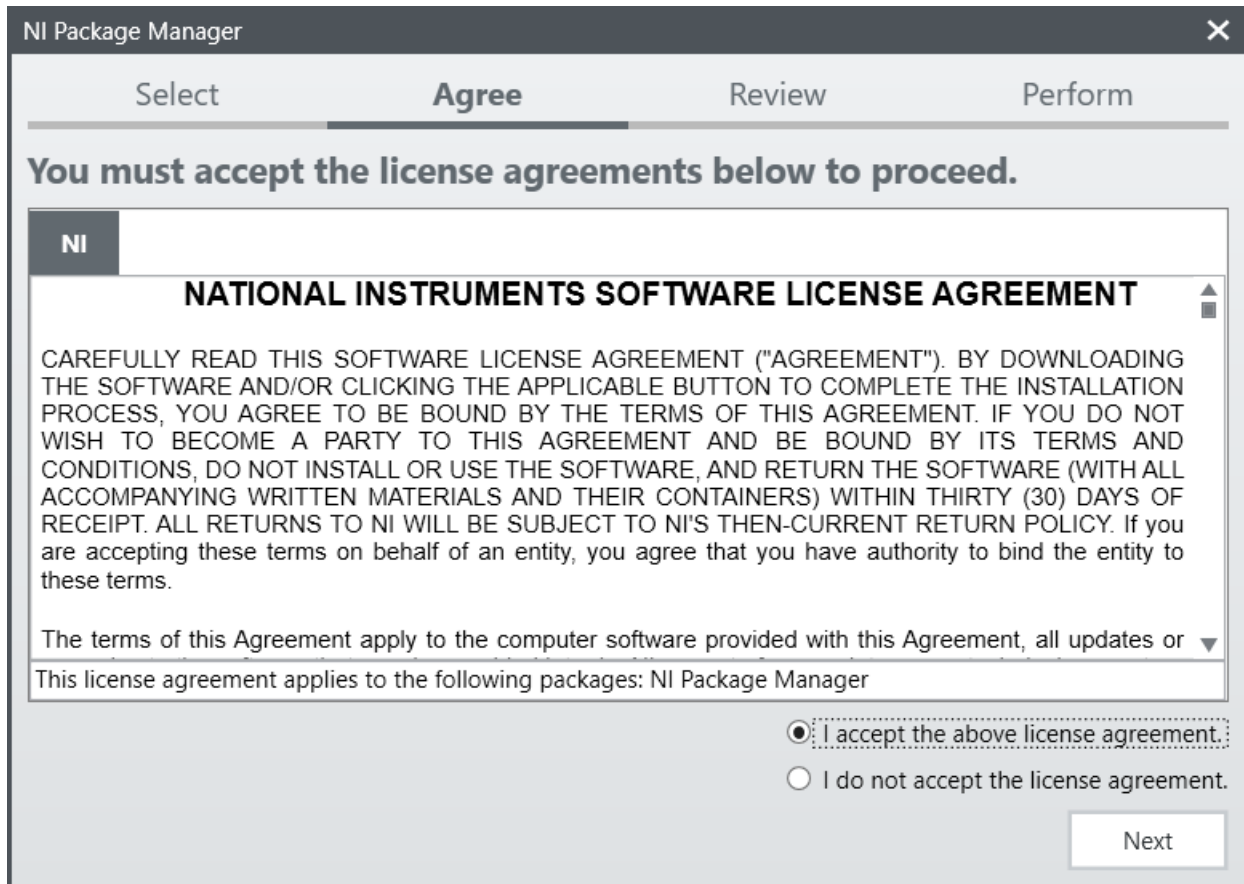
#### Offline Installer (Windows 7, 8, & 8.1)

Install 7-Zip (download [here](#)). As of the writing of this document, the current released version is 19.00 (2019-02-21). Right click on the downloaded iso file and select Extract to.



Run install.exe from the extracted folder. Click “Yes” if a Windows Security prompt appears. Click “Yes” if a Windows Security prompt appears.

### 1.7.5 NI Package Manager License



The image shows a screenshot of the 'NI Package Manager' window. At the top, there is a title bar with the text 'NI Package Manager' and a close button. Below the title bar is a progress bar with four steps: 'Select', 'Agree', 'Review', and 'Perform'. The 'Agree' step is currently selected. The main content area has a heading 'You must accept the license agreements below to proceed.' followed by a section titled 'NI'. Under this section is the 'NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT'. The text of the agreement is as follows: 'CAREFULLY READ THIS SOFTWARE LICENSE AGREEMENT ("AGREEMENT"). BY DOWNLOADING THE SOFTWARE AND/OR CLICKING THE APPLICABLE BUTTON TO COMPLETE THE INSTALLATION PROCESS, YOU AGREE TO BE BOUND BY THE TERMS OF THIS AGREEMENT. IF YOU DO NOT WISH TO BECOME A PARTY TO THIS AGREEMENT AND BE BOUND BY ITS TERMS AND CONDITIONS, DO NOT INSTALL OR USE THE SOFTWARE, AND RETURN THE SOFTWARE (WITH ALL ACCOMPANYING WRITTEN MATERIALS AND THEIR CONTAINERS) WITHIN THIRTY (30) DAYS OF RECEIPT. ALL RETURNS TO NI WILL BE SUBJECT TO NI'S THEN-CURRENT RETURN POLICY. If you are accepting these terms on behalf of an entity, you agree that you have authority to bind the entity to these terms.' Below the agreement text, there is a line that says 'The terms of this Agreement apply to the computer software provided with this Agreement, all updates or' followed by a dropdown arrow. Below this, it says 'This license agreement applies to the following packages: NI Package Manager'. At the bottom right, there are two radio buttons. The first is selected and labeled 'I accept the above license agreement.' The second is labeled 'I do not accept the license agreement.' To the right of these radio buttons is a 'Next' button.

NI Package Manager

Select Agree Review Perform

You must accept the license agreements below to proceed.

NI

**NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT**

CAREFULLY READ THIS SOFTWARE LICENSE AGREEMENT ("AGREEMENT"). BY DOWNLOADING THE SOFTWARE AND/OR CLICKING THE APPLICABLE BUTTON TO COMPLETE THE INSTALLATION PROCESS, YOU AGREE TO BE BOUND BY THE TERMS OF THIS AGREEMENT. IF YOU DO NOT WISH TO BECOME A PARTY TO THIS AGREEMENT AND BE BOUND BY ITS TERMS AND CONDITIONS, DO NOT INSTALL OR USE THE SOFTWARE, AND RETURN THE SOFTWARE (WITH ALL ACCOMPANYING WRITTEN MATERIALS AND THEIR CONTAINERS) WITHIN THIRTY (30) DAYS OF RECEIPT. ALL RETURNS TO NI WILL BE SUBJECT TO NI'S THEN-CURRENT RETURN POLICY. If you are accepting these terms on behalf of an entity, you agree that you have authority to bind the entity to these terms.

The terms of this Agreement apply to the computer software provided with this Agreement, all updates or ▼

This license agreement applies to the following packages: NI Package Manager

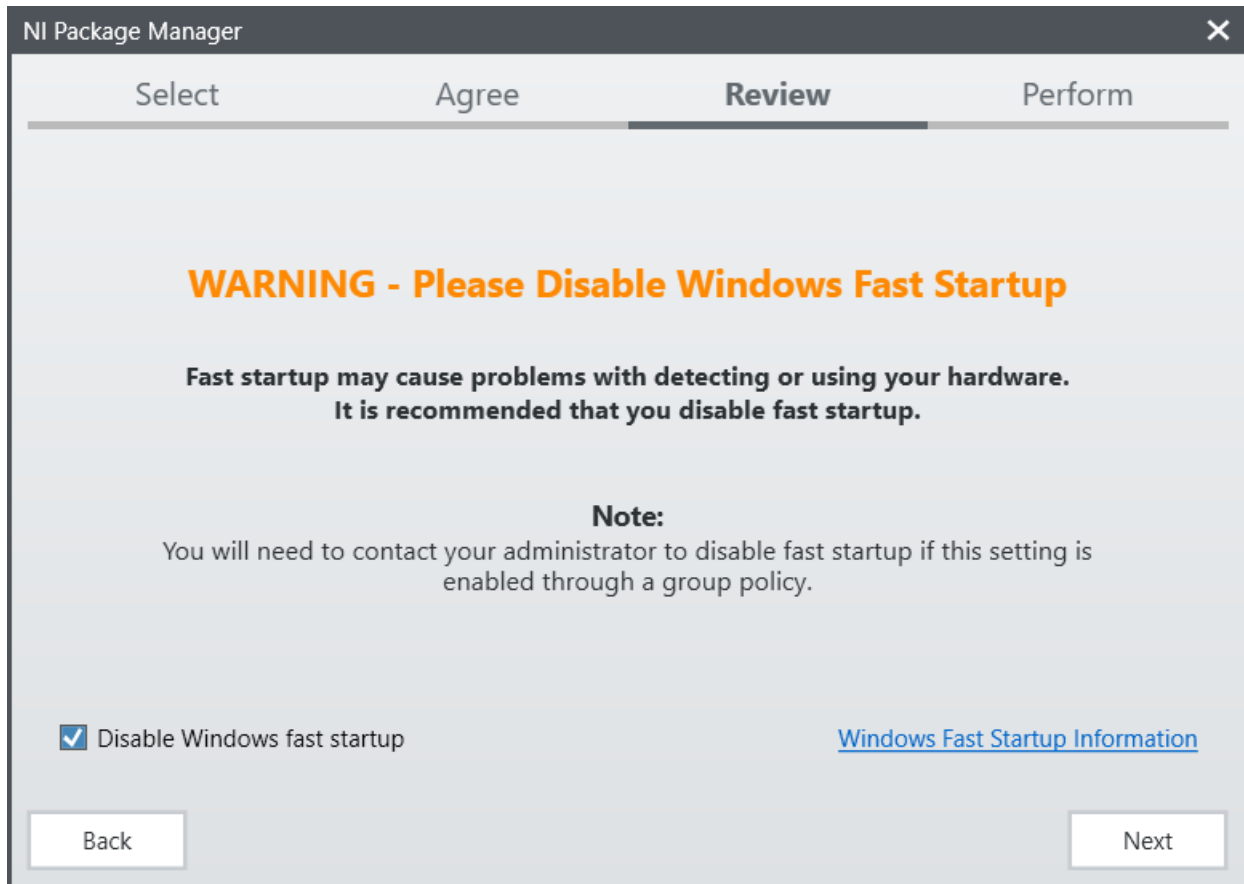
☒ I accept the above license agreement.

☐ I do not accept the license agreement.

Next

If you see this screen, click "Next"

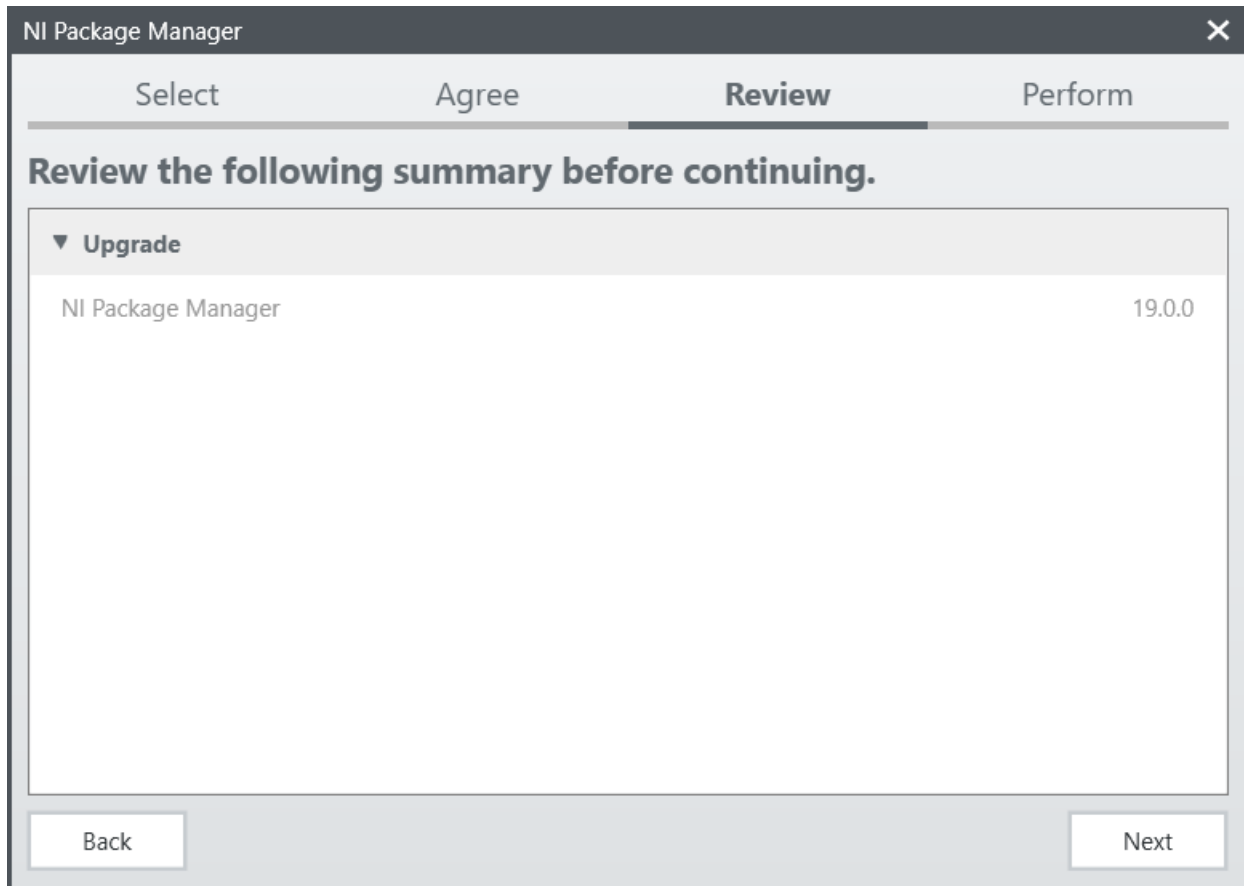
### 1.7.6 Disable Windows Fast Startup



If you see this screen, click "Next"

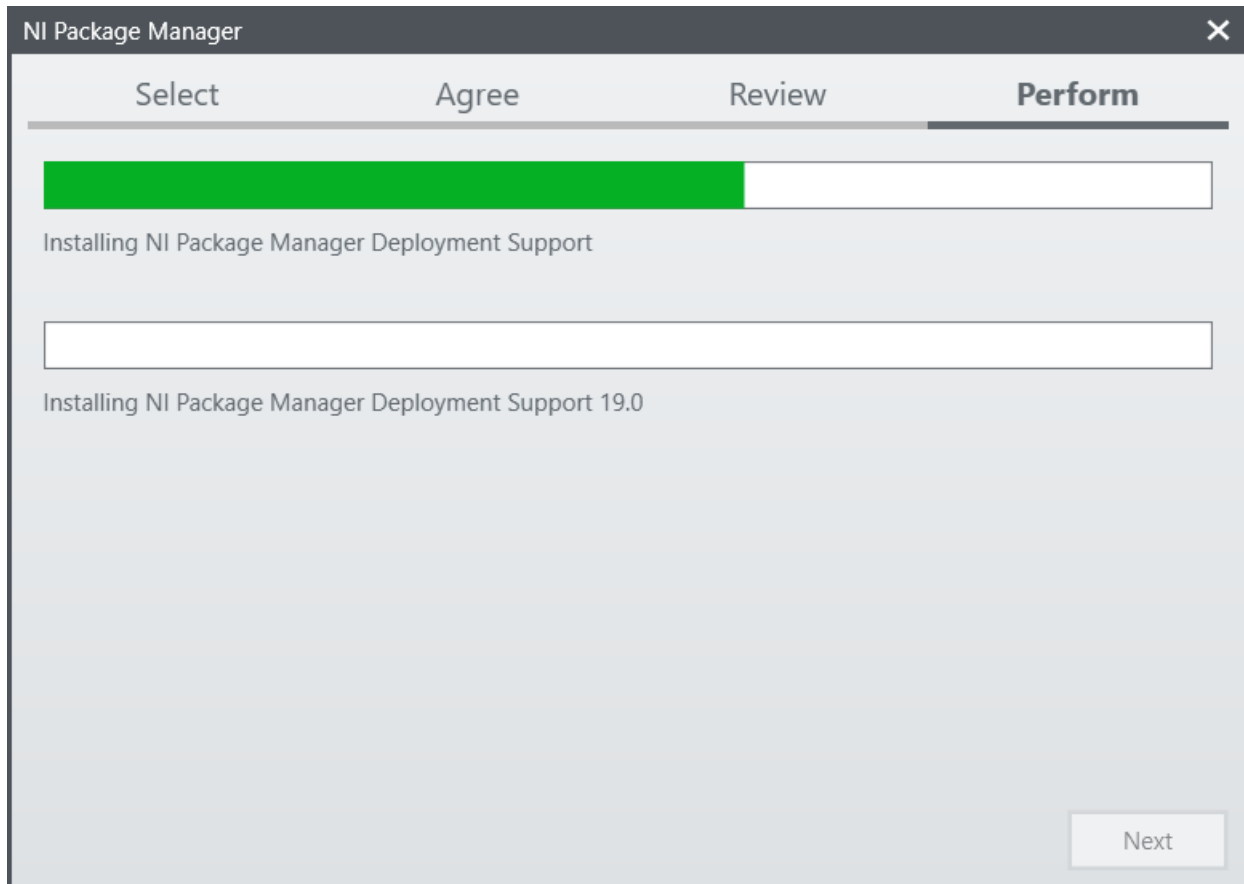


### 1.7.7 NI Package Manager Review



If you see this screen, click “Next”

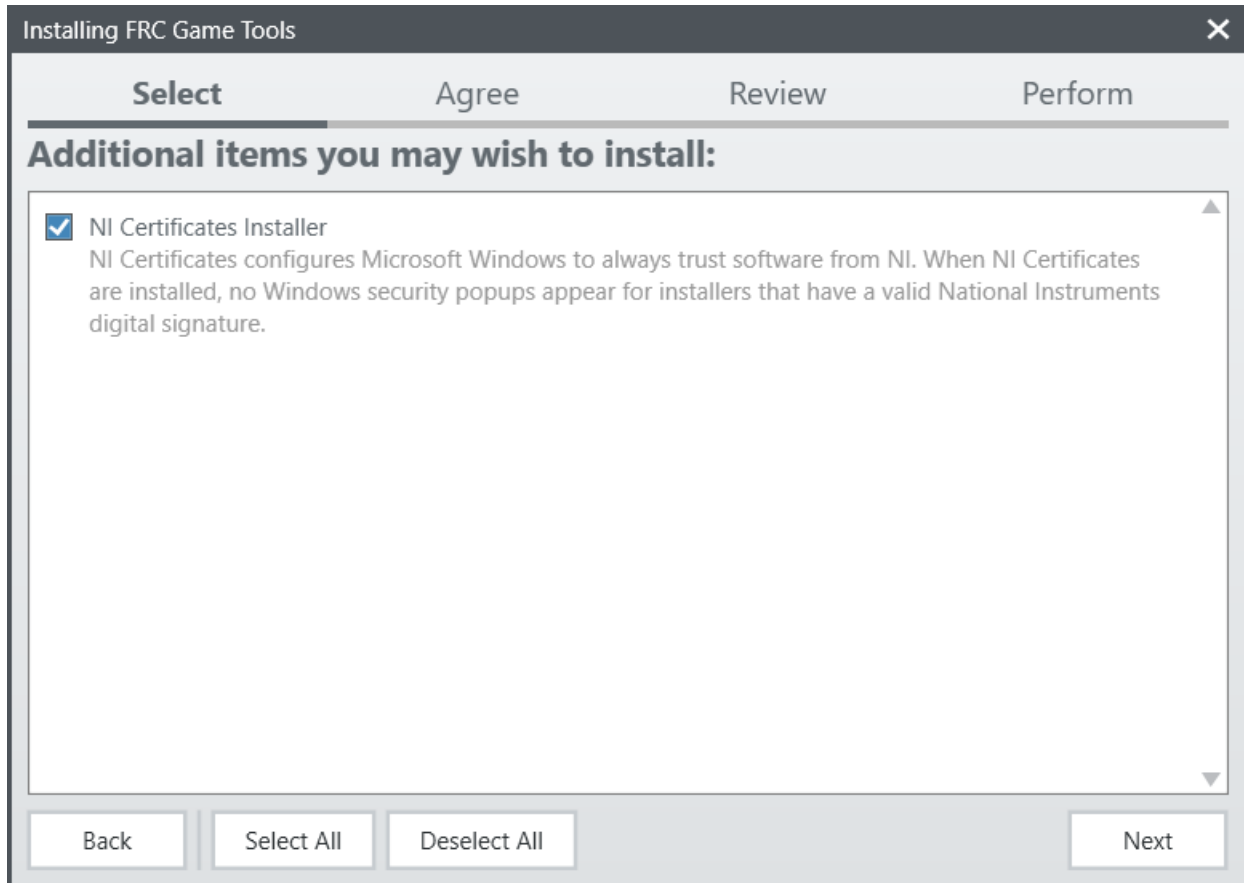
### **1.7.8 NI Package Manager Installation**



Installation progress of the NI Package Manager will be tracked in this window

## 1.7.9 Product List

### 1.7.10 Additional Software



If you see this screen, click "Next"

### 1.7.11 License Agreements

The screenshot shows a window titled "Installing FRC Game Tools" with a close button (X) in the top right corner. The window has a progress bar with four steps: "Select", "Agree" (which is highlighted), "Review", and "Perform". Below the progress bar, a message states: "You must accept the license agreements below to proceed." Below this message is a section for "NI FIRST Competition". The main content area is titled "NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT" and contains the following text: "CAREFULLY READ THIS SOFTWARE LICENSE AGREEMENT ('AGREEMENT'). BY DOWNLOADING THE SOFTWARE AND/OR CLICKING THE APPLICABLE BUTTON TO COMPLETE THE INSTALLATION PROCESS, YOU AGREE TO BE BOUND BY THE TERMS OF THIS AGREEMENT. IF YOU DO NOT WISH TO BECOME A PARTY TO THIS AGREEMENT AND BE BOUND BY ITS TERMS AND CONDITIONS, DO NOT INSTALL OR USE THE SOFTWARE, AND RETURN THE SOFTWARE (WITH ALL ACCOMPANYING WRITTEN MATERIALS AND THEIR CONTAINERS) WITHIN THIRTY (30) DAYS OF RECEIPT. ALL RETURNS TO NI WILL BE SUBJECT TO NI'S THEN-CURRENT RETURN POLICY. If you are accepting these terms on behalf of an entity, you agree that you have authority to bind the entity to these terms." Below this text, it says: "The terms of this Agreement apply to the computer software provided with this Agreement, all updates or upgrades to the software that may be provided later by NI as part of any maintenance, technical support, or" and "This license agreement applies to the following packages: NI FIRST Robotics Utilities". At the bottom right, there are two radio buttons: "I accept the above 2 license agreements." (which is selected) and "I do not accept all the license agreements." At the bottom left is a "Back" button and at the bottom right is a "Next" button.

Installing FRC Game Tools

Select Agree Review Perform

You must accept the license agreements below to proceed.

NI FIRST Competition

**NATIONAL INSTRUMENTS SOFTWARE LICENSE AGREEMENT**

CAREFULLY READ THIS SOFTWARE LICENSE AGREEMENT ("AGREEMENT"). BY DOWNLOADING THE SOFTWARE AND/OR CLICKING THE APPLICABLE BUTTON TO COMPLETE THE INSTALLATION PROCESS, YOU AGREE TO BE BOUND BY THE TERMS OF THIS AGREEMENT. IF YOU DO NOT WISH TO BECOME A PARTY TO THIS AGREEMENT AND BE BOUND BY ITS TERMS AND CONDITIONS, DO NOT INSTALL OR USE THE SOFTWARE, AND RETURN THE SOFTWARE (WITH ALL ACCOMPANYING WRITTEN MATERIALS AND THEIR CONTAINERS) WITHIN THIRTY (30) DAYS OF RECEIPT. ALL RETURNS TO NI WILL BE SUBJECT TO NI'S THEN-CURRENT RETURN POLICY. If you are accepting these terms on behalf of an entity, you agree that you have authority to bind the entity to these terms.

The terms of this Agreement apply to the computer software provided with this Agreement, all updates or upgrades to the software that may be provided later by NI as part of any maintenance, technical support, or

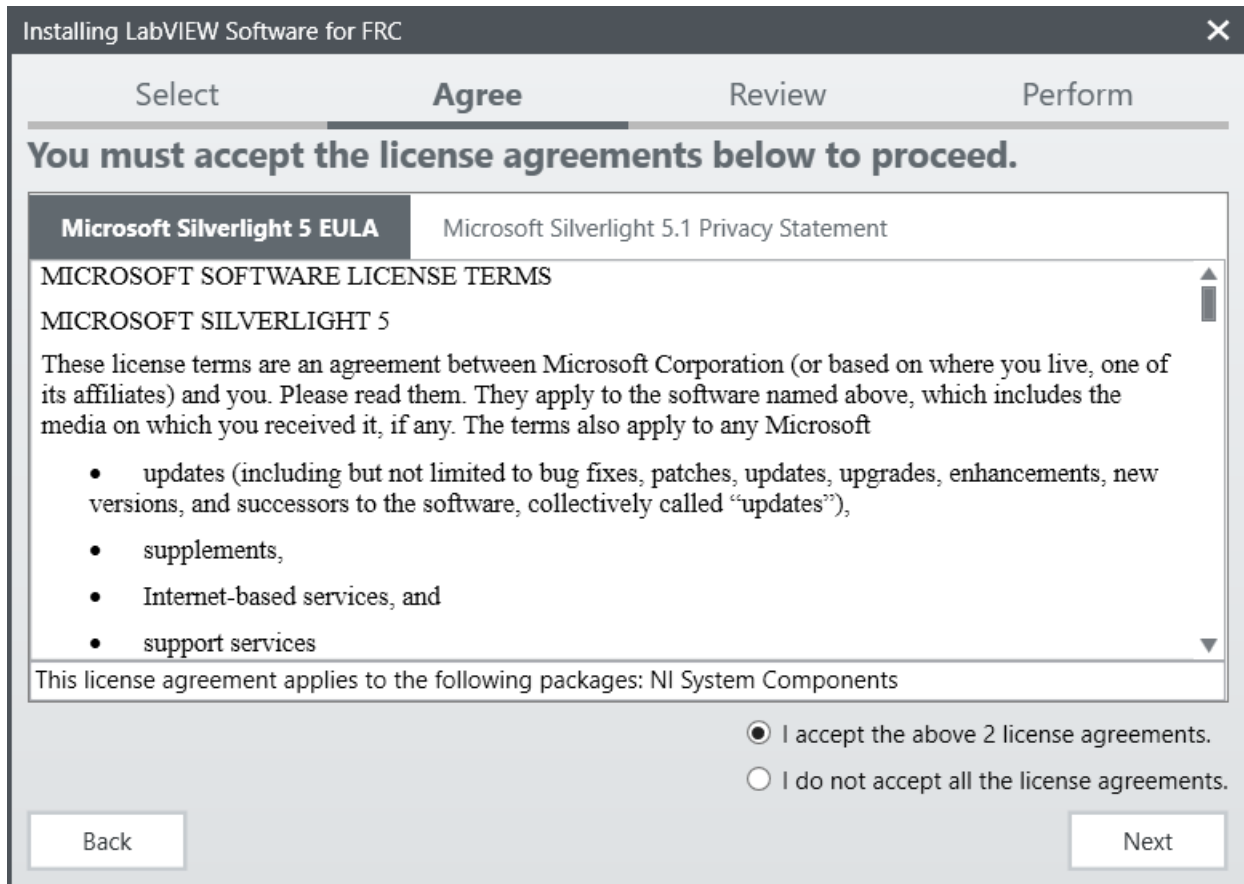
This license agreement applies to the following packages: NI FIRST Robotics Utilities

☒ I accept the above 2 license agreements.  
☐ I do not accept all the license agreements.

Back Next

Select "I accept..." then click "Next"

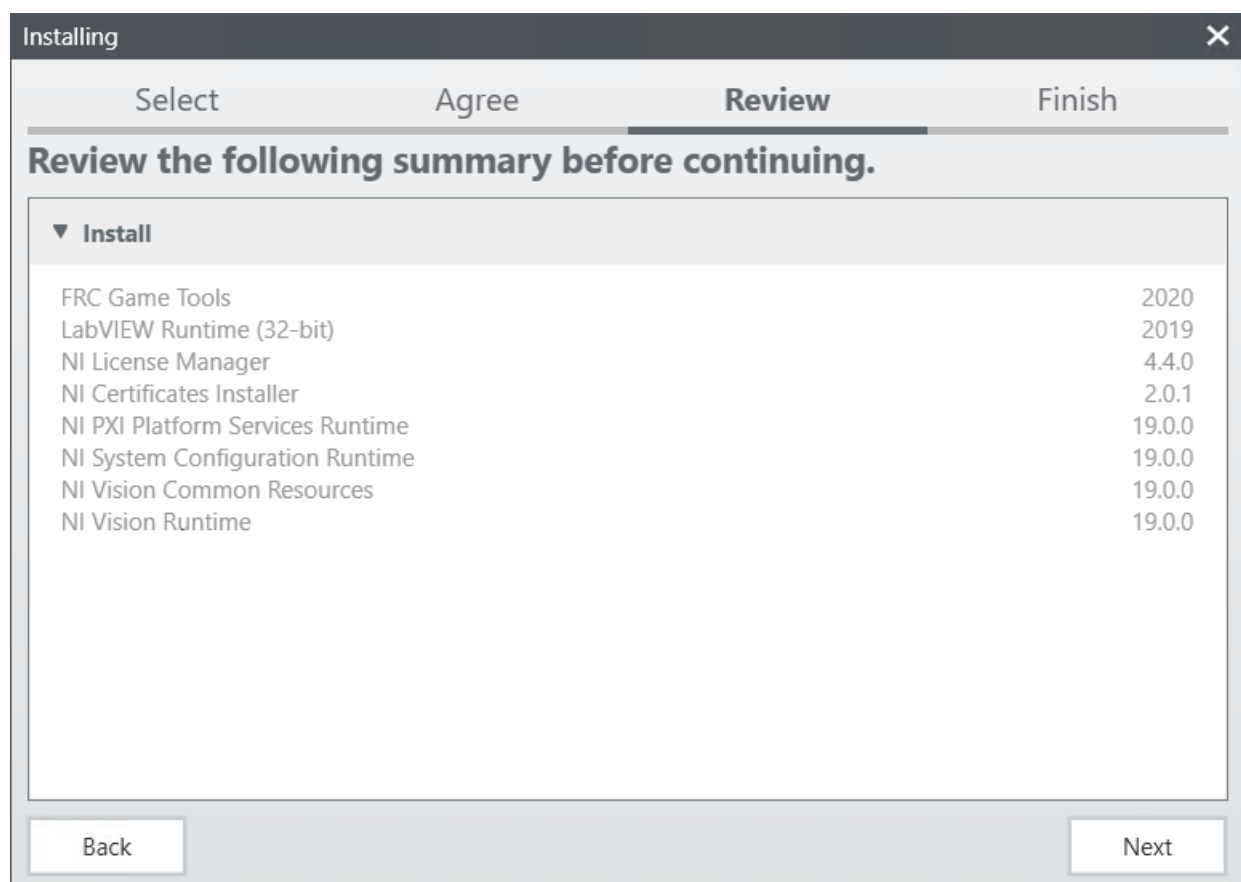
### 1.7.12 License Agreements Page 2



If you see this screen, select “I accept...” then click “Next”

### 1.7.13 Review Summary

Click Next



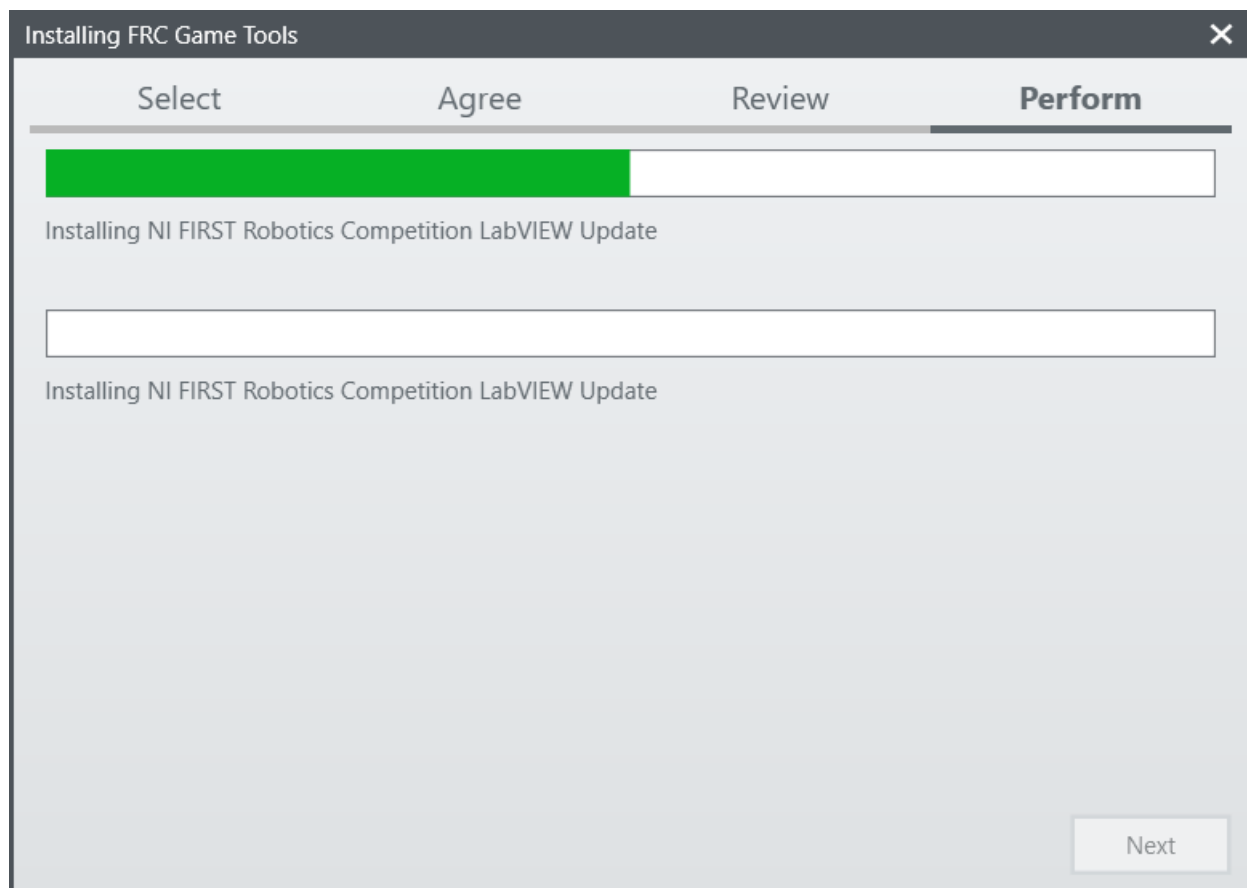
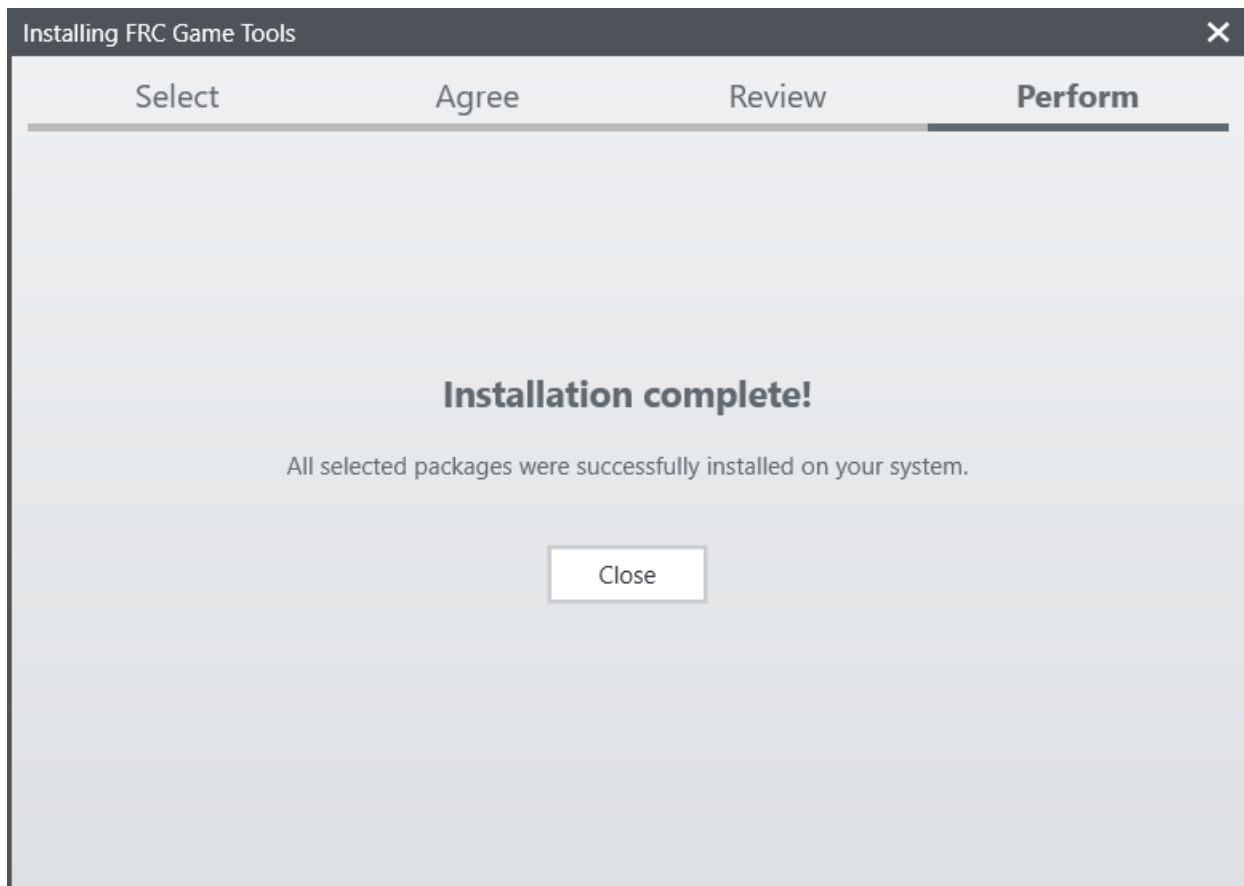


Fig. 1: Detail Progress

### **1.7.14 Detail Progress**

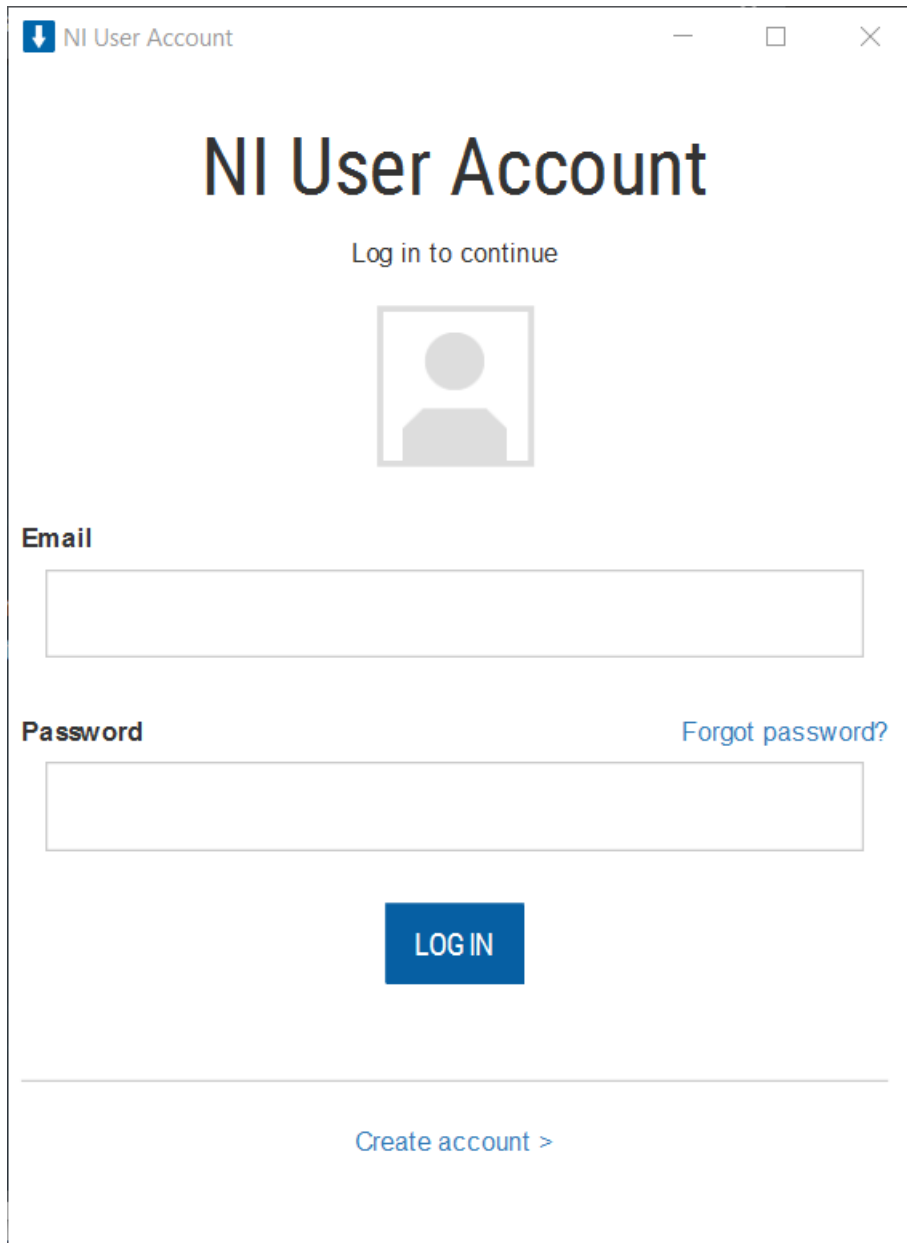
### **1.7.15 Installation Summary**



click Close



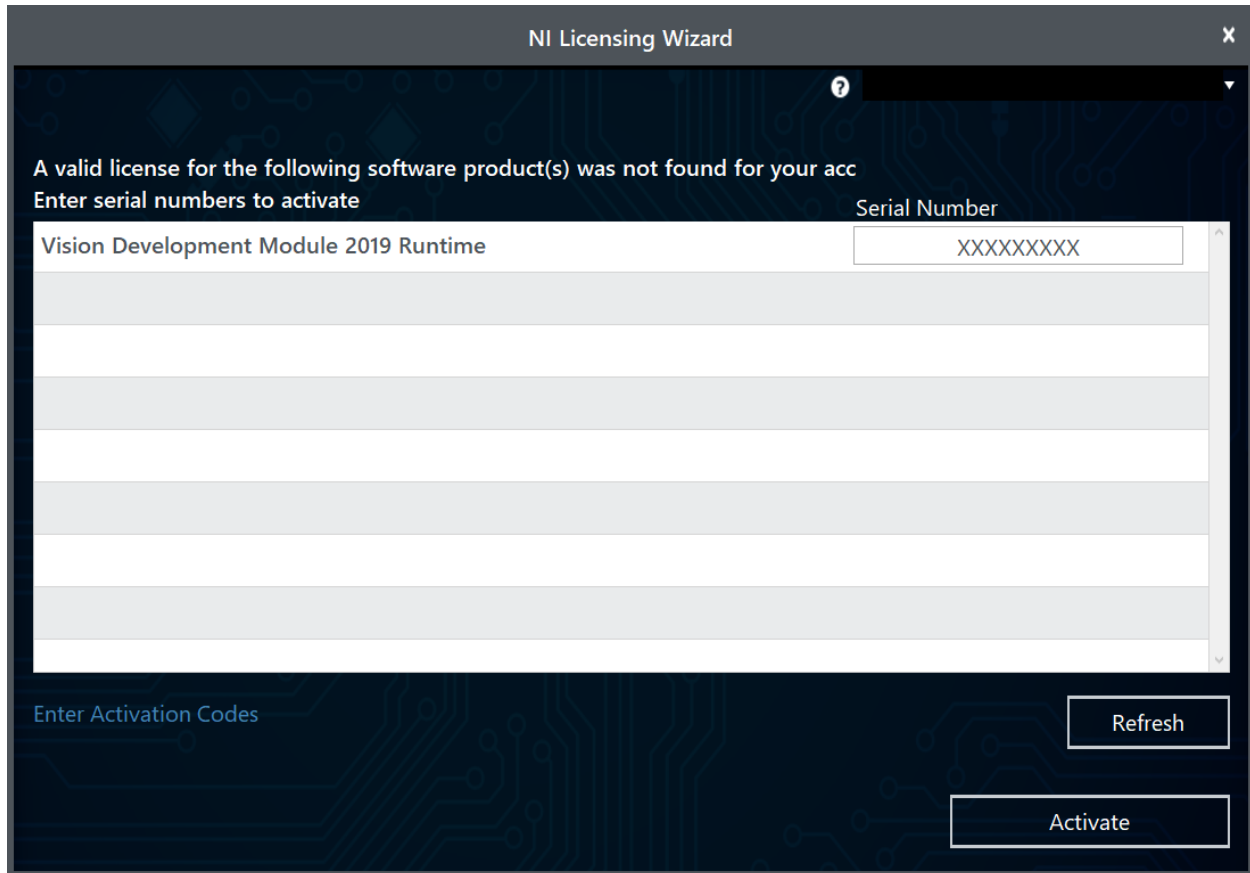
### 1.7.16 NI Activation Wizard



The screenshot shows a window titled "NI User Account" with standard window controls (minimize, maximize, close). The main heading is "NI User Account" in a large, bold font. Below it, the text "Log in to continue" is displayed. A placeholder for a user profile picture is shown as a gray square with a circle and a person silhouette. Below the profile picture are two input fields: "Email" and "Password". To the right of the "Password" field is a link that says "Forgot password?". Below the input fields is a blue "LOG IN" button. At the bottom of the window, there is a link that says "Create account >".

Log into your ni.com account. If you don't have an account, select 'Create account' to create a free account.

### 1.7.17 NI Activation Wizard (2)

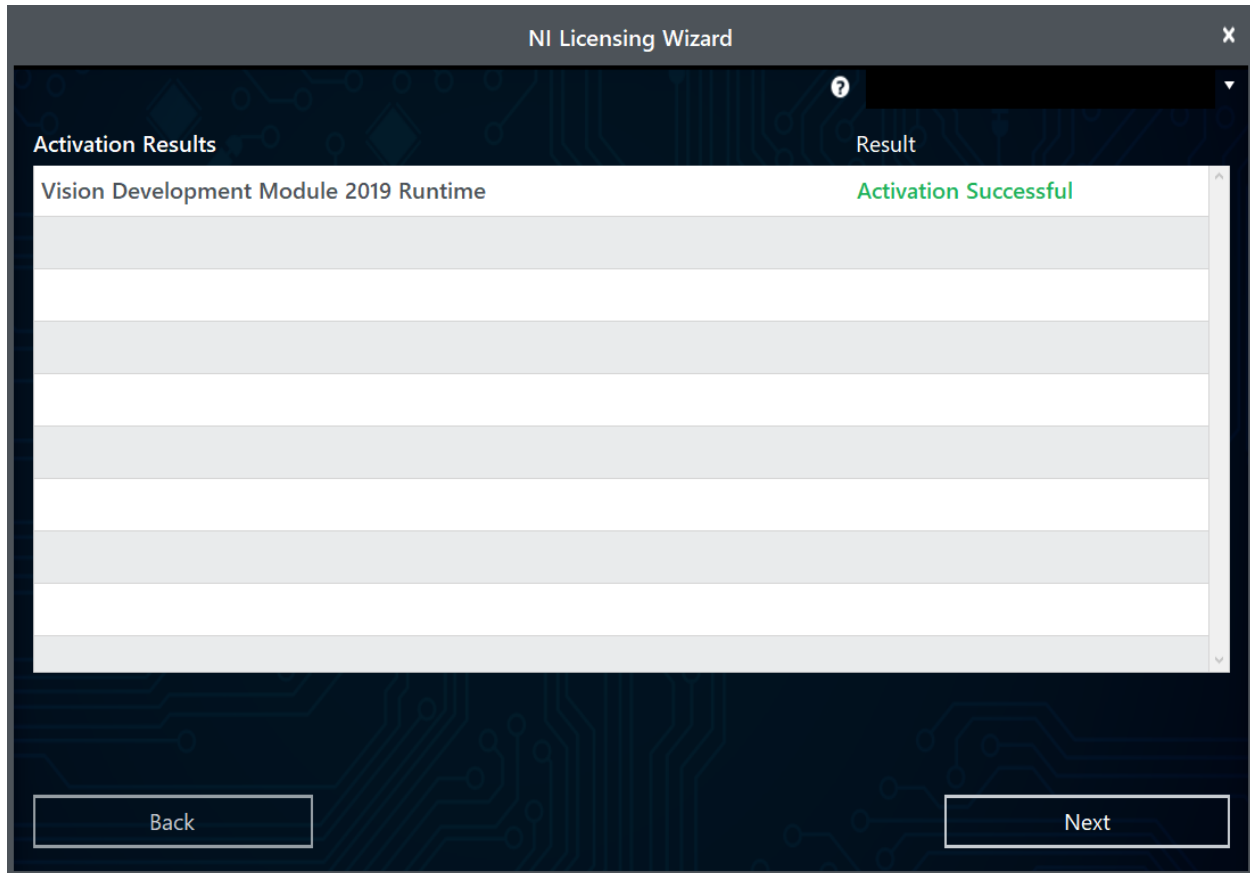


The image shows the 'NI Licensing Wizard' window. At the top, the title bar says 'NI Licensing Wizard' with a close button 'X'. Below the title bar, there is a dark blue header area with a question mark icon and a dropdown menu. The main content area has a dark blue background with a circuit pattern. A message reads: 'A valid license for the following software product(s) was not found for your acc. Enter serial numbers to activate'. Below this message is a table with two columns: 'Serial Number' and 'Enter Activation Codes'. The first row of the table has 'Vision Development Module 2019 Runtime' in the first column and 'XXXXXXXXXX' in the second column. There are seven more empty rows in the table. At the bottom right of the window, there are two buttons: 'Refresh' and 'Activate'.

Serial Number	Enter Activation Codes
XXXXXXXXXX	

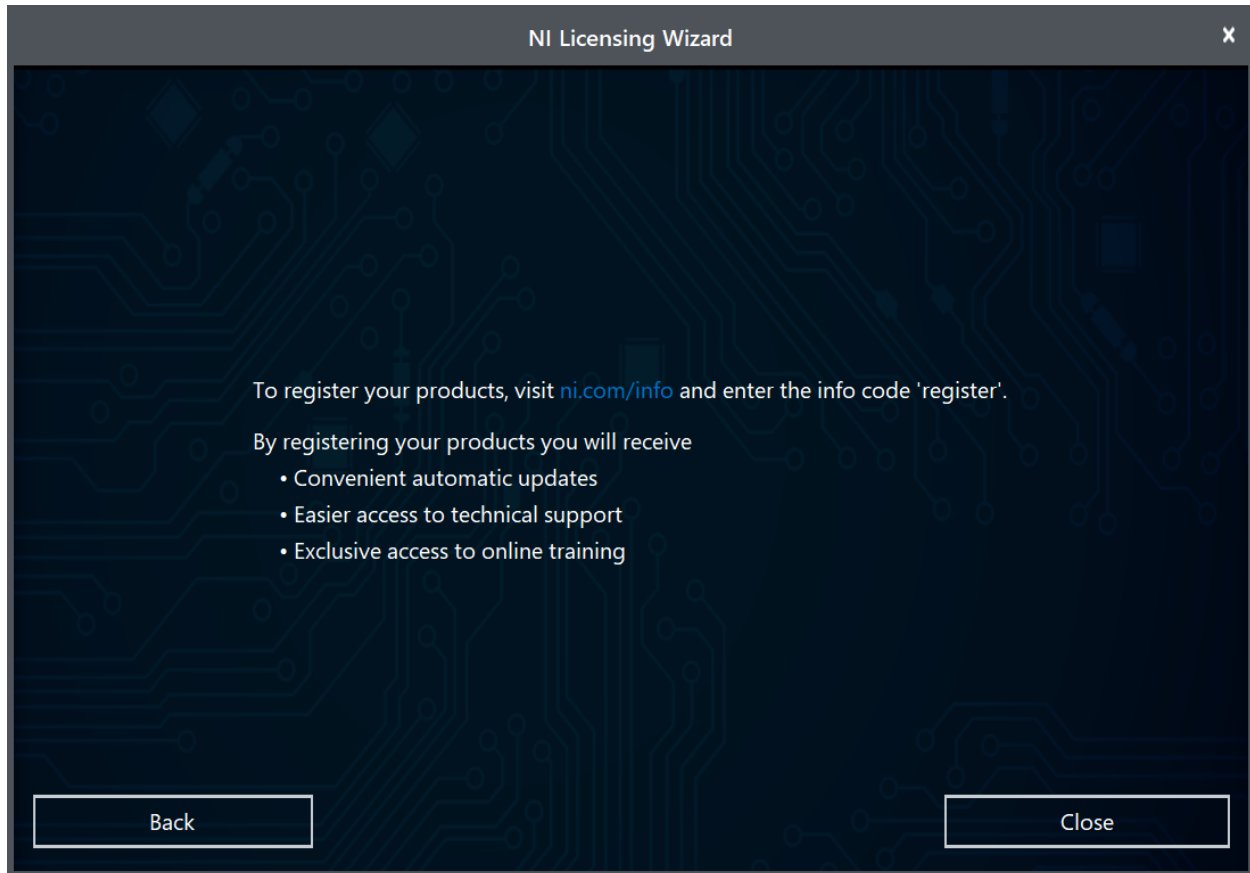
Enter the serial number. Click “Activate”. Note: If this is the first time activating this year’s software on this account, you will see the message shown above about a valid license not being found. You can ignore this.

### 1.7.18 NI Activation Wizard (3)



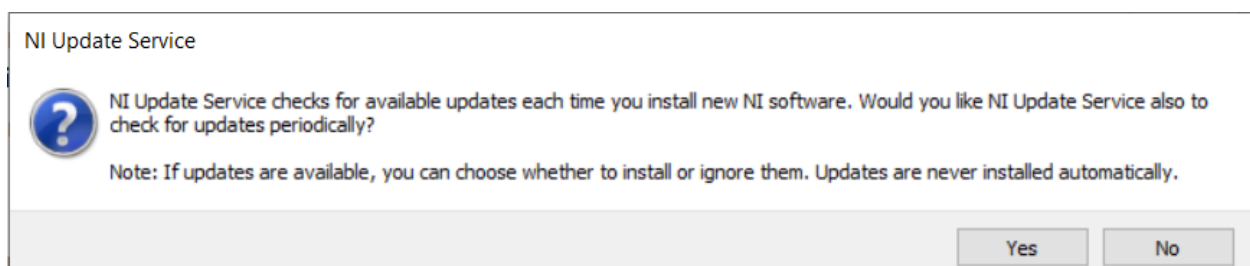
If your products activate successfully, an “Activation Successful” message will appear. If the serial number was incorrect, it will give you a text box and you can re-enter the number and select “Try Again”. If everything activated successfully, click “Next”.

### 1.7.19 NI Activation Wizard (4)



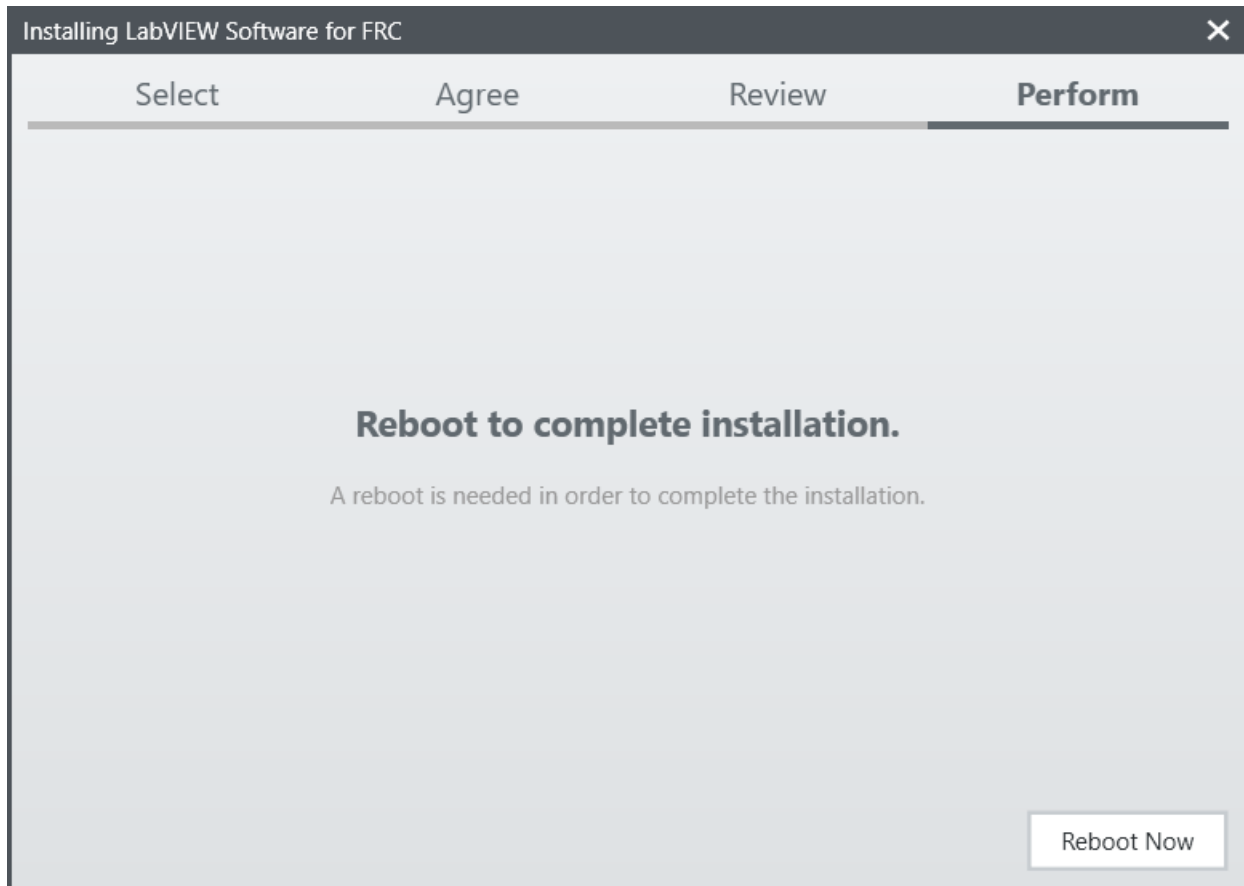
Click "Close".

### 1.7.20 NI Update Service



You will be prompted whether to enable the NI update service. You can choose to not enable the update service.

### 1.7.21 Reboot to Complete Installation



If prompted, Select “Reboot Now” after closing any open programs.

## 1.8 How to Wire an FRC Robot

**Note:** This document details the wiring of a basic electronics board for bench-top testing.

Some images shown in this section reflect the setup for a Robot Control System using Spark motor controllers. Wiring diagram and layout should be similar for other motor controllers. Where appropriate, a second set of images shows the wiring steps for using PWM controllers with integrated wires.

Locate the following control system components and tools

- Kit Materials:
  - Power Distribution Panel (PDP)
  - roboRIO
  - Pneumatics Control Module (PCM)
  - Voltage Regulator Module (VRM)
  - OpenMesh radio (with power cable and Ethernet cable)
  - Robot Signal Light (RSL)
  - 4x Victor SPX or other speed controllers
  - 2x PWM y-cables
  - 120A Circuit breaker
  - 4x 40A Circuit breaker
  - 6 AWG Red wire
  - 10 AWG Red/Black wire
  - 18 AWG Red/Black wire
  - 22AWG yellow/green twisted CAN cable
  - 16x 10-12 AWG (yellow) ring terminals (8x quick disconnect pairs if using integrated wire controllers)
  - 2x Andersen SB50 battery connectors
  - 6AWG Terminal lugs

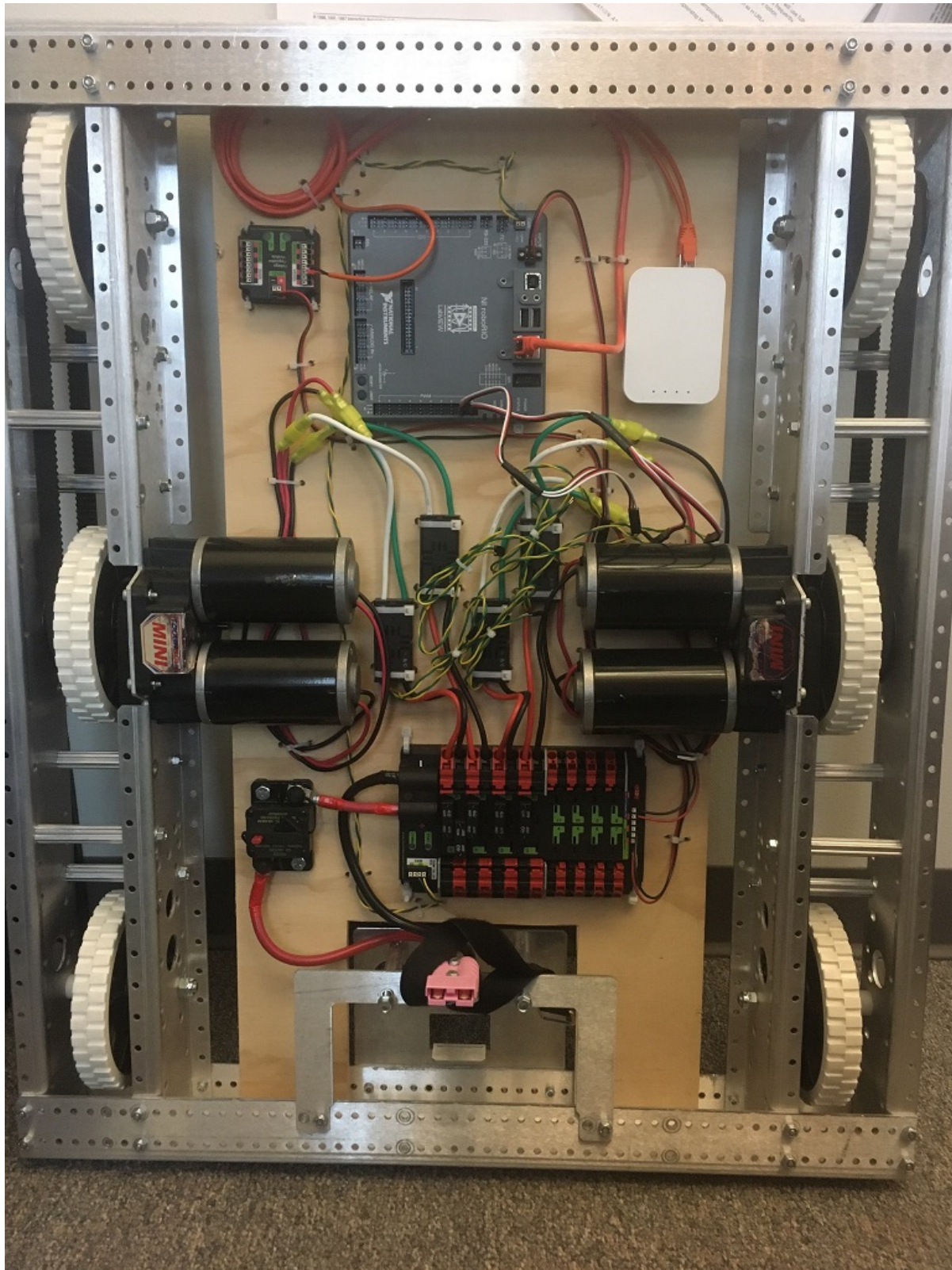
- 12V Battery
- Red/Black Electrical tape
- Dual Lock material or fasteners
- Zip ties
- 1/4" or 1/2" plywood
- Tools Required:
  - Wago Tool or small flat-head screwdriver
  - Very small flat head screwdriver (eyeglass repair size)
  - Philips head screw driver
  - 5mm Hex key (3/16" may work if metric is unavailable)
  - 1/16" Hex key
  - Wire cutters, strippers, and crimpers
  - 7/16" box end wrench or nut driver

### **1.8.2 Create the Base for the Control System**

For a benchtop test board, cut piece of 1/4" or 1/2" material (wood or plastic) approximately 24" x 16". For a Robot Quick Build control board see the supporting documentation for the proper size board for the chosen chassis configuration.



### 1.8.3 Layout the Core Control System Components



Layout the components on the board. One layout that should work is shown in the



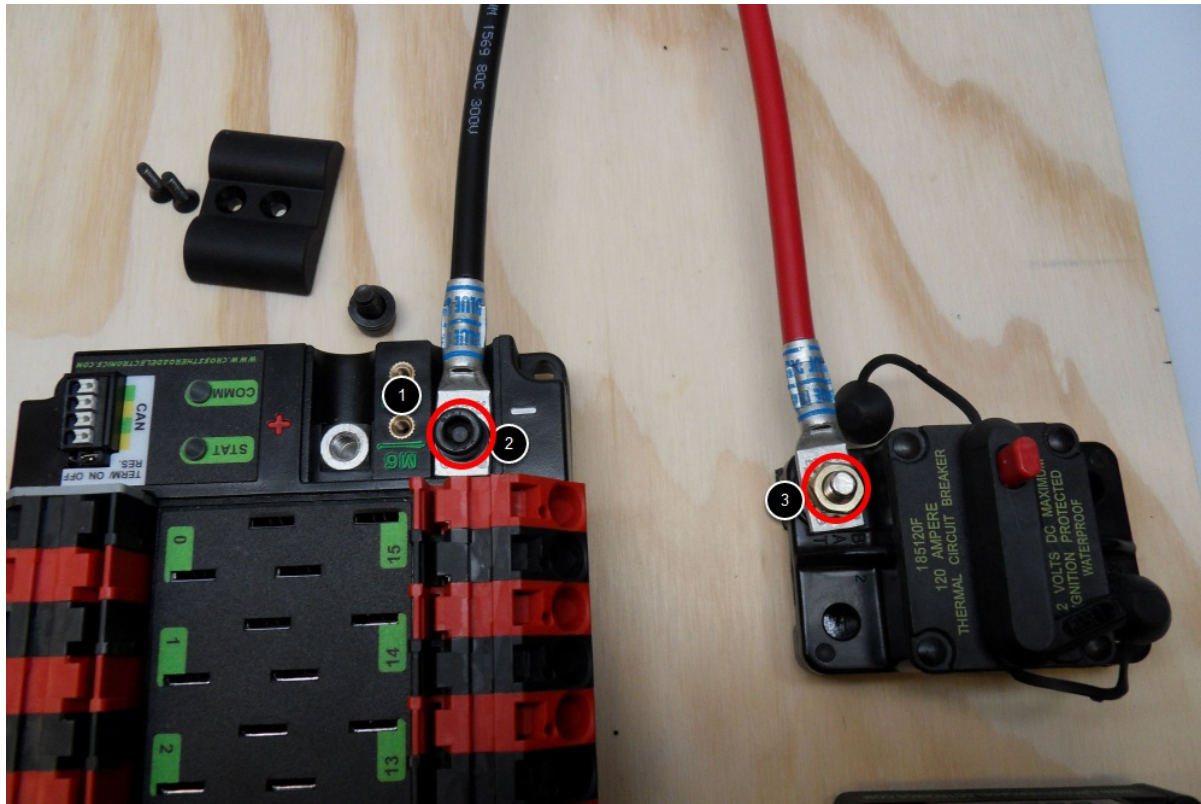
images/how-to-wire-a-robot above.



### **1.8.4 Fasten Components**

Using the Dual Lock or hardware, fasten all components to the board. Note that in many FRC games robot-to-robot contact may be substantial and Dual Lock alone is unlikely to stand up as a fastener for many electronic components. Teams may wish to use nut and bolt fasteners or (as shown in the image above) cable ties, with or without Dual Lock to secure devices to the board.

### 1.8.5 Attach Battery Connector to PDP

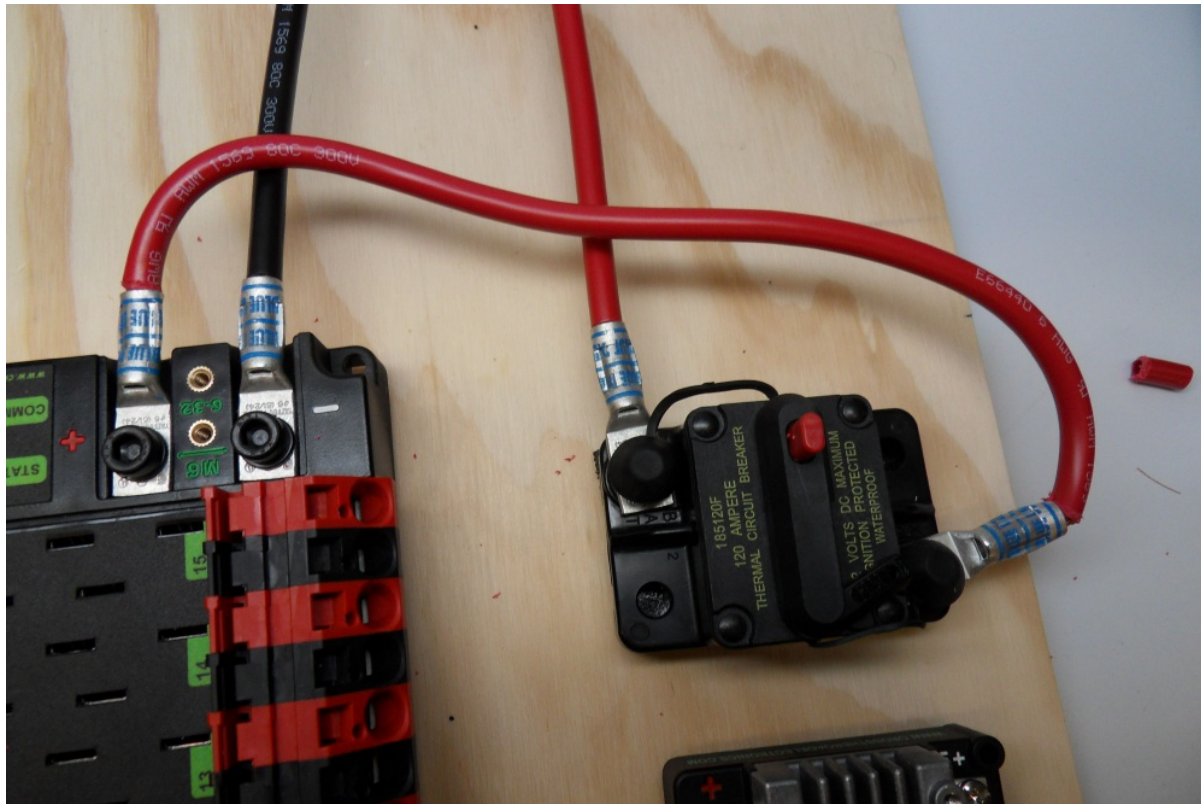


Requires: Battery Connector, 6AWG terminal lugs, 1/16" Allen, 5mm Allen, 7/16" Box end

Attach terminal lugs to battery connector:

1. Using a 1/16" Allen wrench, remove the two screws securing the PDP terminal cover.
2. Using a 5mm Allen wrench (3/16" will work if metric is not available), remove the negative (-) bolt and washer from the PDP and fasten the negative terminal of the battery connector.
3. Using a 7/16" box end wrench, remove the nut on the "Batt" side of the main breaker and secure the positive terminal of the battery connector

### 1.8.6 Wire Breaker to PDP



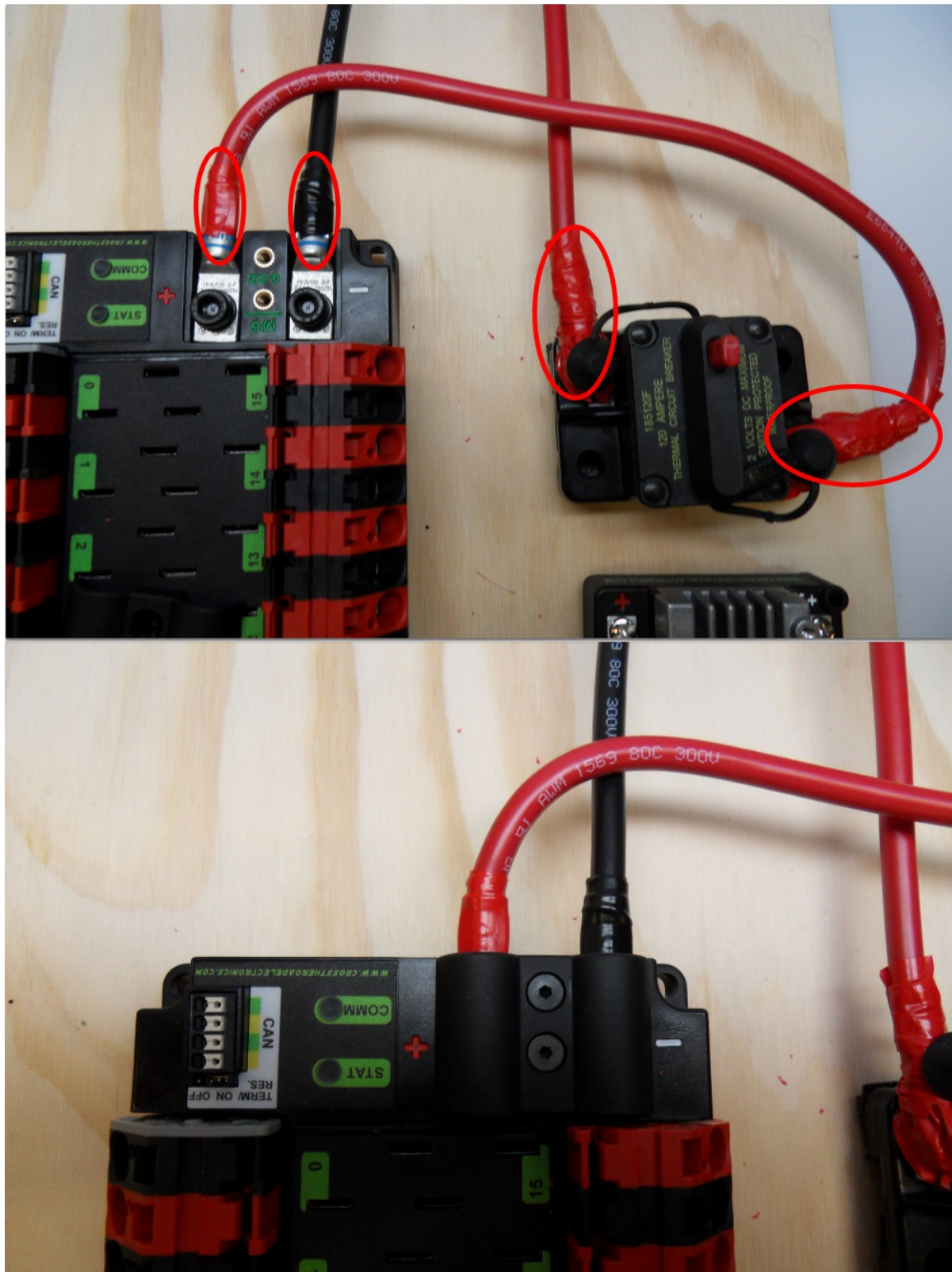
Requires: 6AWG red wire, 2x 6AWG terminal lugs, 5mm Allen, 7/16" box end

Secure one terminal lug to the end of the 6AWG red wire. Using the 7/16" box end, remove the nut from the "AUX" side of the 120A main breaker and place the terminal over the stud. Loosely secure the nut (you may wish to remove it shortly to cut, strip, and crimp the other end of the wire). Measure out the length of wire required to reach the positive terminal of the PDP.

1. Cut, strip, and crimp the terminal to the 2nd end of the red 6AWG wire.
2. Using the 7/16" box end, secure the wire to the "AUX" side of the 120A main breaker.
3. Using the 5mm, secure the other end to the PDP positive terminal.



### 1.8.7 Insulate PDP connections



Requires: 1/16" Allen, Electrical tape

1. Using electrical tape, insulate the two connections to the 120A breaker. Also insulate any part of the PDP terminals which will be exposed when the cover is replaced. One method for insulating the main breaker connections is to wrap the stud and nut first, then use the tape wrapped around the terminal and wire to secure the tape.
2. Using the 1/16" Allen wrench, replace the PDP terminal cover

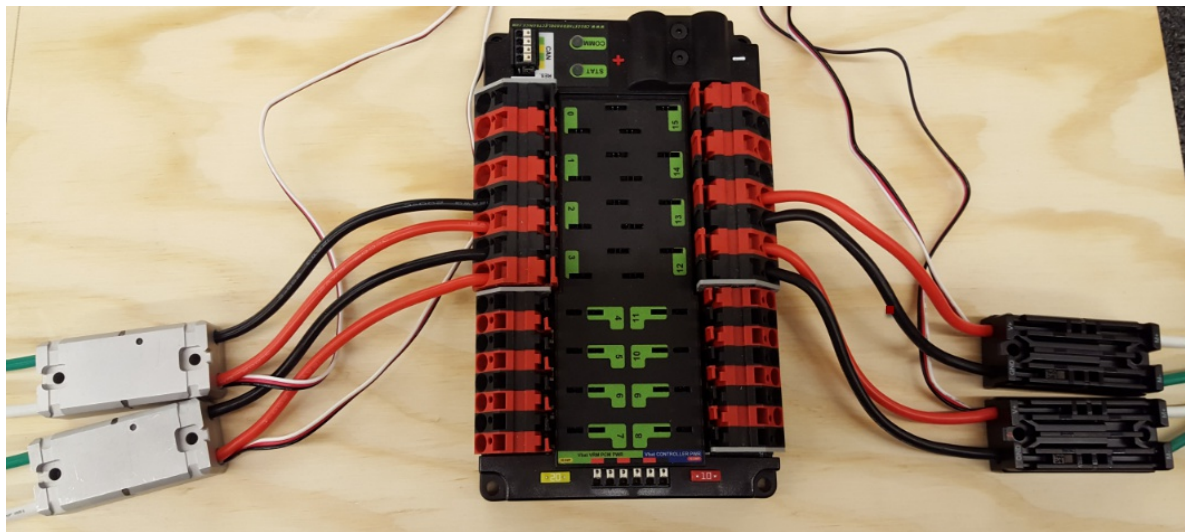
### 1.8.8 Wago connectors

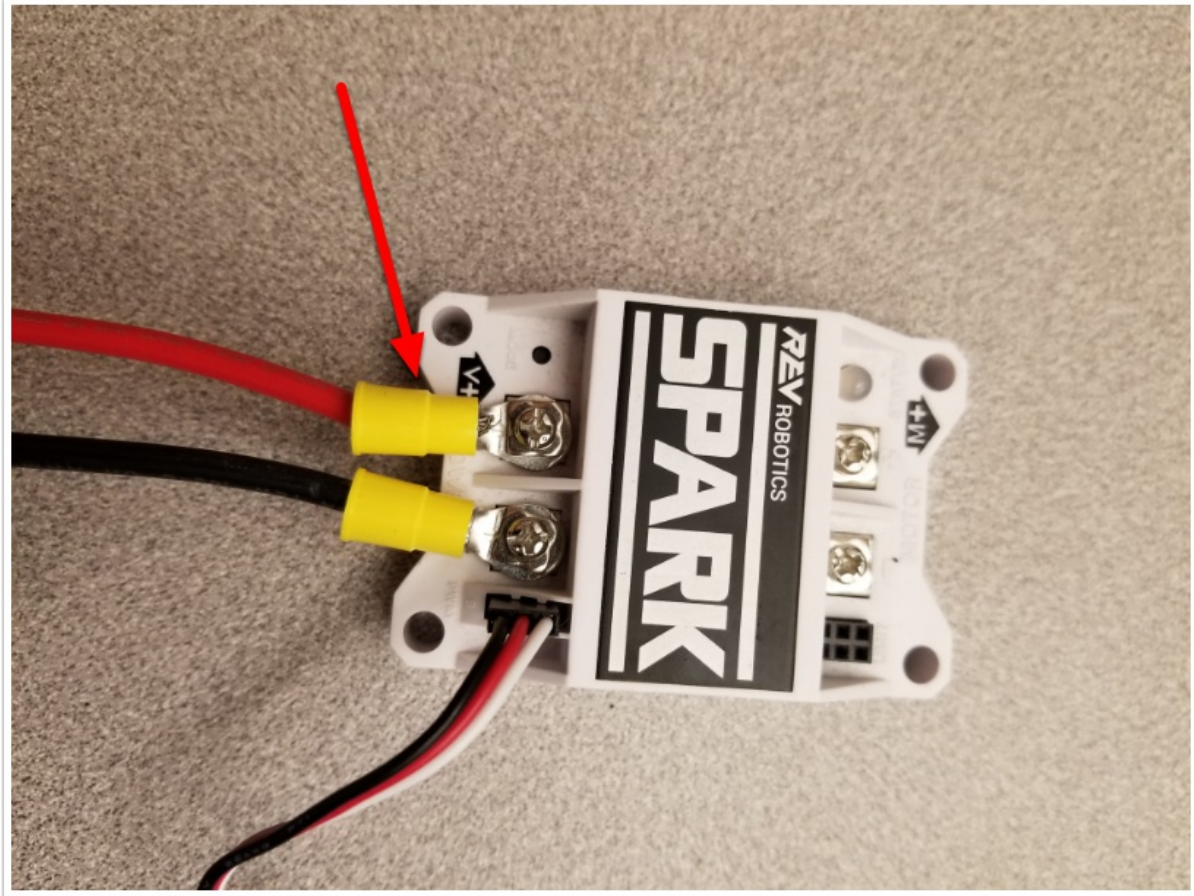
The next step will involve using the Wago connectors on the PDP. To use the Wago connectors, insert a small flat blade screwdriver into the rectangular hole at a shallow angle then angle the screwdriver upwards as you continue to press in to actuate the lever, opening the terminal. Two sizes of Wago connector are found on the PDP:

- Small Wago connector: Accepts 10AWG-24AWG, strip 11-12mm (~7/16")
- Large Wago connector: Accepts 6AWG-12AWG, strip 12-13mm(~1/2")

To maximize pullout force and minimize connection resistance wires should not be tinned (and ideally not twisted) before inserting into the Wago connector.

### 1.8.9 Motor Controller Power





Requires: Wire Stripper, Small Flat Screwdriver, 10 or 12 AWG wire, 10 or 12 AWG fork/ring terminals (terminal controllers only), wire crimper

For Victor SPX or other wire integrated motor controllers (top image):

- Cut and strip the red and black power input wires wire, then insert into one of the 40A (larger) Wago terminal pairs.

For terminal motor controllers (bottom image):

1. Cut red and black wire to appropriate length to reach from one of the 40A (larger) Wago terminal pairs to the input side of the speed controller (with a little extra for the length that will be inserted into the terminals on each end)
2. Strip one end of each of the wires, then insert into the Wago terminals.
3. Strip the other end of each wire, and crimp on a ring or fork terminal
4. Attach the terminal to the speed controller input terminals (red to +, black to -)

### **1.8.10 Weidmuller Connectors**

The correct strip length is  $\sim 5/16''$  (8mm), not the  $5/8''$  mentioned in the video.

A number of the CAN and power connectors in the system use a Weidmuller LSF series wire-to-board connector. There are a few things to keep in mind when using this connector for best results:

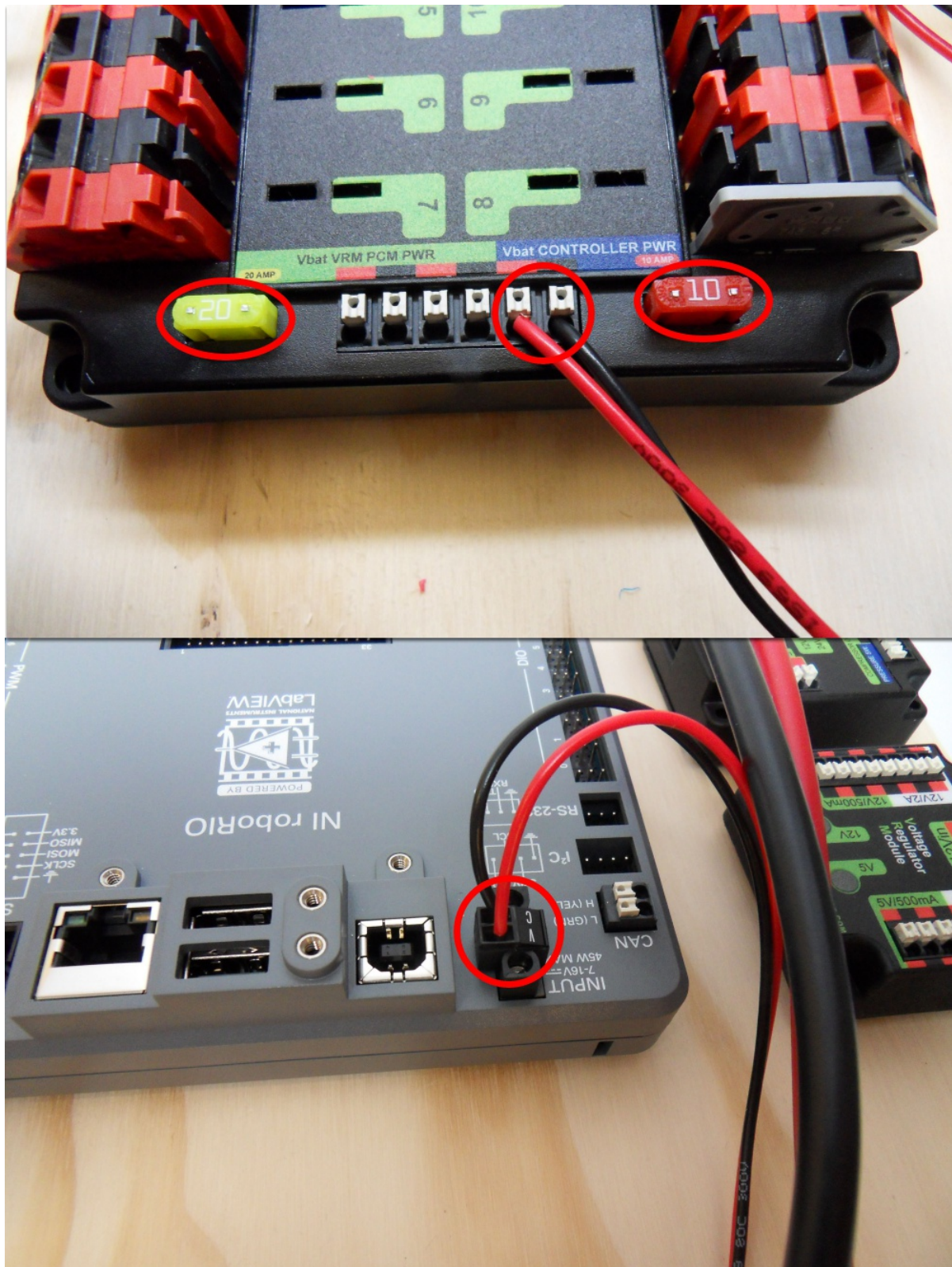


- Wire should be 16AWG to 24AWG (consult rules to verify required gauge for power wiring)
- Wire ends should be stripped approximately 5/16"
- To insert or remove the wire, press down on the corresponding "button" to open the terminal

After making the connection check to be sure that it is clean and secure:

- Verify that there are no "whiskers" outside the connector that may cause a short circuit
- Tug on the wire to verify that it is seated fully. If the wire comes out and is the correct gauge it needs to be inserted further and/or stripped back further.

### 1.8.11 roboRIO Power



Requires: 10A/20A mini fuses, Wire stripper, very small flat screwdriver, 18AWG Red and

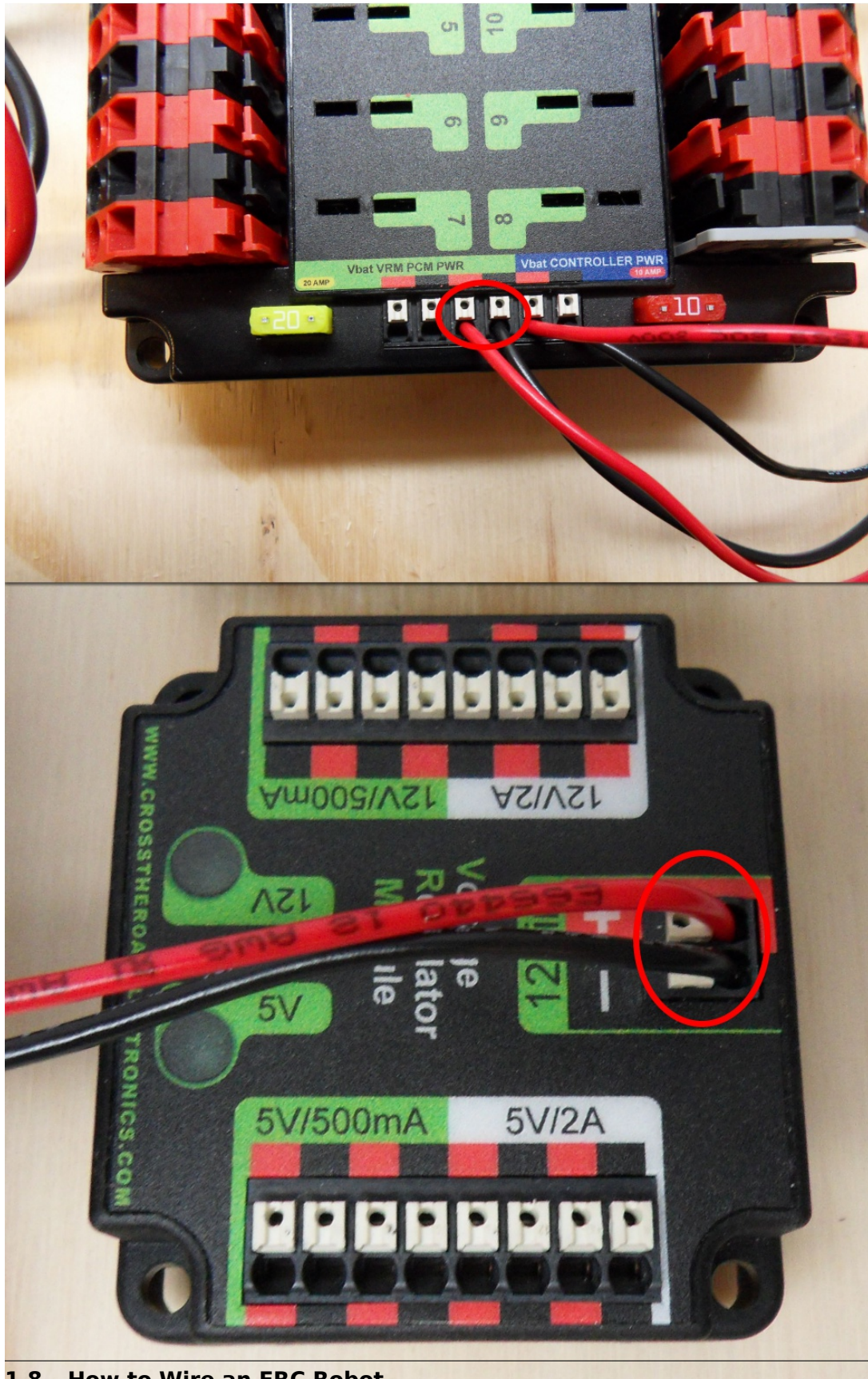


Black

1. Insert the 10A and 20A mini fuses in the PDP in the locations shown on the silk screen (and in the image above)
2. Strip ~5/16" on both the red and black 18AWG wire and connect to the "Vbat Controller PWR" terminals on the PDB
3. Measure the required length to reach the power input on the roboRIO. Take care to leave enough length to route the wires around any other components such as the battery and to allow for any strain relief or cable management.
4. Cut and strip the wire.
5. Using a very small flat screwdriver connect the wires to the power input connector of the roboRIO (red to V, black to C). Also make sure that the power connector is screwed down securely to the roboRIO.



### 1.8.12 Voltage Regulator Module Power

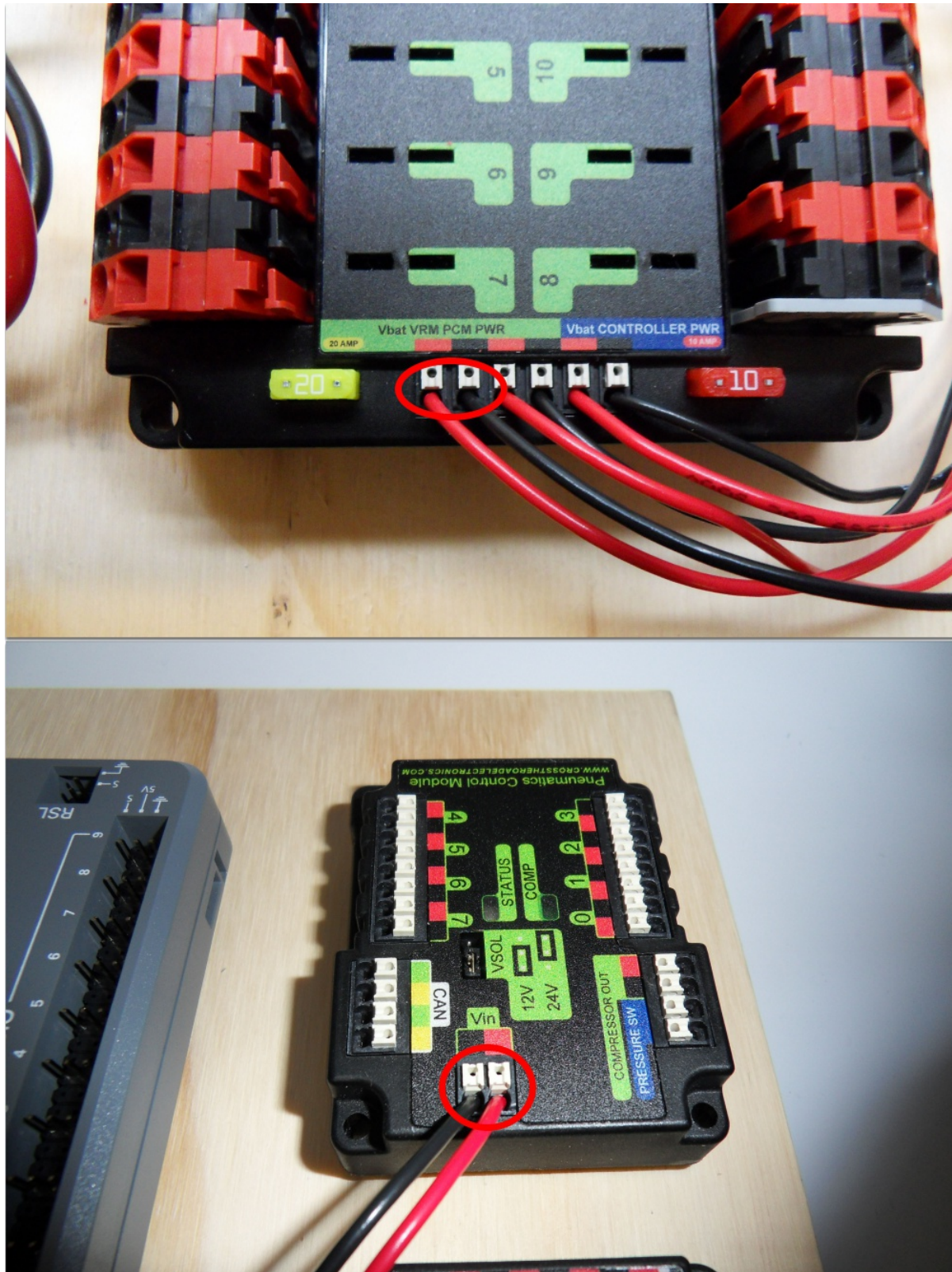


Requires: Wire stripper, small flat screwdriver (optional), 18AWG red and black wire:

1. Strip ~5/16" on the end of the red and black 18AWG wire.
2. Connect the wire to one of the two terminal pairs labeled "Vbat VRM PCM PWR" on the PDP.
3. Measure the length required to reach the "12Vin" terminals on the VRM. Take care to leave enough length to route the wires around any other components such as the battery and to allow for any strain relief or cable management.
4. Cut and strip ~5/16" from the end of the wire.
5. Connect the wire to the VRM 12Vin terminals.



### 1.8.13 Pneumatics Control Module Power (Optional)



Requires: Wire stripper, small flat screwdriver (optional), 18AWG red and black wire

Note: The PCM is an optional component used for controlling pneumatics on the robot.

1. Strip ~5/16" on the end of the red and black 18AWG wire.
2. Connect the wire to one of the two terminal pairs labeled "Vbat VRM PCM PWR" on the PDP.
3. Measure the length required to reach the "Vin" terminals on the PCM. Take care to leave enough length to route the wires around any other components such as the battery and to allow for any strain relief or cable management.
4. Cut and strip ~5/16" from the end of the wire.
5. Connect the wire to the PCM 12Vin terminals.

### 1.8.14 Radio Power and Ethernet

**Warning:** DO NOT connect the Rev passive POE injector cable directly to the roboRIO. The roboRIO MUST connect to the female end of the cable using an additional Ethernet cable as shown in the next step.



Requires: Small flat screwdriver (optional), Rev radio PoE cable

1. Insert the ferrules of the passive PoE injector cable into the corresponding colored ter-

minals on the 12V/2A section of the VRM.

2. Connect the male RJ45 (Ethernet) end of the cable into the Ethernet port on the radio closest to the barrel connector (labeled 18-24v POE)



### 1.8.15 roboRIO to Radio Ethernet

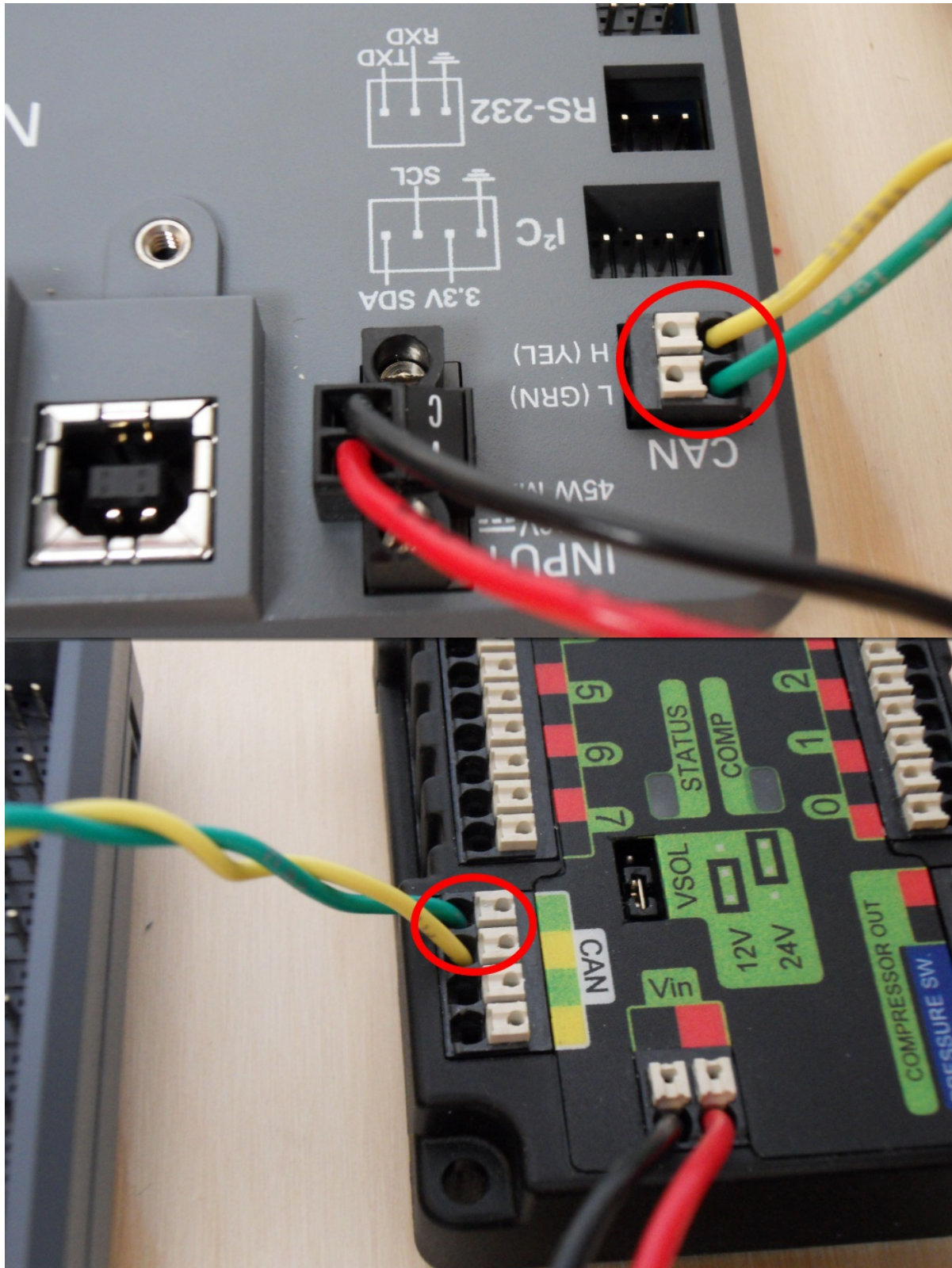


Requires: Ethernet cable

Connect an Ethernet cable from the female RJ45 (Ethernet) port of the Rev Passive POE cable to the RJ45 (Ethernet) port on the roboRIO.

### **1.8.16 CAN Devices**

## roboRIO to PCM CAN



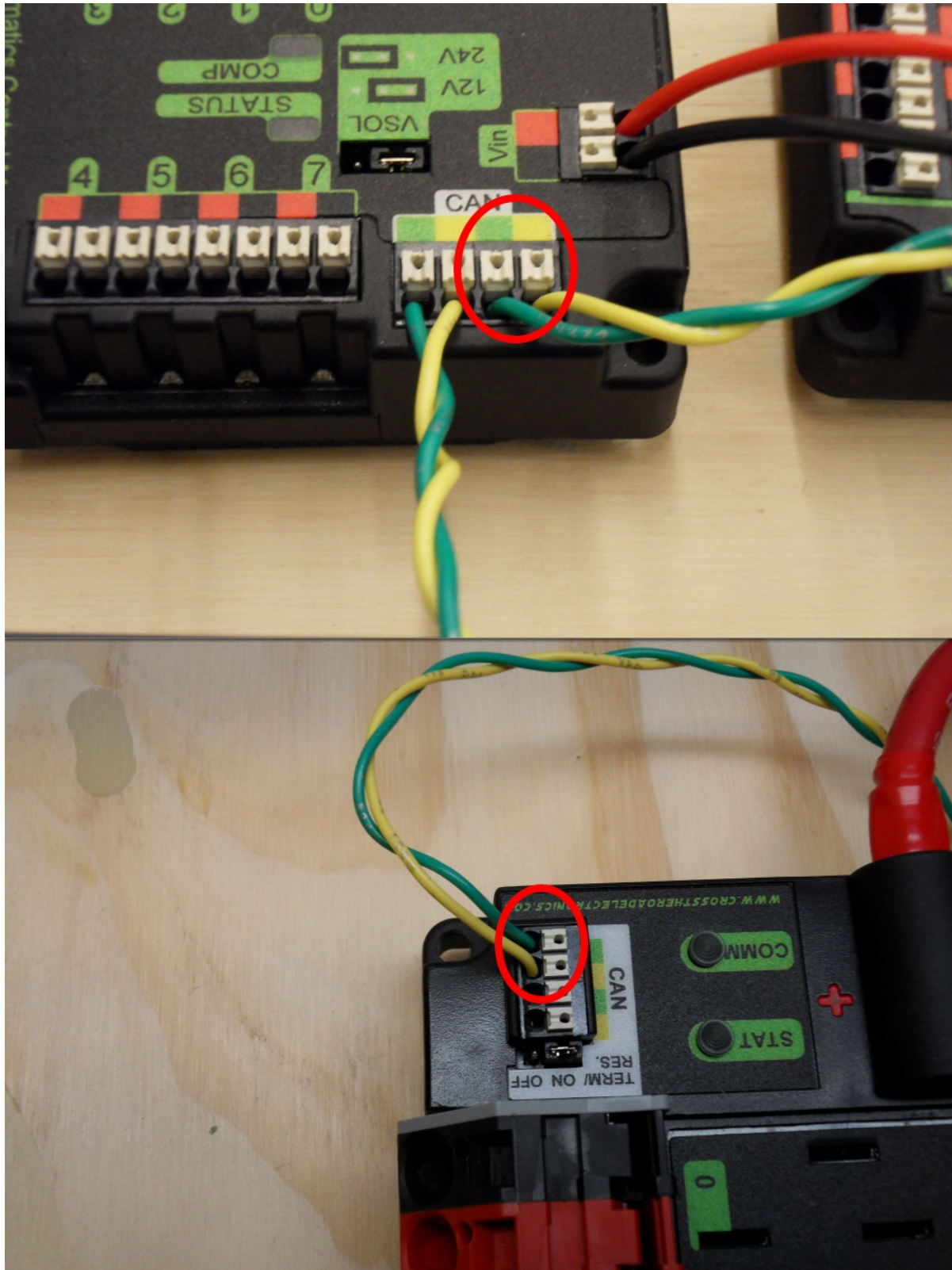
Requires: Wire stripper, small flat screwdriver (optional), yellow/green twisted CAN cable

Note: The PCM is an optional component used for controlling pneumatics on the robot. If you are not using the PCM, wire the CAN connection directly from the roboRIO (shown in this step) to the PDP (shown in the next step).

1. Strip ~5/16" off of each of the CAN wires.
2. Insert the wires into the appropriate CAN terminals on the roboRIO (Yellow->YEL, Green->GRN).
3. Measure the length required to reach the CAN terminals of the PCM (either of the two available pairs). Cut and strip ~5/16" off this end of the wires.
4. Insert the wires into the appropriate color coded CAN terminals on the PCM. You may use either of the Yellow/Green terminal pairs on the PCM, there is no defined in or out.



## PCM to PDP CAN



Requires: Wire stripper, small flat screwdriver (optional), yellow/green twisted CAN cable

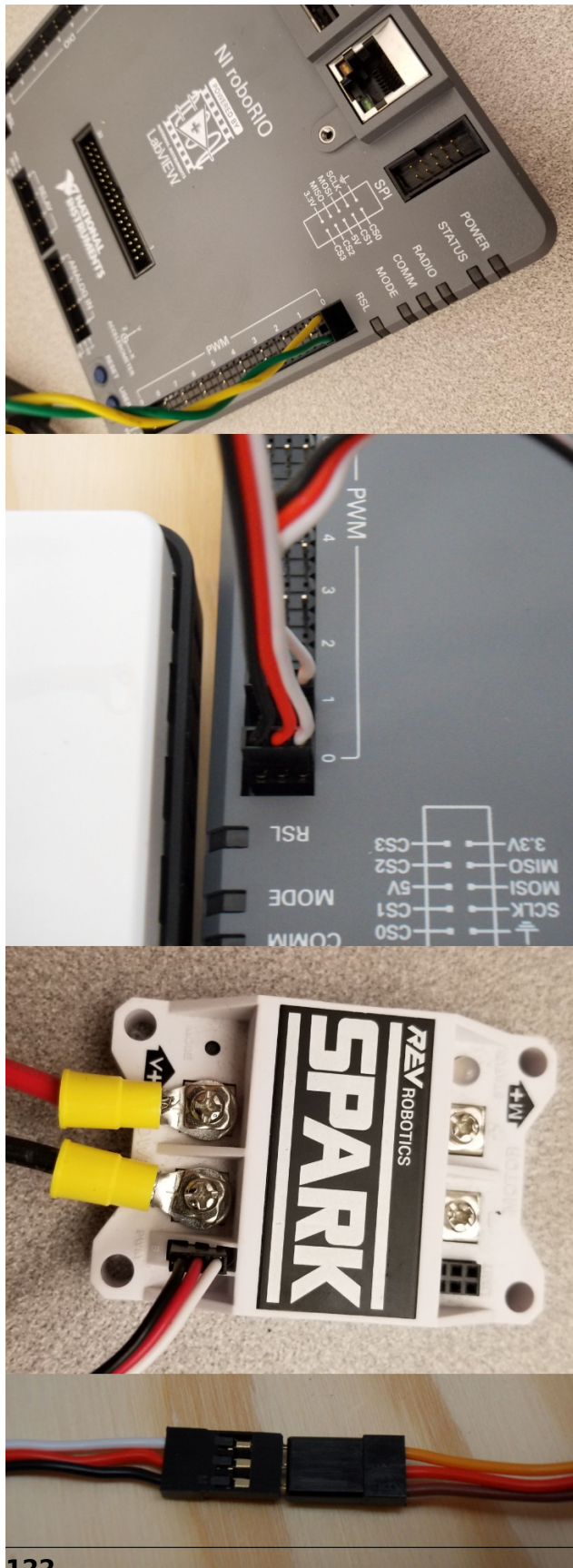
Note: The PCM is an optional component used for controlling pneumatics on the robot. If you are not using the PCM, wire the CAN connection directly from the roboRIO (shown in the above step) to the PDP (shown in this step).

1. Strip ~5/16" off of each of the CAN wires.
2. Insert the wires into the appropriate CAN terminals on the PCM.
3. Measure the length required to reach the CAN terminals of the PDP (either of the two available pairs). Cut and strip ~5/16" off this end of the wires.
4. Insert the wires into the appropriate color coded CAN terminals on the PDP. You may use either of the Yellow/Green terminal pairs on the PDP, there is no defined in or out.

Note: The PDP ships with the CAN bus terminating resistor jumper in the "ON" position. It is recommended to leave the jumper in this position and place any additional CAN nodes between the roboRIO and the PDP (leaving the PDP as the end of the bus). If you wish to place the PDP in the middle of the bus (utilizing both pairs of PDP CAN terminals) move the jumper to the "OFF" position and place your own 120 ohm terminating resistor at the end of your CAN bus chain.



### 1.8.17 PWM Cables





Requires: 4x PWM cables (if using non-integrated wire controllers), 2x PWM Y-cable (Optional)

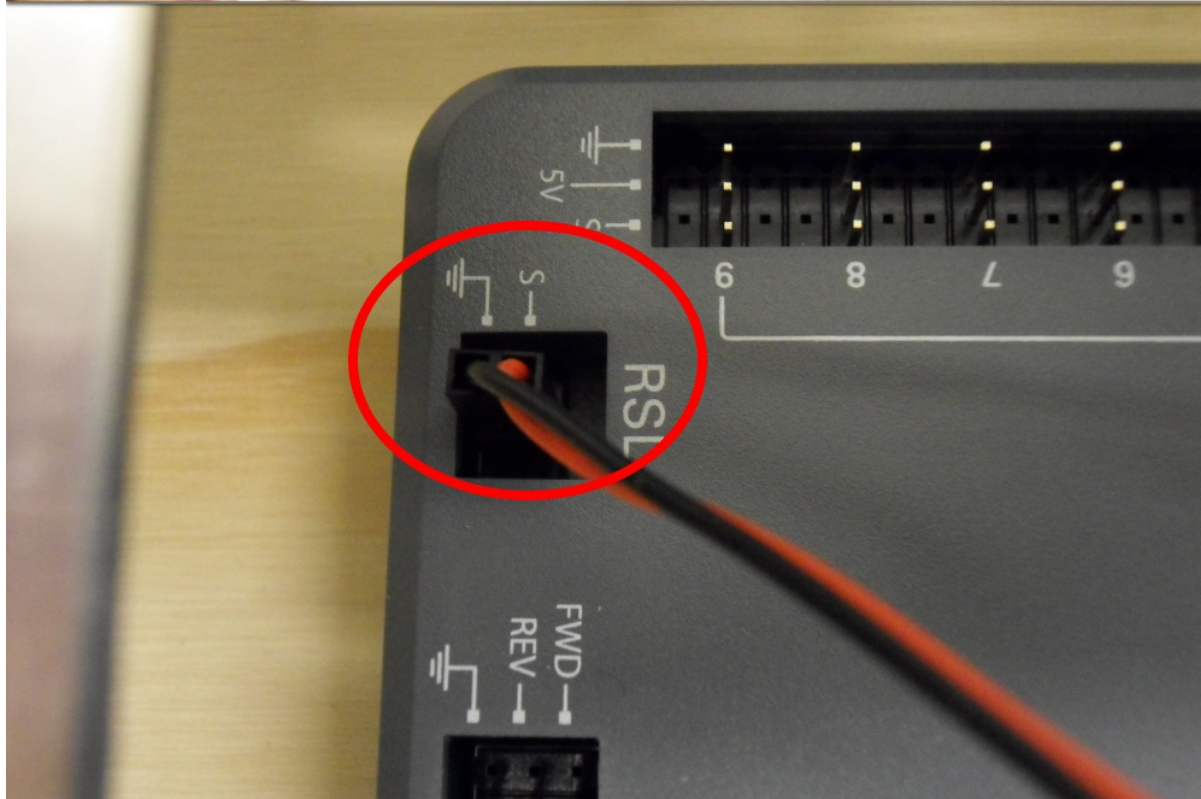
Option 1 (Direct connect):

- Connect the PWM cables from each controller directly to the roboRIO. For Victor SPX's and other PWM/CAN controllers, the green wire (black wire for non-integrated controllers) should be towards the outside of the roboRIO. For controllers without integrated wires, make sure the controller side of the black wire is located according to the markings on the controller. It is recommended to connect the left side to PWM 0 and 1 and the right side to PWM 2 and 3 for the most straightforward programming experience, but any channel will work as long as you note which side goes to which channel and adjust the code accordingly.

Option 2 (Y-cable):

1. Connect 1 PWM Y-cable to the PWM cables for the controllers controlling one side of the robot. The brown wire on the Y-cable should match the green/black wire on the PWM cable.
2. Connect the PWM Y-cables to the PWM ports on the roboRIO. The brown wire should be towards the outside of the roboRIO. It is recommended to connect the left side to PWM 0 and the right side to PWM 1 for the most straightforward programming experience, but any channel will work as long as you note which side goes to which channel and adjust the code accordingly.

### 1.8.18 Robot Signal Light



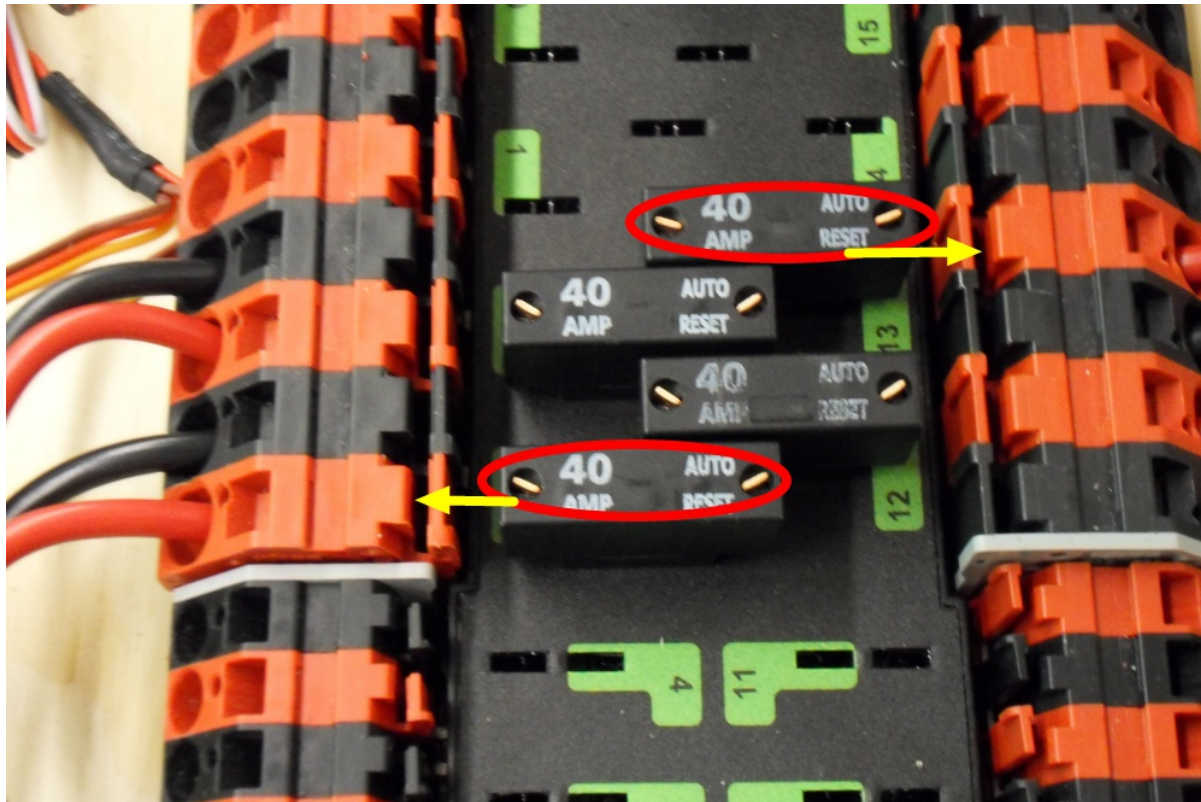
Requires: Wire stripper, 2 pin cable, Robot Signal Light, 18AWG red wire, very small flat

screwdriver

1. Cut one end off of the 2 pin cable and strip both wires
2. Insert the black wire into the center, “N” terminal and tighten the terminal.
3. Strip the 18AWG red wire and insert into the “La” terminal and tighten the terminal.
4. Cut and strip the other end of the 18AWG wire to insert into the “Lb” terminal
5. Insert the red wire from the two pin cable into the “Lb” terminal with the 18AWG red wire and tighten the terminal.
6. Connect the two-pin connector to the RSL port on the roboRIO. The black wire should be closest to the outside of the roboRIO.

You may wish to temporarily secure the RSL to the control board using cable ties or Dual Lock (it is recommended to move the RSL to a more visible location as the robot is being constructed) Circuit Breakers

### 1.8.19 Circuit Breakers



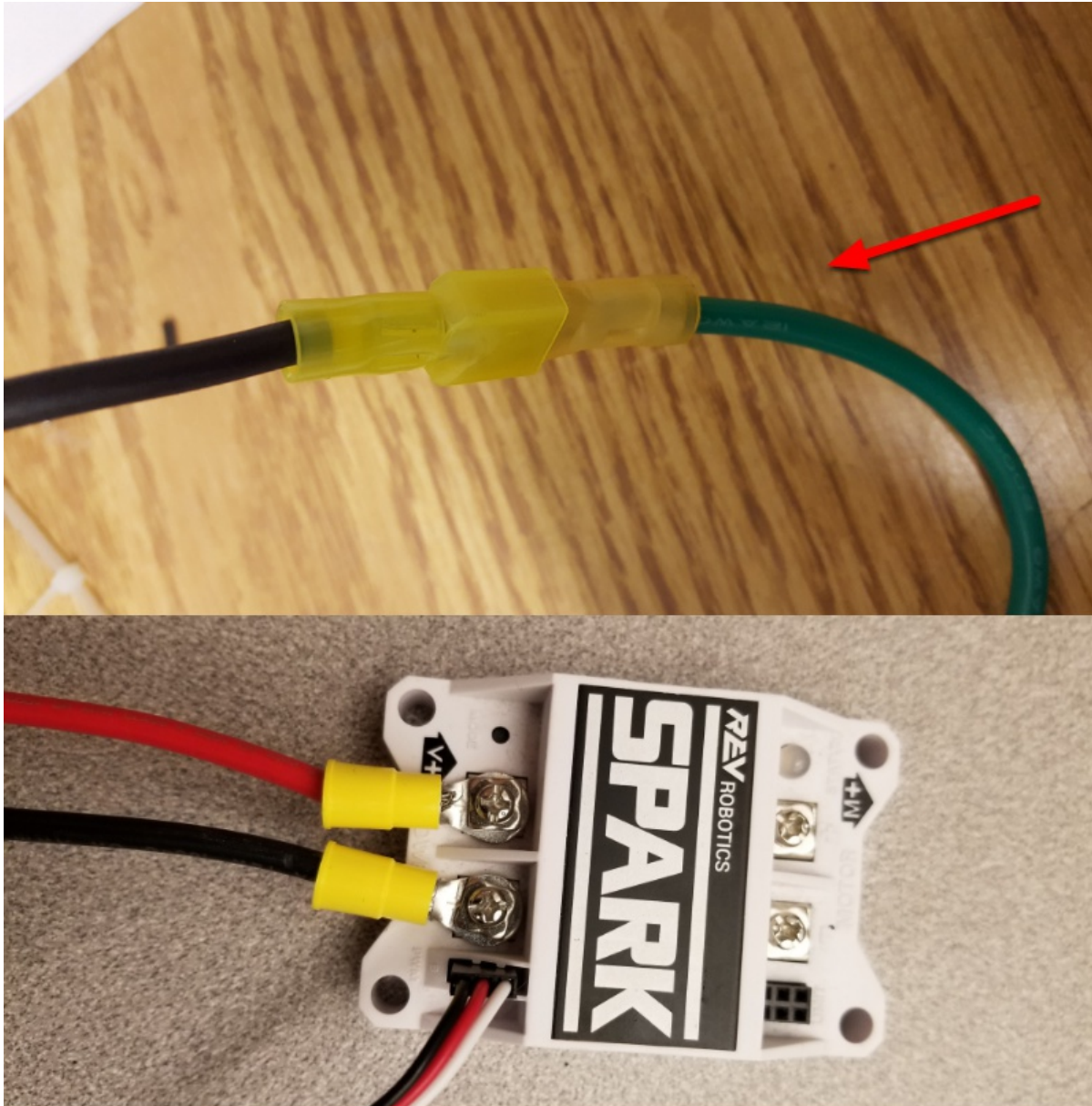
Requires: 4x 40A circuit breakers

Insert 40-amp Circuit Breakers into the positions on the PDP corresponding with the Wago connectors the Victors are connected to. Note that, for all breakers, the breaker corresponds with the nearest positive (red) terminal (see graphic above). All negative terminals on the board are directly connected internally.

If working on a Robot Quick Build, stop here and insert the board into the robot chassis before continuing.



## 1.8.20 Motor Power



Requires: Wire stripper, wire crimper, phillips head screwdriver, wire connecting hardware  
For each CIM motor:

- Strip the ends of the red and black wires from the CIM

For integrated wire controllers (including Victor SPX):

1. Strip the white and green wires from the controller
2. Connect the motor wires to the controller output wires (it is recommended to connect the red wire to the white M+ output). The images/how-to-wire-a-robot above show examples using quick disconnect terminals.

For Sparks or other non-integrated-wire controllers:

1. Crimp a ring/fork terminal on each of the motor wires.
2. Attach the wires to the output side of the motor controller (red to +, black to -)

### **1.8.21 STOP**



**Danger:** STOP!!

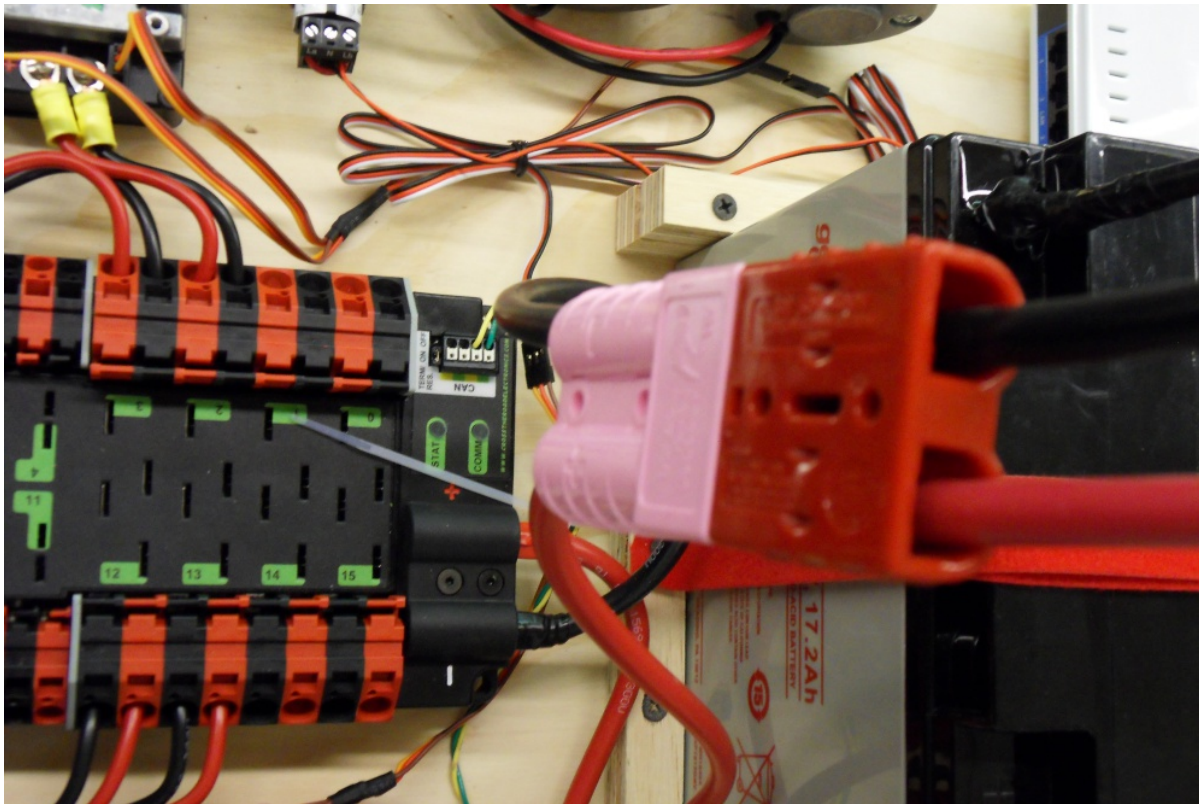
**Danger:** Before plugging in the battery, make sure all connections have been made with the proper polarity. Ideally have someone that did not wire the robot check to make sure all connections are correct.

Before plugging in the battery, make sure all connections have been made with the proper polarity. Ideally have someone that did not wire the robot check to make sure all connections are correct.

- Start with the battery and verify that the red wire is connected to the positive terminal
- Check that the red wire passes through the main breaker and to the + terminal of the PDP and that the black wire travels directly to the - terminal.
- For each motor controller, verify that the red wire goes from the red PDP terminal to the Red wire on the Victor SPX (not the white M+!!!!)
- For each device on the end of the PDP, verify that the red wire connects to the red terminal on the PDP and the red terminal on the component.
- Make sure that the orange Passive PoE cable is plugged directly into the radio NOT THE roboRIO! It must be connected to the roboRIO using an additional Ethernet cable.

It is also recommended to put the robot on blocks so the wheels are off the ground before proceeding. This will prevent any unexpected movement from becoming dangerous.

### 1.8.22 Manage Wires



Requires: Zip ties

Now may be a good time to add a few zip ties to manage some of the wires before proceeding. This will help keep the robot wiring neat. Connect Battery Connect BatteryZoom: Connect Battery

Connect the battery to the robot side of the Andersen connector. Power on the robot by moving the lever on the top of the 120A main breaker into the ridge on the top of the housing.

If stuff blinks, you probably did it right. From here, you should connect to the roboRIO and try uploading your code!

## 1.9 Imaging your roboRIO

**Warning:** Before imaging your roboRIO, you must have completed installation of the *FRC Game Tools*. You also must have the roboRIO power properly wired to the Power Distribution Panel. Make sure the power wires to the roboRIO are secure and that the connector is secure firmly to the roboRIO (4 total screws to check).

### 1.9.1 Configuring the roboRIO

The roboRIO Imaging Tool will be used to image your roboRIO with the latest software.

#### USB Connection



Connect a USB cable from the roboRIO USB Device port to the PC. This requires a USB Type A male (standard PC end) to Type B male cable (square with 2 cut corners), most commonly found as a printer USB cable.

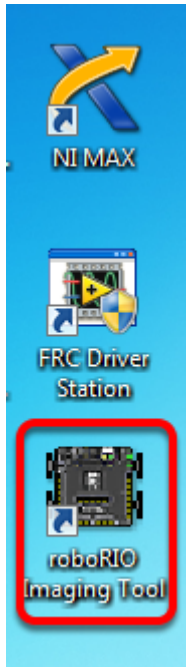
**Note:** The roboRIO should only be imaged via the USB connection. It is not recommended to attempt imaging using the Ethernet connection.

#### Driver Installation

The device driver should install automatically. If you see a “New Device” pop-up in the bottom right of the screen, wait for the driver install to complete before continuing.



### 1.9.2 Launching the Imaging Tool



The roboRIO imaging tool and latest image are installed with the NI FRC Game Tools. Launch the imaging tool by double clicking on the shortcut on the Desktop. If you have difficulties imaging your roboRIO, you may need to try right-clicking on the icon and selecting Run as Administrator instead.

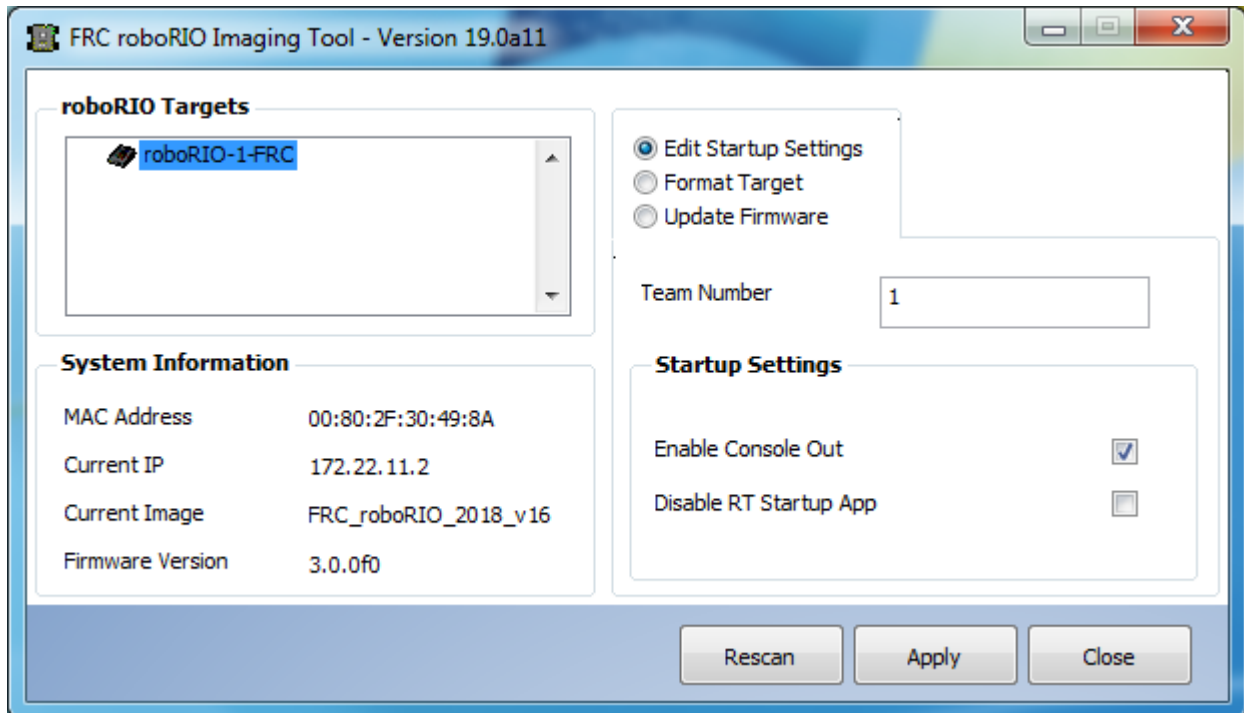
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**Note:** The roboRIO imaging tool is also located at C:\Program Files (x86)\National Instruments\LabVIEW YYYY\project\roboRIO Tool where YYYY is the current year - 1. If it's 2020, the directory would be LabVIEW 2019.

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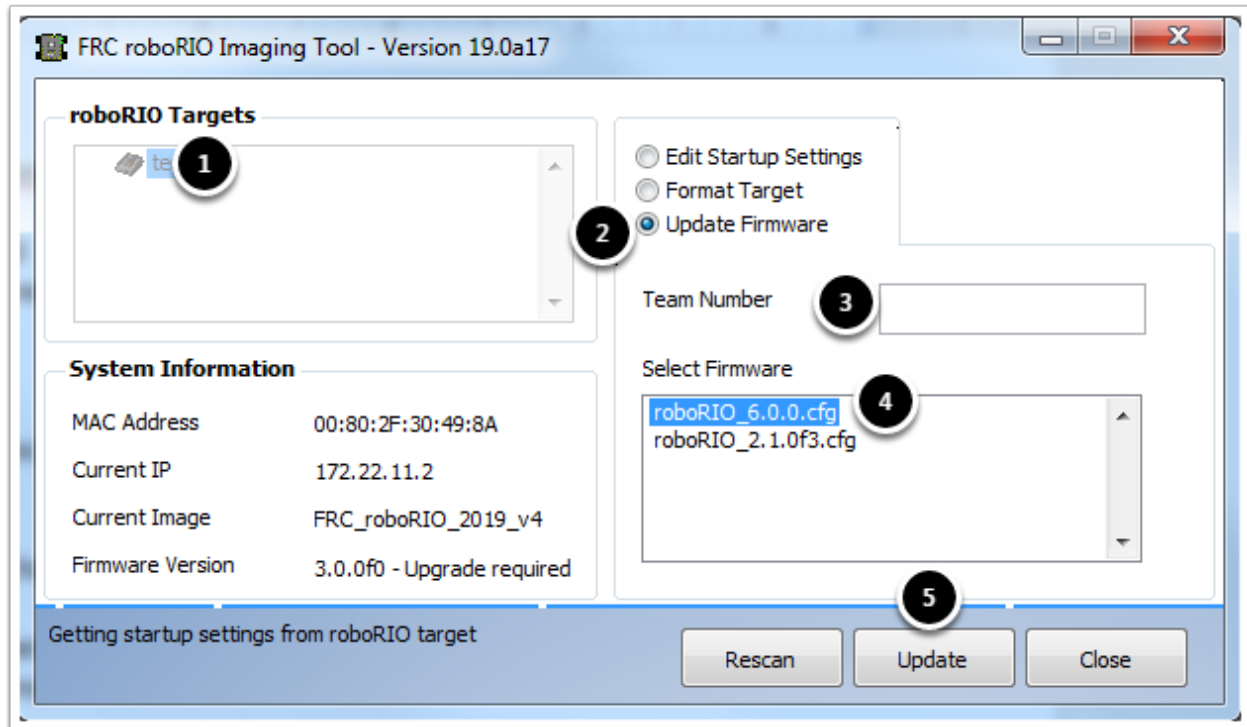
### 1.9.3 roboRIO Imaging Tool



After launching, the roboRIO Imaging Tool will scan for available roboRIOs and indicate any found in the top left box. The bottom left box will show information and settings for the roboRIO currently selected. The right hand pane contains controls for modifying the roboRIO settings:

- **Edit Startup Settings** - This option is used when you want to configure the startup settings of the roboRIO (the settings in the right pane), without imaging the roboRIO.
- **Format Target** - This option is used when you want to load a new image on the roboRIO (or reflash the existing image). This is the most common option.
- **Update Firmware** - This option is used to update the roboRIO firmware. For this season, the imaging tool will require roboRIO firmware to be version 5.0 or greater.

### Updating Firmware

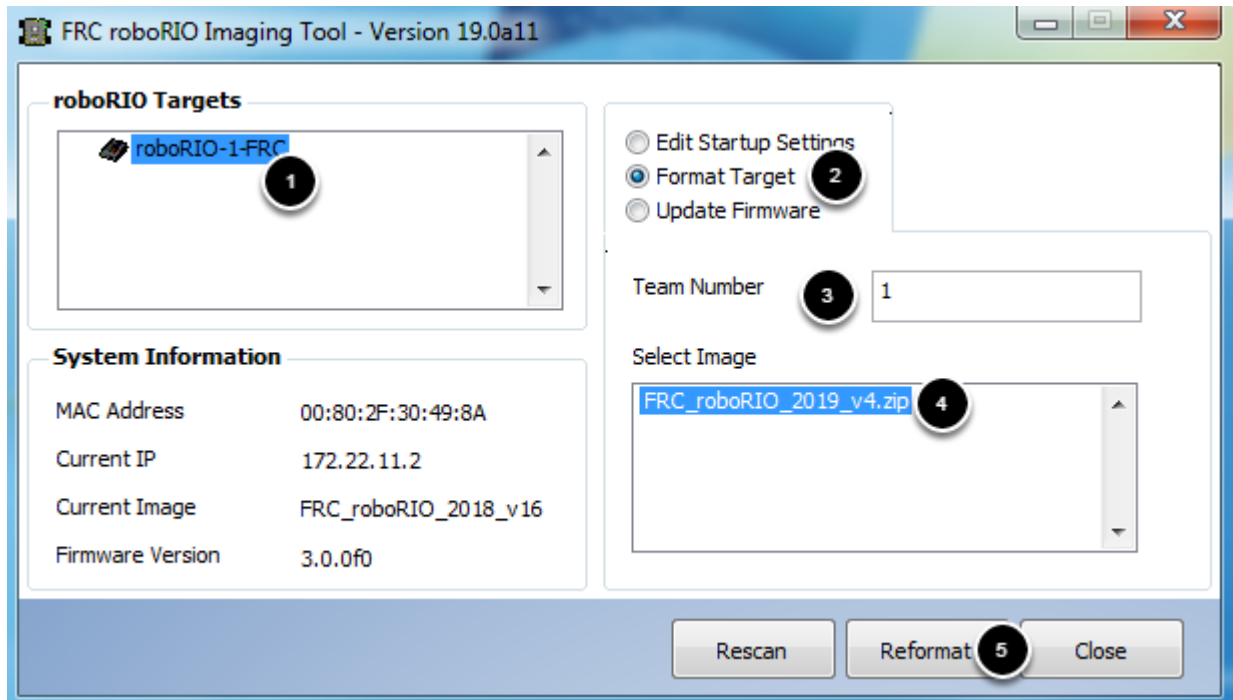


roboRIO firmware must be at least v5.0 to work with the 2019 image. If your roboRIO is at least version 5.0 (as shown in the bottom left of the imaging tool) you do not need to update.

To update roboRIO firmware:

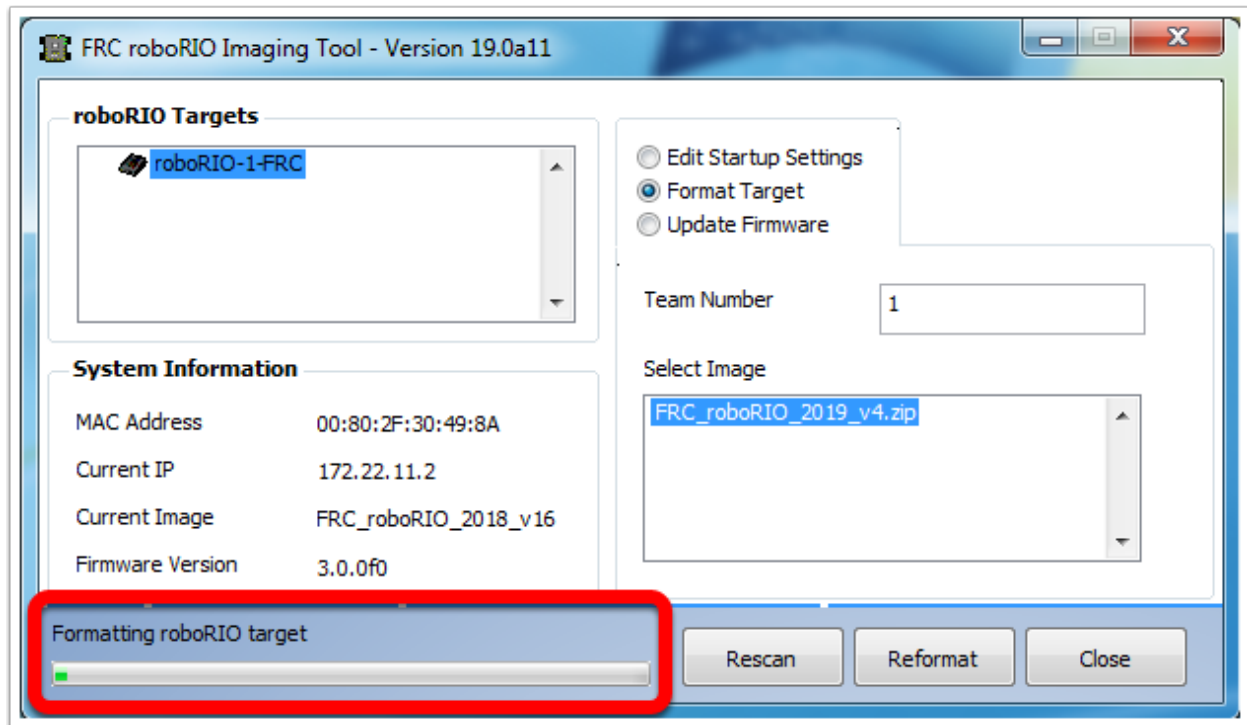
1. Make sure your roboRIO is selected in the top left pane.
2. Select Update Firmware in the top right pane
3. Enter a team number in the Team Number box
4. Select the latest firmware file in the bottom right
5. Click the **Update** button

### 1.9.4 Imaging the roboRIO



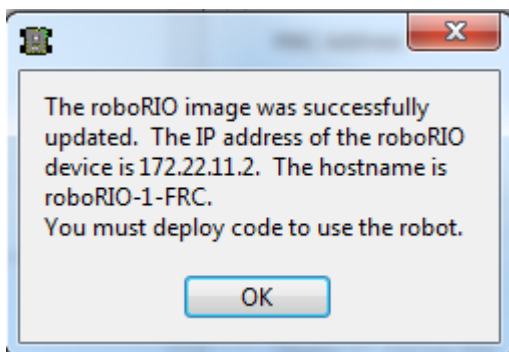
1. Make sure the roboRIO is selected in the top left pane
2. Select Format Target in the right pane
3. Enter your team number in the box
4. Select the latest image version in the box.
5. Click Reformat to begin the imaging process.

### 1.9.5 Imaging Progress



The imaging process will take approximately 3-10 minutes. A progress bar in the bottom left of the window will indicate progress.

### 1.9.6 Imaging Complete



When the imaging completes you should see the dialog above. Click Ok, then click the Close button at the bottom right to close the imaging tool. Reboot the roboRIO using the Reset button to have the new team number take effect.

**Note:** The default CAN webdash functionality has been removed from the image (CAN devices will still work from robot code). You will need to use the tools provided by individual vendors to service their CAN devices.

### 1.9.7 Troubleshooting

If you are unable to image your roboRIO, troubleshooting steps include:

- Try running the roboRIO Imaging Tool as Administrator by right-clicking on the Desktop icon to launch it.
- Try accessing the roboRIO webpage with a web-browser at <http://172.22.11.2/> and/or verify that the NI network adapter appears in your list of Network Adapters in the Control Panel. If not, try re-installing the NI FRC Game Tools or try a different PC.
- Make sure your firewall is turned off.
- Try a different PC
- Some teams have experienced an issue where imaging fails if the device name of the computer you're using has a dash (-) in it. Try renaming the computer (or using a different PC).
- Try booting the roboRIO into Safe Mode by pressing and holding the reset button for at least 5 seconds.

## 1.10 Programming your Radio

This guide will show you how to use the FRC Radio Configuration Utility software to configure your robot's wireless bridge for use outside of FRC events.

Before you begin using the software:

1. Disable WiFi connections on your computer, as it may prevent the configuration utility from properly communicating with the bridge
2. Make sure no devices are connected to your computer via ethernet, other than the wireless bridge.

**Warning:** The OM5P-AN and AC use the same power plug as the D-Link DAP1522, however they are 12V radios. Wire the radio to the 12V 2A terminals on the VRM (center-pin positive).

### 1.10.1 Pre-Requisites

The FRC Radio Configuration Utility requires the Java Runtime Engine (JRE). If you do not have Java installed, you can download the JRE from here: <https://www.java.com/en/download/>

The FRC Radio Configuration Utility requires Administrator privileges to configure the network settings on your machine. The program should request the necessary privileges automatically (may require a password if run from a non-Administrator account), but if you are having trouble, try running it from an Administrator account.

### 1.10.2 Application Notes

By default, the Radio Configuration Utility will program the radio to enforce the 4Mbps bandwidth limit on traffic exiting the radio over the wireless interface. In the home configuration

(AP mode) this is a total, not a per client limit. This means that streaming video to multiple clients is not recommended.

The Utility has been tested on Windows 7, 8 and 10. It may work on other operating systems, but has not been tested.

### Programmed Configuration

Power	
Blue	On or Powering Up
Blue Blinking	Powering Up
Eth Link	
Blue	Link Up
Blue Blinking	Traffic Present
Wifi	
	Bridge Mode, Unlinked or non-FRC firmware
Off	
Red	AP, Unlinked
Yellow\Orange	AP, Linked
Green	Bridge Mode, Linked

**WiFi light only works after radio has been power cycled.**



The Radio Configuration Utility programs a number of configuration settings into the radio when run. These settings apply to the radio in all modes (including at events). These include:

- Set a static IP of 10.TE.AM.1
- Set an alternate IP on the wired side of 192.168.1.1 for future programming
- Bridge the wired ports so they may be used interchangeably
- The LED configuration noted in the graphic above.
- 4Mb/s bandwidth limit on the outbound side of the wireless interface (may be disabled for home use)
- QoS rules for internal packet prioritization (affects internal buffer and which packets to discard if bandwidth limit is reached). These rules are:
  - Robot Control and Status (UDP 1110, 1115, 1150)
  - Robot TCP & Network Tables (TCP 1735, 1740)
  - Bulk (All other traffic). (disabled if BW limit is disabled)
- DHCP server enabled. Serves out:
  - 10.TE.AM.11 - 10.TE.AM.111 on the wired side
  - 10.TE.AM.130 - 10.TE.AM.230 on the wireless side
  - Subnet mask of 255.255.255.0
  - Broadcast address 10.TE.AM.255

- DNS server enabled. DNS server IP and domain suffix (.lan) are served as part of the DHCP.

At home only:

- SSID may have a “Robot Name” appended to the team number to distinguish multiple networks.
- Firewall option may be enabled to mimic the field firewall rules (open ports may be found in the Game Manual)

**Warning:** It is not possible to modify the configuration manually

Download the software Download the latest FRC Radio Configuration Utility Installer from the following links:

[FRC Radio Configuration 20.0.0](#)

[FRC Radio Configuration 20.0.0 Israel Version](#)

**Note:** The \_IL version is for Israel teams and contains a version of the OM5PAC firmware with restricted channels for use in Israel.

**Warning:** Version 19.1.1 corrects an issue with applying the Bandwidth Limit present in version 19.1.0. Teams should install the new version, then re-program their radio (there is no need to re-flash the firmware).

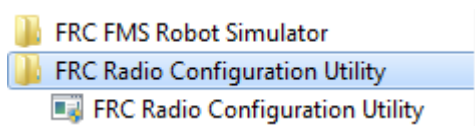
### 1.10.3 Install the software

FRC	2/20/2015 1:27 PM	FRC Icon
FRC_Radio_Configuration_10_8_15.exe	10/8/2015 1:50 PM	Application
FRCicon_RGB_Border.bmp	2/20/2015 1:27 PM	Bitmap Image

Double click on FRC\_Radio\_Configuration\_VERSION.exe to launch the installer. Follow the prompts to complete the installation.

Part of the installation prompts will include installing Npcap if it is not already present. The Npcap installer contains a number of checkboxes to configure the install. You should leave the options as the defaults.

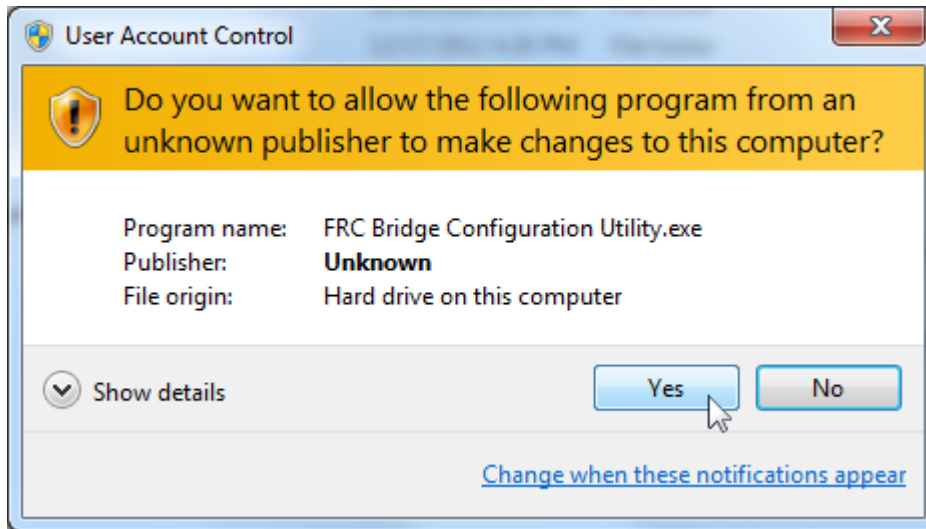
### 1.10.4 Launch the software



Use the Start menu or desktop shortcut to launch the program.

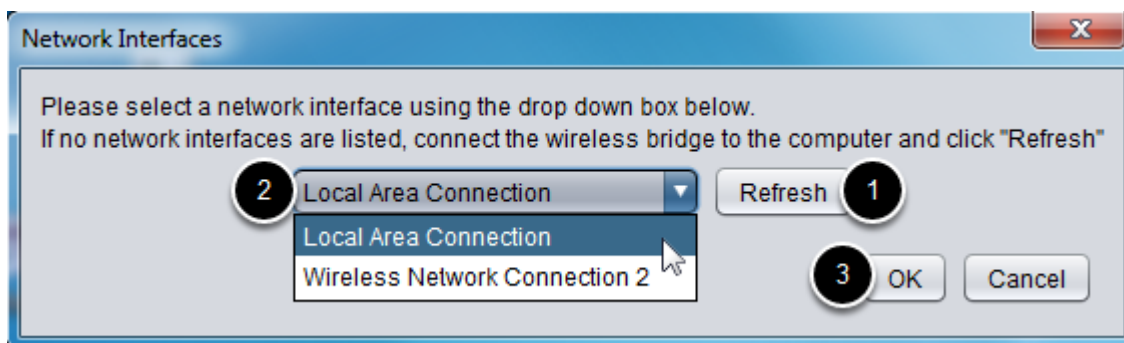
Note: If you need to locate the program it is installed to C:\Program Files (x86)\FRC Radio Configuration Utility. For 32-bit machines the path is C:\Program Files\FRC Radio Configuration Utility

### 1.10.5 Allow the program to make changes, if prompted



If the your computer is running Windows Vista or Windows 7, a prompt may appear about allowing the configuration utility to make changes to the computer. Click "Yes" if the prompt appears.

### 1.10.6 Select the network interface



Use the pop-up window to select the which ethernet interface the configuration utility will use to communicate with the wireless bridge. On Windows machines, ethernet interfaces are typically named "Local Area Connection". The configuration utility can not program a bridge over a wireless connection.

1. If no ethernet interfaces are listed, click "Refresh" to re-scan for available interfaces
2. Select the interface you want to use from the drop-down list
3. Click "OK"



### 1.10.7 Open Mesh Firmware Note

For the FRC Radio Configuration Utility to program the OM5P-AN and OM5P-AC radio, the radio must be running an FRC specific build of the OpenWRT firmware. OM5P-AC radios in the 2019 KoP should not need an update.

If you do not need to update or re-load the firmware, skip the next step.

**Warning:** Note: Radios used in 2019 **do not** need to be updated before configuring, the 2020 tool uses the same 2019 firmware.

### 1.10.8 Loading FRC Firmware to OpenMesh radio

**Team Number:**  **Robot Name:**

**WPA Key:**  **Firewall:** ☐

**Radio:**  **BW Limit:** ☒

**Mode:**  **Load Firmware**

**Configure**

**To program your wireless bridge:**

- 1) Connect power and Ethernet to the wireless bridge.
- 2) Make sure to use the Ethernet port shown above.
- 3) Wait for the Power light to turn and stay solid.
- 4) Enter your team number, and a WPA key (optional), above
- 5) Press "Configure", the process should take 15-60 seconds

**If asked to reset your wireless bridge:**

- 1) If Event WPA Kiosk: Follow on-screen prompts
- 1) If Radio Config Utility: Select OpenMesh
- 2) Unplug power from the radio
- 3) Press the "Load Firmware" button.
- 4) Follow the on-screen prompts.

If you need to load the FRC firmware (or reset the radio), you can do so using the FRC Radio Configuration Utility.

1. Follow the instructions above to install the software, launch the program and select the Ethernet interface.
2. Make sure the OpenMesh radio is selected in the Radio dropdown.
3. Make sure the radio is connected to the PC via Ethernet.

4. Unplug the power from the radio. (If using a PoE cable, this will also be unplugging the Ethernet to the PC, this is fine)
5. Press the Load Firmware button
6. When prompted, plug in the radio power. The software should detect the radio, load the firmware and prompt you when complete.

**Warning:** If you see an error about NPF name, try disabling all adapters other than the one being used to program the radio. If only one adapter is found, the tool should attempt to use that one. See the steps in *“Troubleshooting: Disabling Network Adapters”* for more info.

Teams may also see this error with foreign language Operating Systems. If you experience issues loading firmware or programming on a foreign language OS, try using an English OS, such as on the KOP provided PC or setting the Locale setting to “en\_us” as described on [this page](#).

### 1.10.9 Select a bridge model and operating mode

**Team Number:**  **Robot Name:**

**WPA Key:**  **Firewall:** ☐

**Radio:**  **BW Limit:** ☒

**Mode:**  **Load Firmware**

**Configure**

**To program your wireless bridge:**

- 1) Connect power and Ethernet to the wireless bridge.
- 2) Make sure to use the Ethernet port shown above.
- 3) Wait for the Power light to turn and stay solid.
- 4) Enter your team number, and a WPA key (optional), above
- 5) Press "Configure", the process should take 15-60 seconds

**If asked to reset your wireless bridge:**

- 1) If Event WPA Kiosk: Follow on-screen prompts
- 1) If Radio Config Utility: Select OpenMesh
- 2) Unplug power from the radio
- 3) Press the "Load Firmware" button.
- 4) Follow the on-screen prompts.

1. Select which radio you are configuring using the drop-down list.

2. Select which operating mode you want to configure. For most cases, the default selection of 2.4GHz Access Point will be sufficient. If your computers support it, the 5GHz AP mode is recommended, as 5GHz is less congested in many environments.

### 1.10.10 Select Options

**Team Number:**

**Robot Name:**

**WPA Key:**

**Radio:**

**Mode:**

**Firewall:** ☐

**BW Limit:** ☒

**Load Firmware**

**Configure**

**To program your wireless bridge:**

- 1) Connect power and Ethernet to the wireless bridge.
- 2) Make sure to use the Ethernet port shown above.
- 3) Wait for the Power light to turn and stay solid.
- 4) Enter your team number, and a WPA key (optional), above
- 5) Press "Configure", the process should take 15-60 seconds

**If asked to reset your wireless bridge:**

- 1) If Event WPA Kiosk: Follow on-screen prompts
- 1) If Radio Config Utility: Select OpenMesh
- 2) Unplug power from the radio
- 3) Press the "Load Firmware" button.
- 4) Follow the on-screen prompts.

The default values of the options have been selected to match the use case of most teams, however, you may wish to customize these options to your specific scenario:

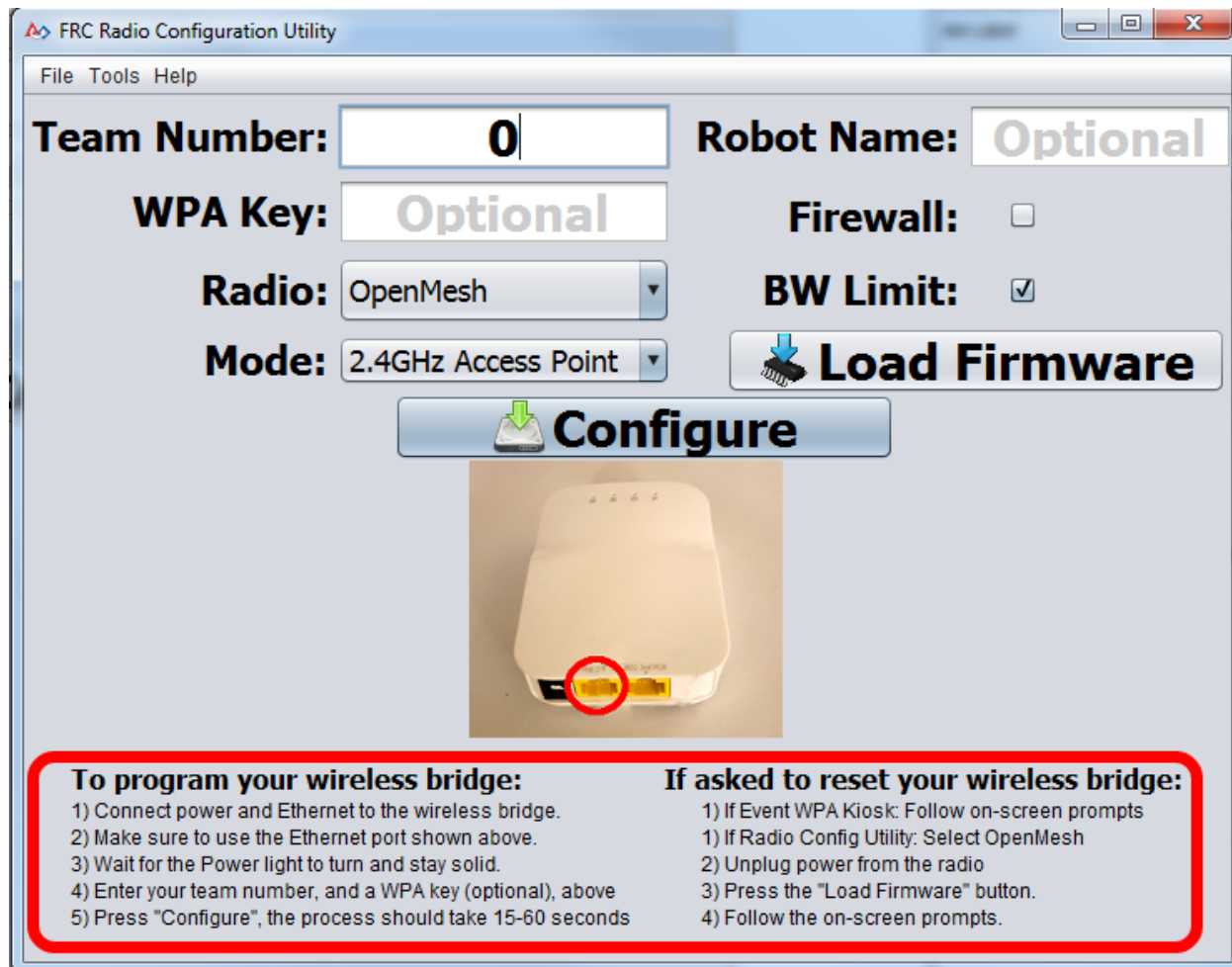
1. Robot Name: This is a string that gets appended to the SSID used by the radio. This allows you to have multiple networks with the same team number and still be able to distinguish them.
2. Firewall: If this box is checked, the radio firewall will be configured to attempt to mimic the port blocking behavior of the firewall present on the FRC field. For a list of open ports, please see the FRC Game Manual.
3. BW Limit: If this box is checked, the radio enforces a 4MB/s bandwidth limit like it does when programmed at events. Note that in AP mode, this is a total limit, not per client, so streaming video to multiple clients simultaneously may cause undesired behavior.

**Note:** Firewall and BW Limit only apply to the OpenMesh radios. These options have no

effect on D-Link radios.

**Warning:** The “Firewall” option configures the radio to emulate the field firewall. This means that you will not be able to deploy code wirelessly with this option enabled.

### 1.10.11 Prepare and start the configuration process



**Team Number:**  **Robot Name:**

**WPA Key:**  **Firewall:** ☐

**Radio:**  **BW Limit:** ☒

**Mode:**  **Load Firmware**

**Configure**

**To program your wireless bridge:**

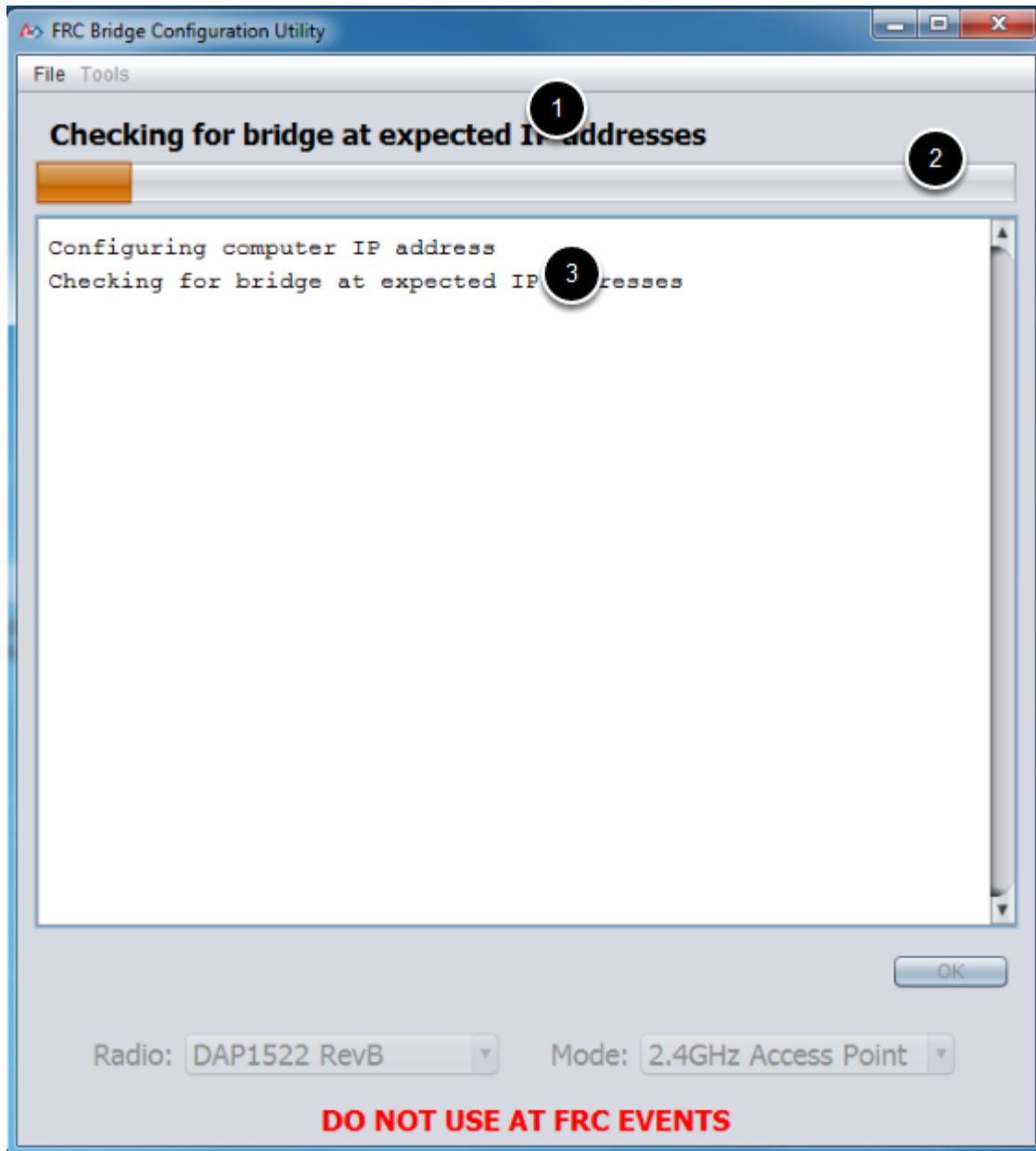
- 1) Connect power and Ethernet to the wireless bridge.
- 2) Make sure to use the Ethernet port shown above.
- 3) Wait for the Power light to turn and stay solid.
- 4) Enter your team number, and a WPA key (optional), above
- 5) Press "Configure", the process should take 15-60 seconds

**If asked to reset your wireless bridge:**

- 1) If Event WPA Kiosk: Follow on-screen prompts
- 1) If Radio Config Utility: Select OpenMesh
- 2) Unplug power from the radio
- 3) Press the "Load Firmware" button.
- 4) Follow the on-screen prompts.

Follow the on-screen instructions for preparing your wireless bridge, entering the settings the bridge will be configured with, and starting the configuration process. These on-screen instructions update to match the bridge model and operating mode chosen.

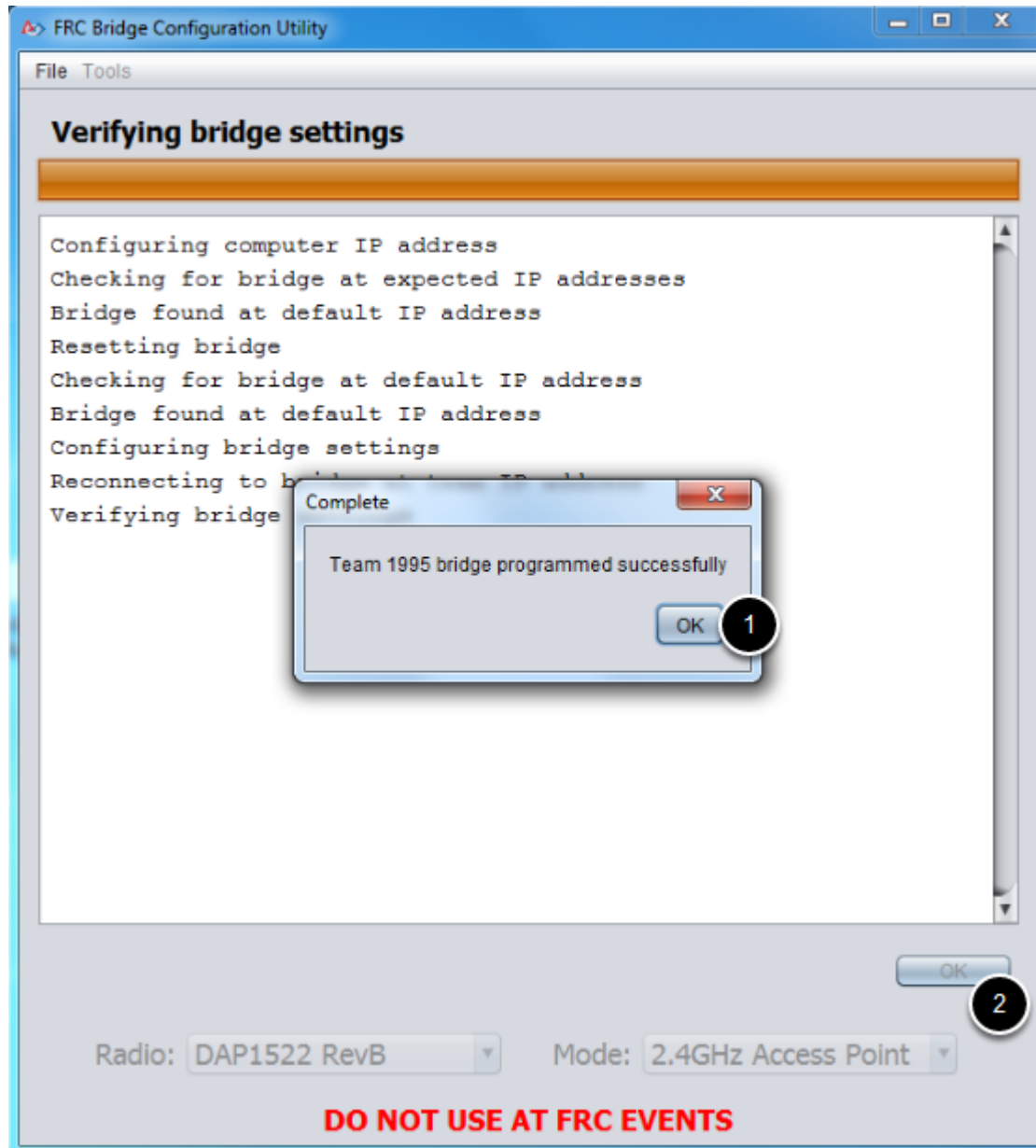
### 1.10.12 Configuration Progress



Throughout the configuration process, the window will indicate:

1. The step currently being executed
2. The overall progress of the configuration process
3. All steps executed so far

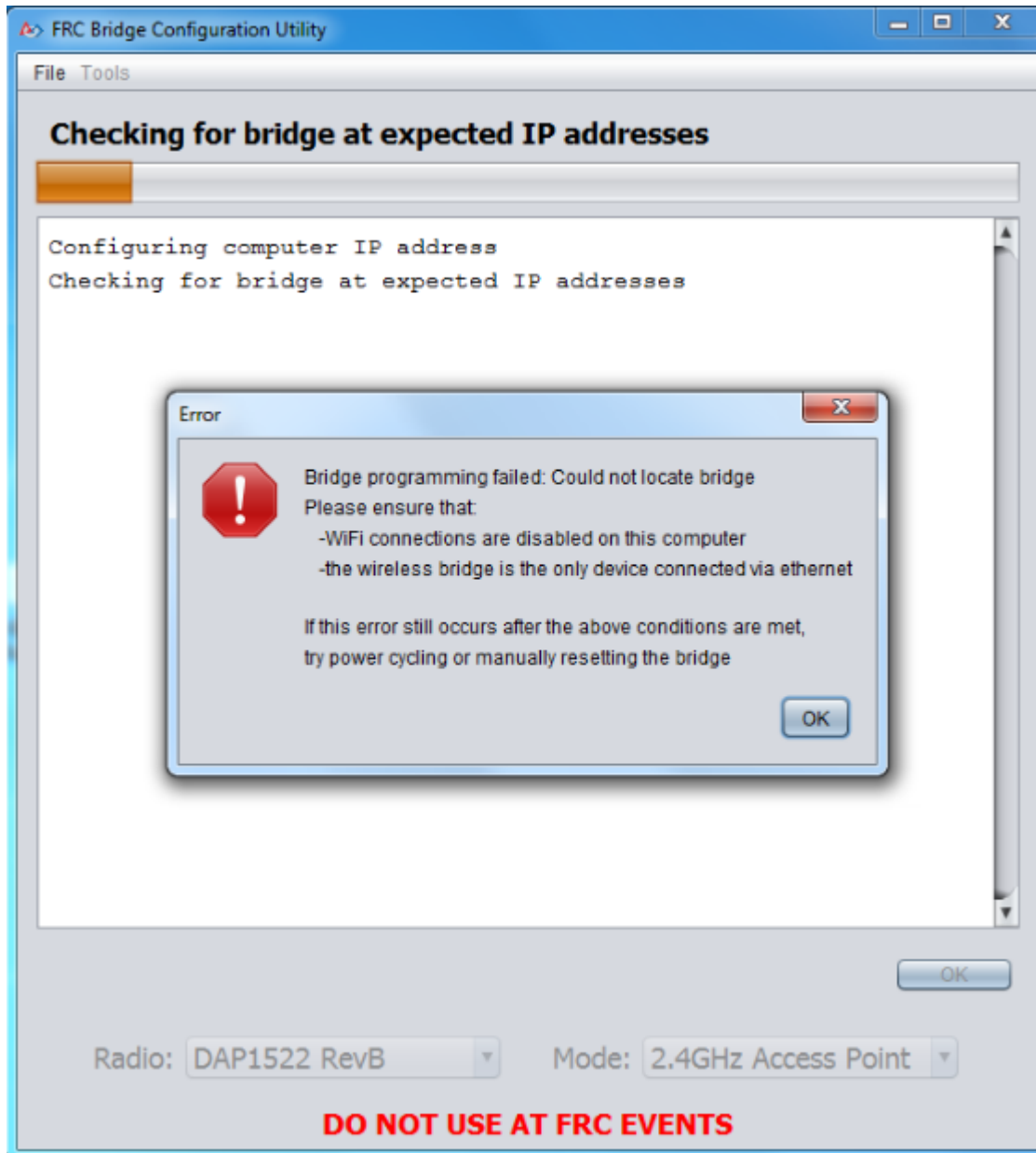
### 1.10.13 Configuration completed



Once the configuration is complete:

1. Press "OK" on the dialog window
2. Press "OK" on the main window to return to the settings screen

### 1.10.14 Configuration errors

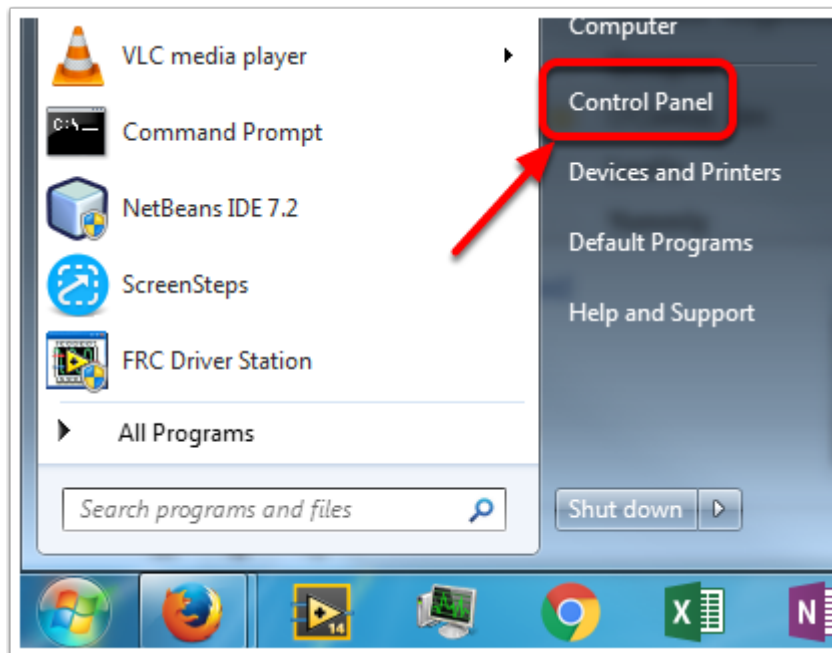


If an error occurs during the configuration process, follow the instructions in the error message to correct the problem.

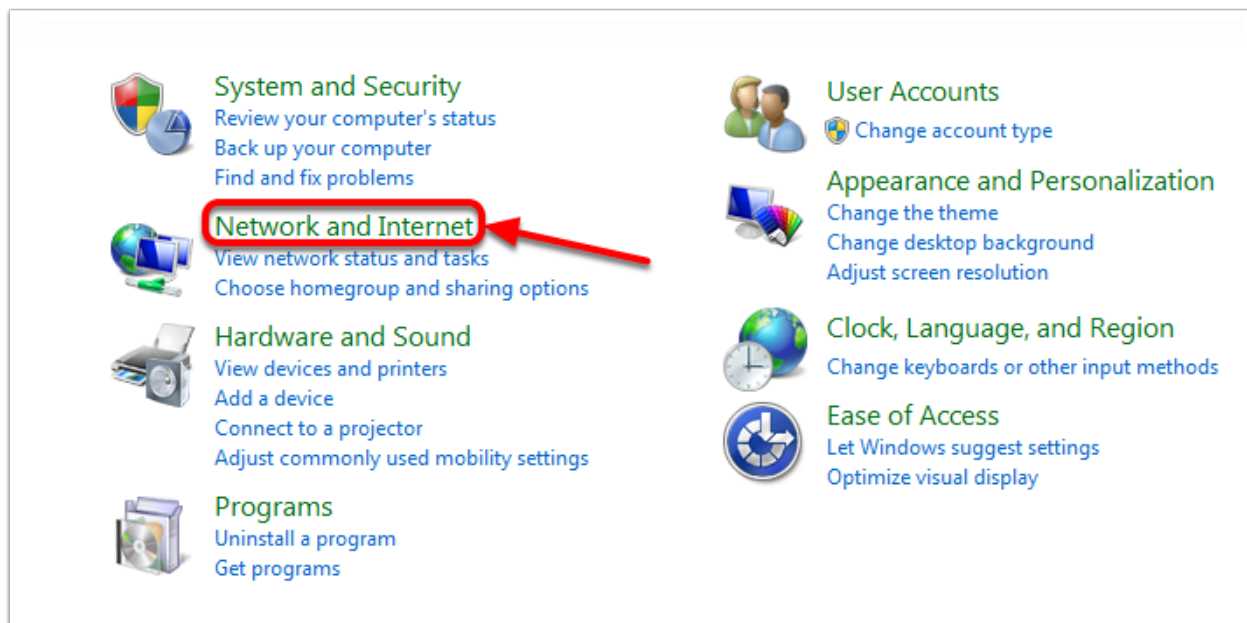
### 1.10.15 Troubleshooting: Disabling Network Adapters

If you get an error message about “NPF adapter” when attempting to load firmware, you need to disable all other adapters. This is not always the same as turning the adapters off with a physical button or putting the PC into airplane mode. The following steps provide more detail on how to disable adapters.

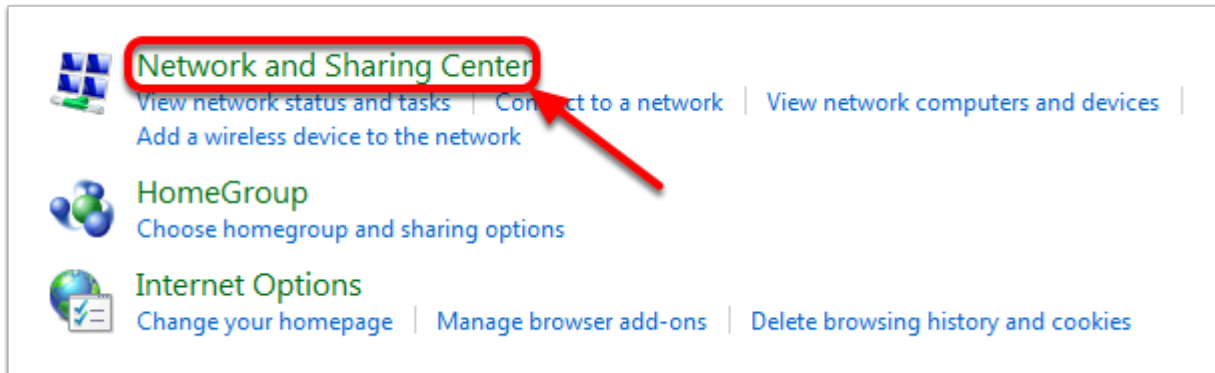




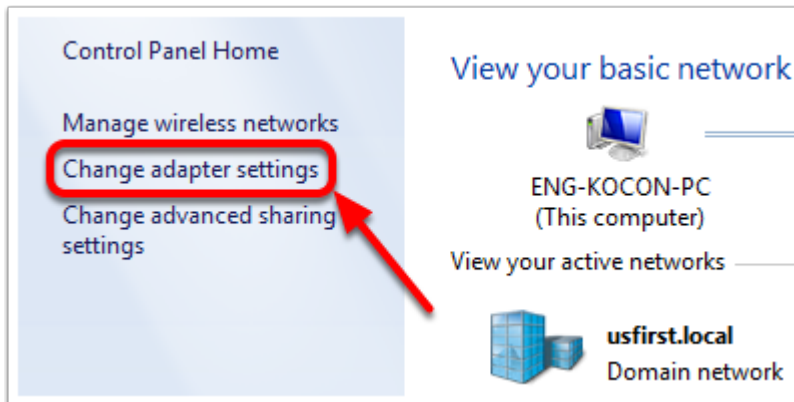
Open the Control Panel by going to Start->Control Panel



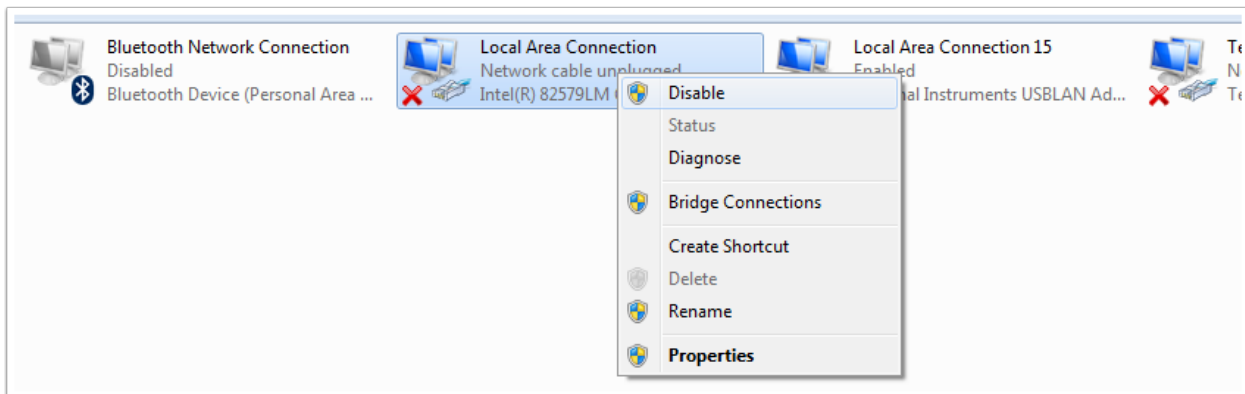
Choose the Network and Internet category.



Click Network and Sharing Center



On the left pane, click Change Adapter Settings



For each adapter other than the one connected to the radio, right click on the adapter and select Disable from the menu.

## 1.11 Updating and Configuring Pneumatics Control Module and Power Distribution Panel

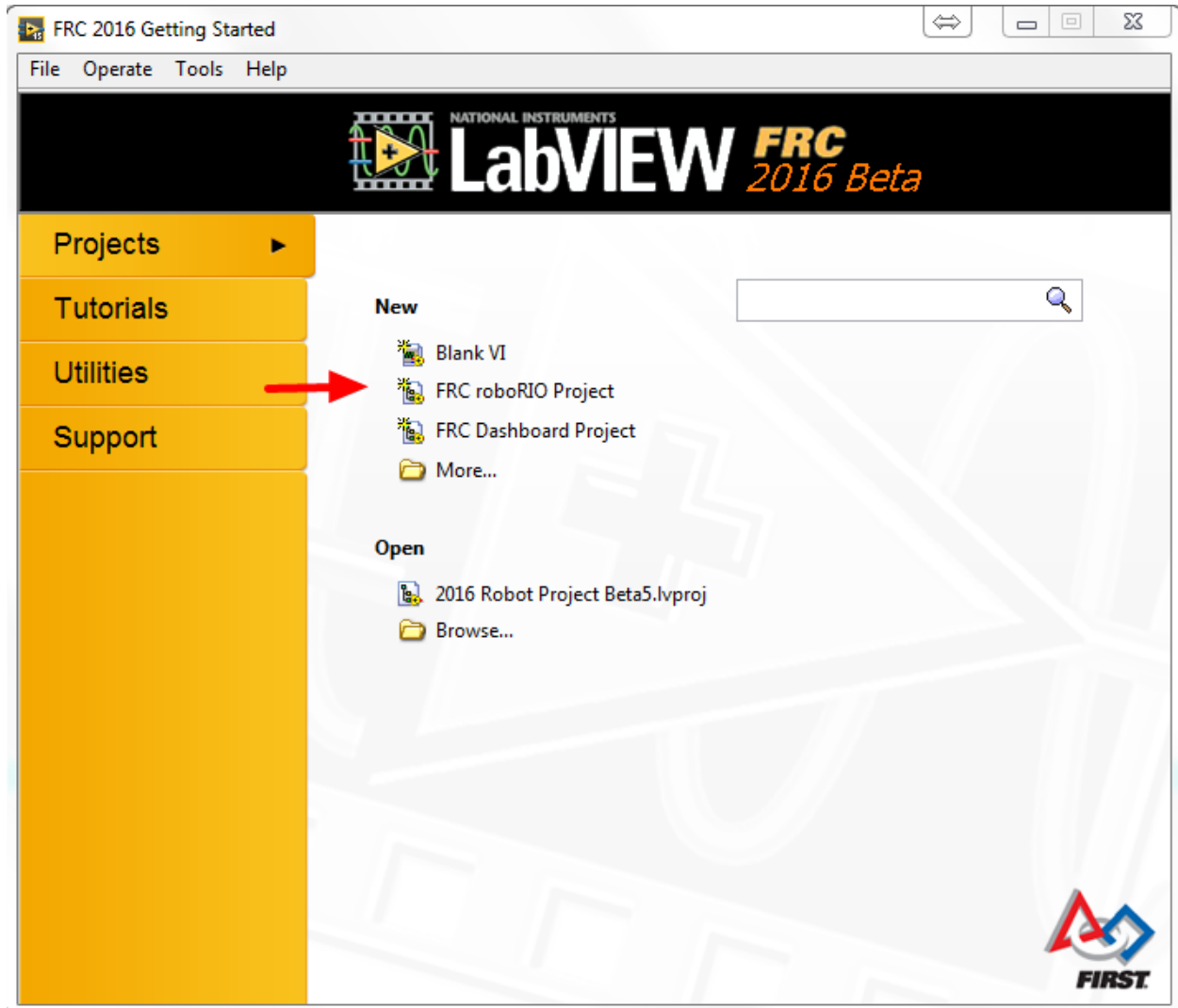
**Warning:** The CAN Web Dashboard plugin is no longer supported by the roboRIO Web Dashboard. To configure CTRE CAN devices such as the PCM and PDP, use [CTRE Phoenix Tuner](#)

## **Getting Started with a Benchtop Robot**

### **2.1 Creating your Benchtop Test Program (LabVIEW)**

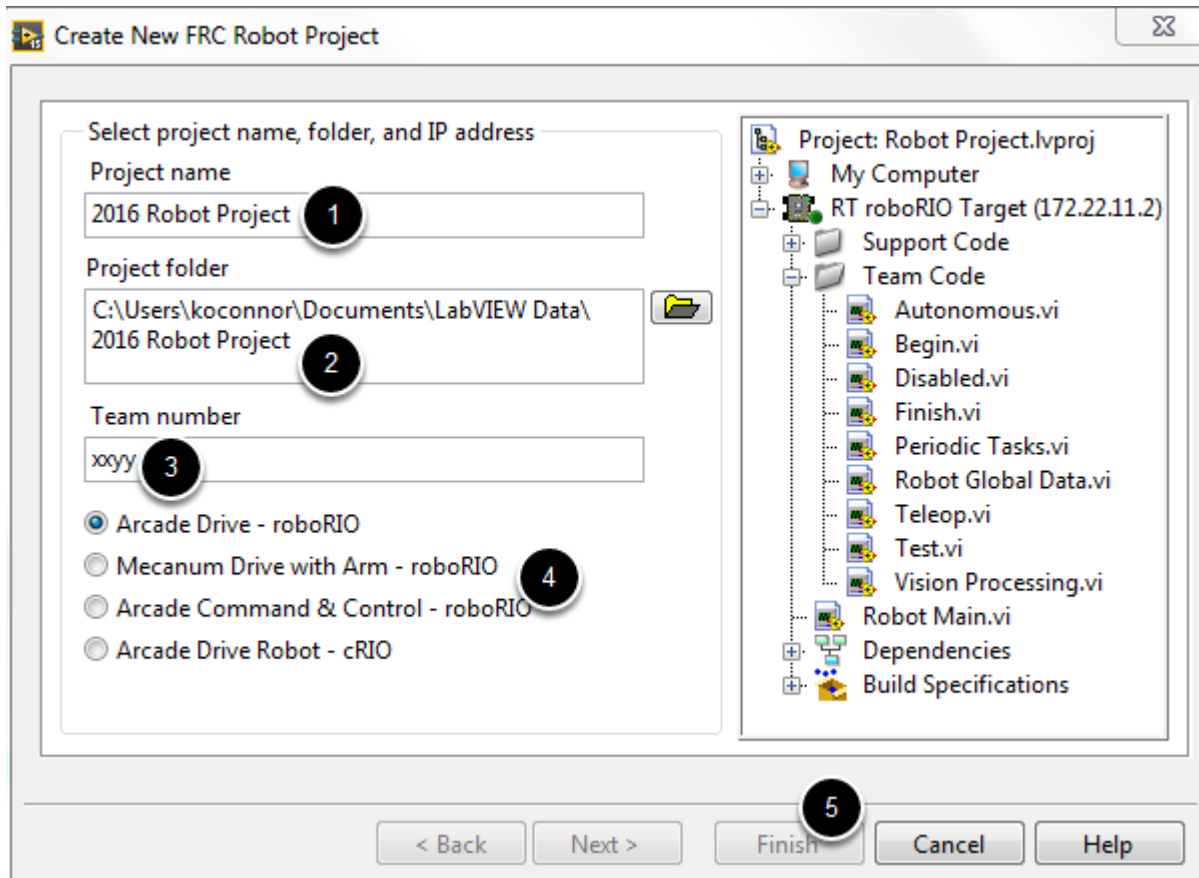
This document covers how to create, build and load an FRC LabVIEW program onto a roboRIO. Before beginning, make sure that you have installed LabVIEW for FRC and the FRC Driver Station and that you have configured and imaged your roboRIO as described previously.

## 2.1.1 Creating a Project



Launch LabVIEW and click the FRC roboRIO Robot Project link in the Projects window to display the Create New FRC Robot Project dialog box.

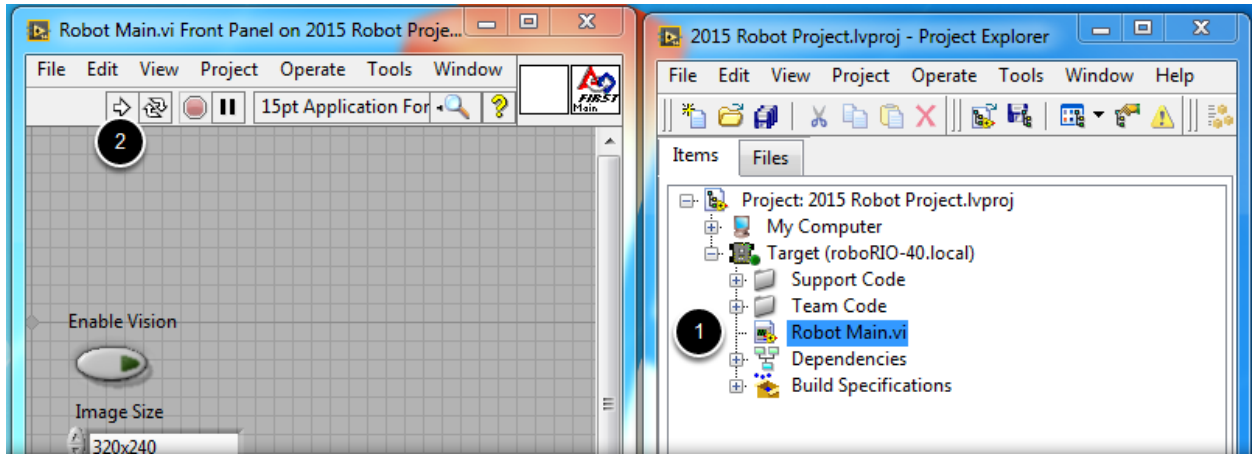
## 2.1.2 Configuring Project



Fill in the Create New FRC Project Dialog:

1. Pick a name for your project
2. Select a folder to place the project in.
3. Enter your team number
4. Select a project type. If unsure, select Arcade Drive - roboRIO.
5. Click Finish

### 2.1.3 Running the Program



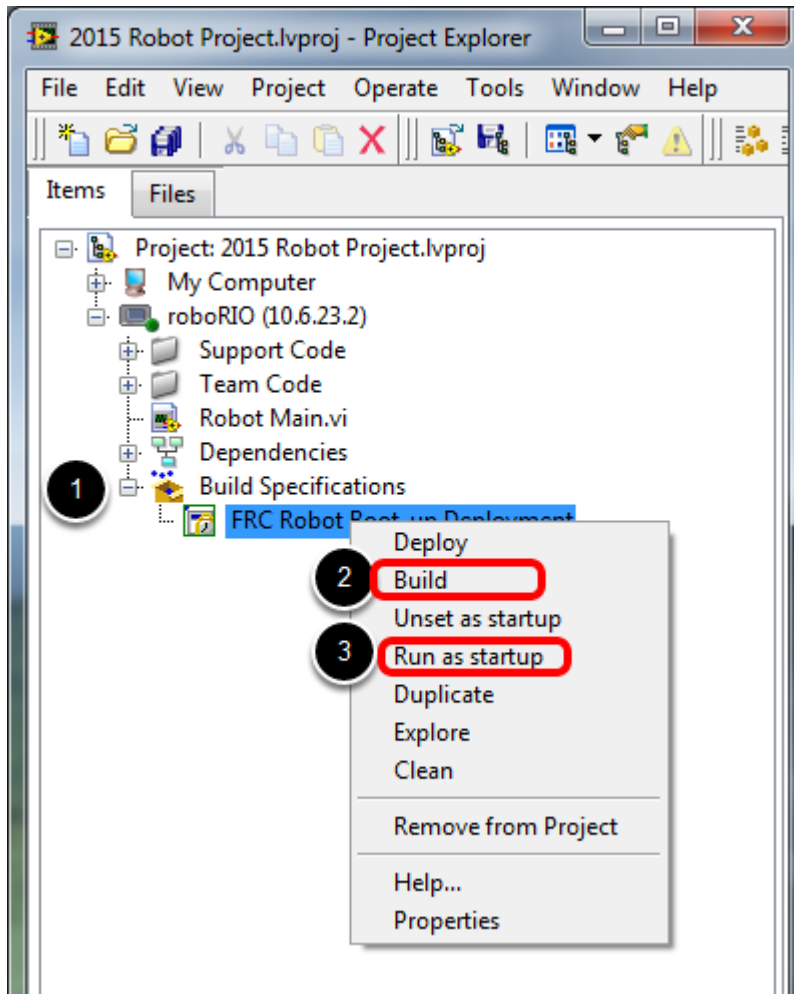
1. In the Project Explorer window, double-click the Robot Main.vi item to open the Robot Main VI.
2. Click the Run button (White Arrow on the top ribbon) of the Robot Main VI to deploy the VI to the roboRIO. LabVIEW deploys the VI, all items required by the VI, and the target settings to memory on the roboRIO. If prompted to save any VIs, click Save on all prompts.
3. Click the Abort button of the Robot Main VI. Notice that the VI stops. When you deploy a program with the Run button, the program runs on the roboRIO, but you can manipulate the front panel objects of the program from the host computer.

---

**Note:** A program deployed in this manner will not remain on the roboRIO after a power cycle. To deploy a program to run every time the roboRIO starts follow the next step, Deploying the program.

---

### 2.1.4 Deploying the program



To run in the competition, you will need to deploy a program to your roboRIO. This allows the program to survive across reboots of the controller, but doesn't allow the same debugging features (front panel, probes, highlight execution) as running from the front panel. To deploy your program:

1. In the Project Explorer, click the + next to Build Specifications to expand it.
2. Right-click on FRC Robot Boot-up Deployment and select Build. Wait for the build to complete.
3. Right-click again on FRC Robot Boot-Up Deployment and select Run as Startup. If you receive a conflict dialog, click OK. This dialog simply indicates that there is currently a program on the roboRIO which will be terminated/replaced.
4. Either check the box to close the deployment window on successful completion or click the close button when the deployment completes.
5. The roboRIO will automatically start running the deployed code within a few seconds of the dialog closing.

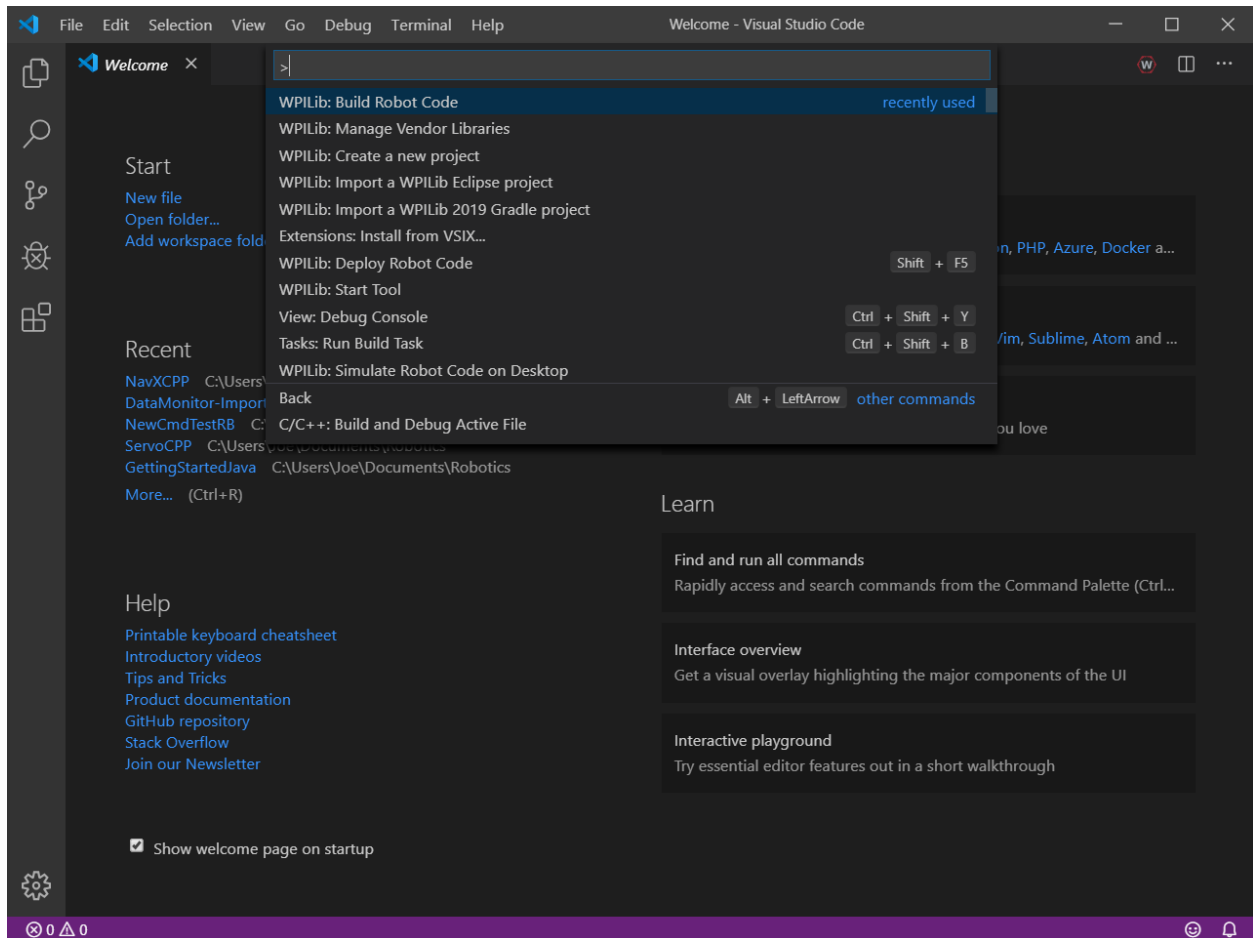


## 2.2 Creating your Benchtop Test Program (C++/Java)

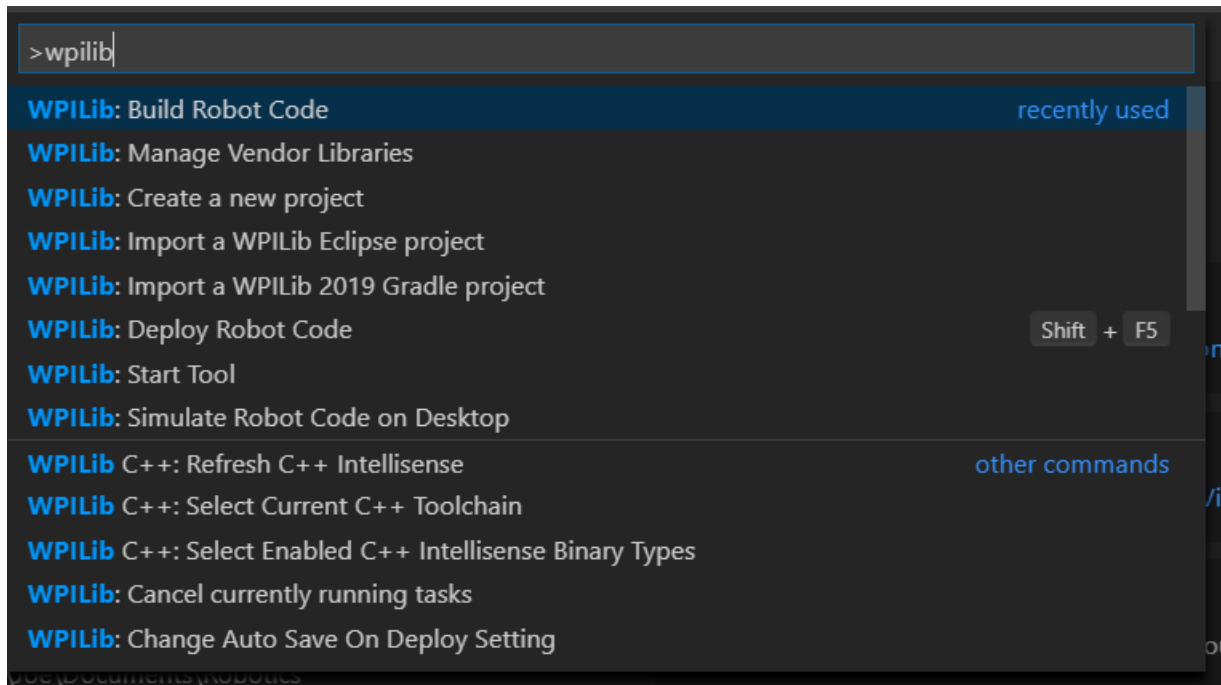
Once everything is installed, we're ready to create a robot program. WPILib comes with several templates for robot programs. Use of these templates is highly recommended for new users; however, advanced users are free to write their own robot code from scratch. This article walks through creating a project from one of the provided examples which has some code already written to drive a basic robot.

### 2.2.1 Creating a New WPILib Project

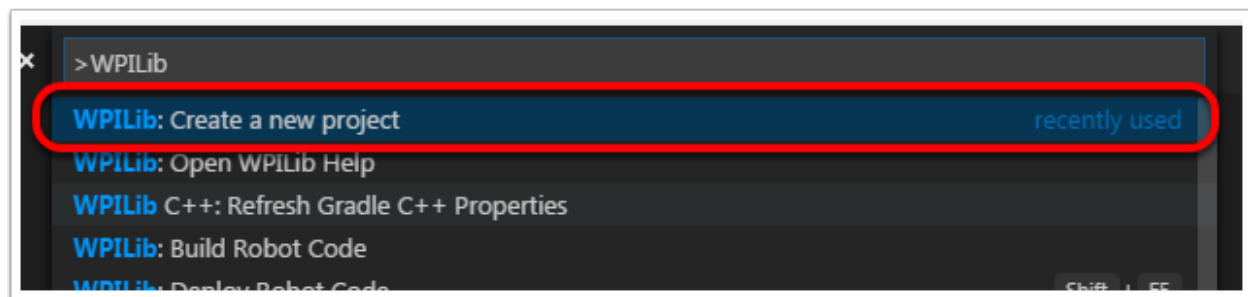
Bring up the Visual Studio Code command palette with **Control+Shift+P**:



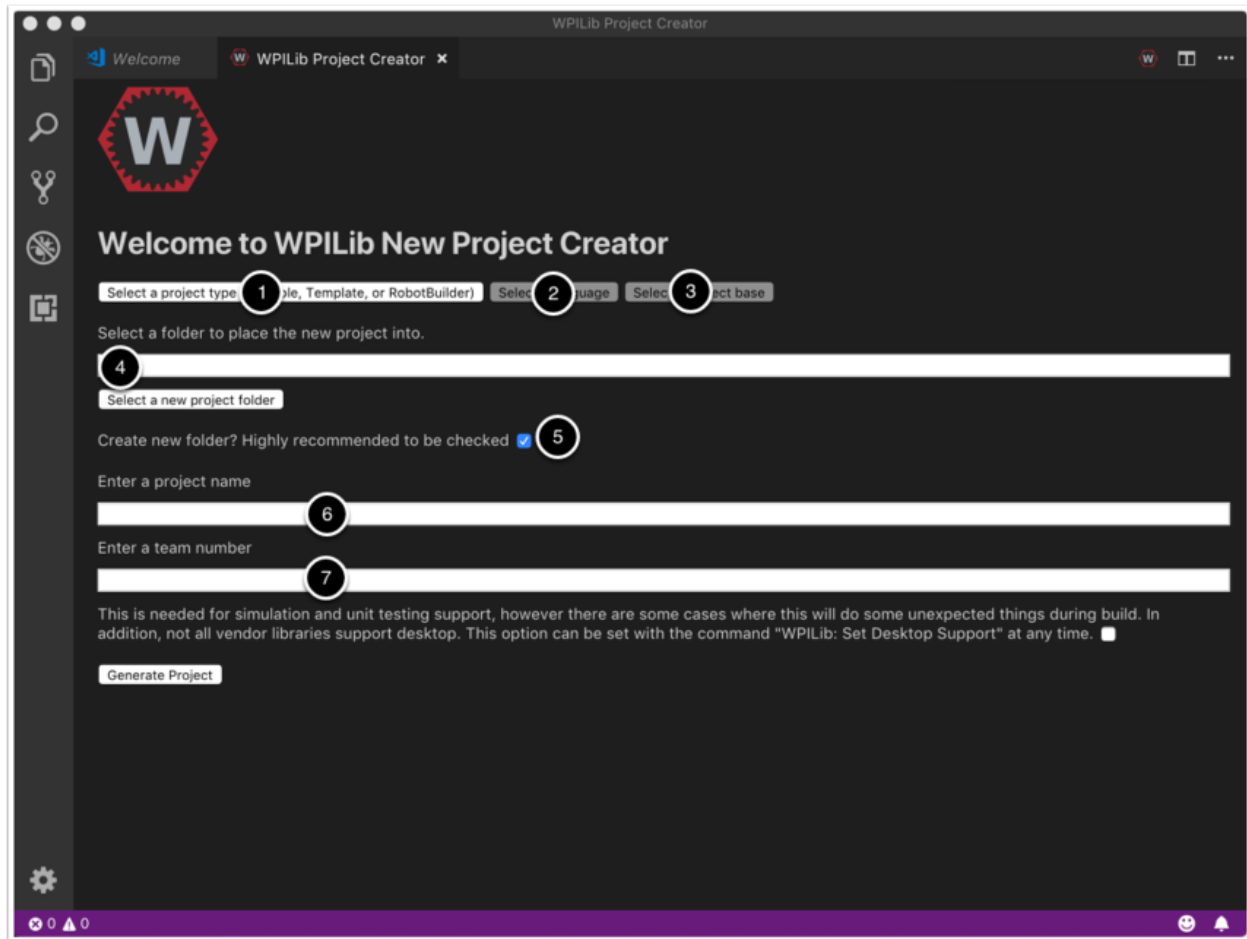
Then, type “WPILib” into the prompt. Since all WPILib commands start with “WPILib,” this will bring up the list of WPILib-specific VS Code commands:



Now, select the “Create a new project” command:



This will bring up the “New Project Creator Window:”



The elements of the New Project Creator Window are explained below:

1. **Project Type:** The kind of project we wish to create. For this example, select **Example**
2. **Language:** This is the language (C++ or Java) that will be used for this project.
3. **Project Base:** This box is used to select the base class or example to generate the project from. For this example, select **Getting Started**
4. **Project Location:** This determines the folder in which the robot project will be located.
5. **Create New Folder:** If this is checked, a new folder will be created to hold the project within the previously-specified folder. If it is *not* checked, the project will be located directly in the previously-specified folder. An error will be thrown if the folder is not empty and this is not checked.
6. **Project Name:** The name of the robot project. This also specifies the name that the project folder will be given if the Create New Folder box is checked.
7. **Team Number:** The team number for the project, which will be used for package names within the project and to locate the robot when deploying code.
8. **Desktop Support:** Enables unit test and simulation. While WPILib supports this, third party software libraries may not. If libraries do not support desktop, then your code may not compile or may crash. It should be left unchecked unless unit testing or simulation is needed and all libraries support it. For this example, do not check this box.

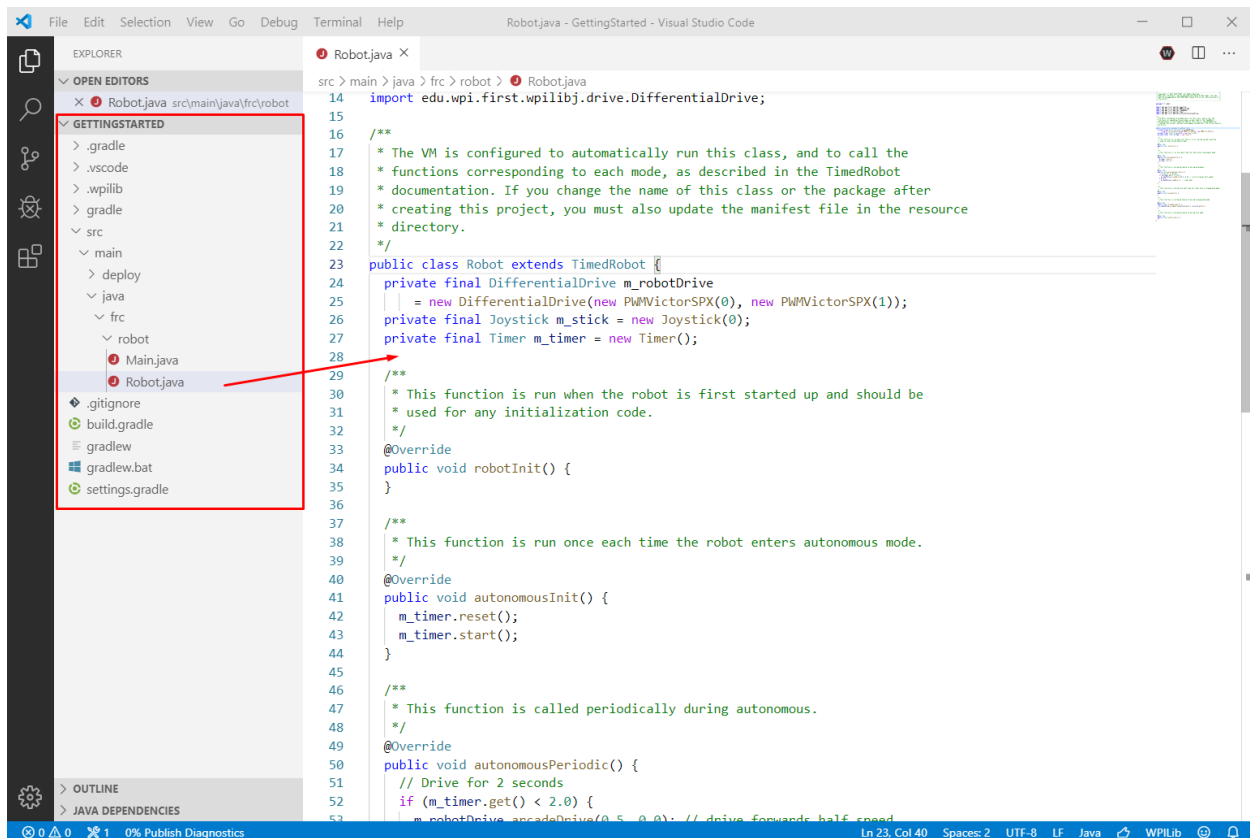
Once all the above have been configured, click “Generate Project” and the robot project will be created.

**Note:** Any errors in project generation will appear in the bottom right-hand corner of the screen.

## 2.2.2 Opening The New Project

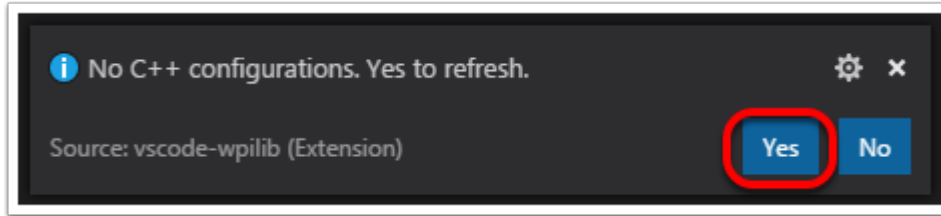
After successfully creating your project, VS Code will give the option of opening the project as shown below. We can choose to do that now or later by typing Ctrl-K then Ctrl-O (or just Command+O on macOS) and select the folder where we saved our project.

Once opened we will see the project hierarchy on the left. Double clicking on the file will open that file in the editor.



## 2.2.3 C++ Configurations (C++ Only)

For C++ projects, there is one more step to set up IntelliSense. Whenever we open a project, we should get a pop-up in the bottom right corner asking to refresh C++ configurations. Click “Yes” to set up IntelliSense.



### 2.2.4 Imports/Includes

Java

```
import edu.wpi.first.wpilibj.Joystick;
import edu.wpi.first.wpilibj.PWMVictorSPX;
import edu.wpi.first.wpilibj.TimedRobot;
import edu.wpi.first.wpilibj.Timer;
import edu.wpi.first.wpilibj.drive.DifferentialDrive;
```

C++

```
#include <frc/Joystick.h>
#include <frc/PWMVictorSPX.h>
#include <frc/TimedRobot.h>
#include <frc/Timer.h>
#include <frc/drive/DifferentialDrive.h>
#include <frc/livewindow/LiveWindow.h>
```

Our code needs to reference the components of WPILib that are used. In C++ this is accomplished using `#include` statements; in Java it is done with `import` statements. The program references classes for Joystick (for driving), PWMVictorSPX (for controlling motors), TimedRobot (the base class used for the example), Timer (used for autonomous), DifferentialDrive (for connecting the joystick control to the motors), and LiveWindow (C++ only).

### 2.2.5 Defining the variables for our sample robot

Java

```
public class Robot extends TimedRobot {
    private final DifferentialDrive m_robotDrive = new DifferentialDrive(new
    PWMVictorSPX(0), new PWMVictorSPX(1));
    private final Joystick m_stick = new Joystick(0);
    private final Timer m_timer = new Timer();
}
```

C++

```
class Robot : public frc::TimedRobot
{
public:
    Robot() {
        m_robotDrive.SetExpiration(0.1);
        m_timer.Start();
    }
}
```

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```
private:
// Robot drive system
frc::PWMVictorSPX m_left{0};
frc::PWMVictorSPX m_right{1};
frc::DifferentialDrive m_robotDrive{m_left, m_right};
frc::Joystick m_stick{0};
frc::LiveWindow m_lw = *frc::LiveWindow::GetInstance();
frc::Timer m_timer;
```

The sample robot in our examples will have a joystick on USB port 0 for arcade drive and two motors on PWM ports 0 and 1. Here we create objects of type DifferentialDrive (m\_robotDrive), Joystick (m\_stick) and time (m\_timer). This section of the code does three things:

1. Defines the variables as members of our Robot class.
2. Initializes the variables.

**Note:** The variable initializations for C++ are in the private section at the bottom of the program. This means they are private to the class (Robot). The C++ code also sets the Motor Safety expiration to 0.1 seconds (the drive will shut off if we don't give it a command every .1 seconds) and starts the Timer used for autonomous.

## 2.2.6 Robot Initialization

Java

```
@Override
public void robotInit() {}
```

C++

```
void RobotInit() {}
```

The RobotInit method is run when the robot program is starting up, but after the constructor. The RobotInit for our sample program gets a pointer to the LiveWindow instance (this is used in the test method discussed below). This method is omitted from the code, meaning the default version will be run (if we wanted to run something here we could provide the code above to override the default).

## 2.2.7 Simple Autonomous Example

Java

```
@Override
public void autonomousInit() {
    m_timer.reset();
    m_timer.start();
}
```

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```
@Override
public void autonomousPeriodic() {
    // Drive for 2 seconds
    if (m_timer.get() < 2.0) {
        m_robotDrive.arcadeDrive(0.5, 0.0); // drive forwards half speed
    } else {
        m_robotDrive.stopMotor(); // stop robot
    }
}
```

C++

```
void AutonomousInit() override {
    m_timer.Reset();
    m_timer.Start();
}

void AutonomousPeriodic() override {
    // Drive for 2 seconds
    if (m_timer.Get() < 2.0) {
        // Drive forwards half speed
        m_robotDrive.ArcadeDrive(0.5, 0.0);
    } else {
        // Stop robot
        m_robotDrive.ArcadeDrive(0.0, 0.0);
    }
}
```

The `AutonomousInit` method is run once each time the robot transitions to autonomous from another mode. In this program, we reset the `Timer` and then start it in this method.

`AutonomousPeriodic` is run once every period while the robot is in autonomous mode. In the `TimedRobot` class the period is a fixed time, which defaults to 20ms. In this example, the periodic code checks if the timer is less than 2 seconds and if so, drives forward at half speed using the `ArcadeDrive` method of the `DifferentialDrive` class. If more than 2 seconds has elapsed, the code stops the robot drive.

## 2.2.8 Joystick Control for teleoperation

Java

```
@Override
public void teleopInit() {
}

@Override
public void teleopPeriodic() {
    m_robotDrive.arcadeDrive(m_stick.getY(), m_stick.getX());
}
```

C++

```
void TeleopInit() override {}
void TeleopPeriodic() override {
```

(continues on next page)

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```
// Drive with arcade style (use right stick)
m_robotDrive.ArcadeDrive(m_stick.GetY(), m_stick.GetX());
}
```

Like in Autonomous, the Teleop mode has a TeleopInit and TeleopPeriodic function. In this example we don't have anything to do in TeleopInit, it is provided for illustration purposes only. In TeleopPeriodic, the code uses the ArcadeDrive method to map the Y-axis of the Joystick to forward/back motion of the drive motors and the X-axis to turning motion.

### 2.2.9 Test Mode

Java

```
@Override
public void testPeriodic() {}
```

C++

```
void TestPeriodic() override {}
```

Test Mode is used for testing robot functionality. Similar to TeleopInit, the TestPeriodic is provided here for example.

### 2.2.10 Deploying the Project to a Robot

Please see the instructions [here](#) for deploying the program onto a robot.

## 2.3 Running your Benchtop Test Program

### 2.3.1 Overview

You should create and download a Benchtop Test Program as described for your programming language:

*C++/Java*

*LabVIEW*

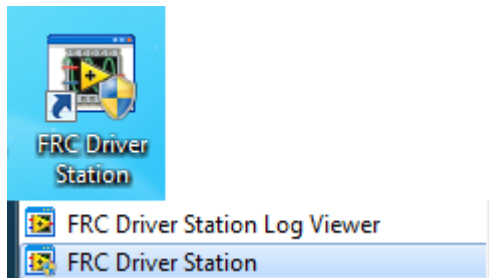
### 2.3.2 Tethered Operation

Running your benchtop testing program while tethered to the Driver Station via ethernet or USB cable will confirm the the program was successfully deployed and that the driver station and roboRIO are properly configured.

The roboRIO should be powered on and connected to the PC over Ethernet or USB.

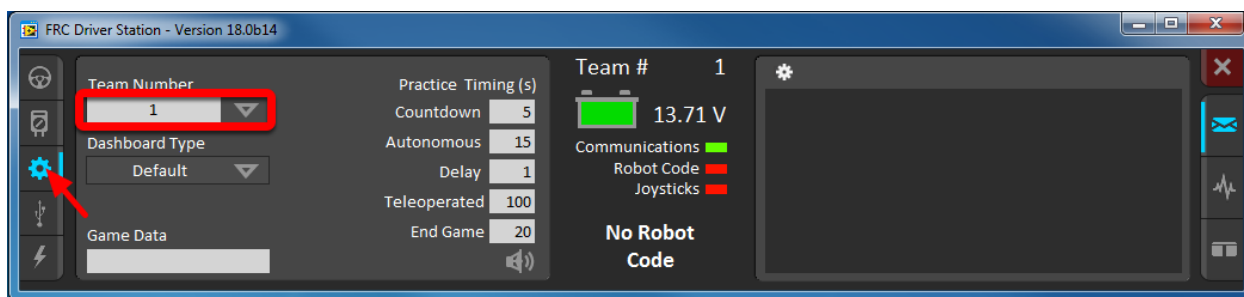


### 2.3.3 Starting the FRC Driver Station



The FRC Driver Station can be launched by double-clicking the icon on the Desktop or by selecting Start->All Programs->FRC Driver Station.

### 2.3.4 Setting Up the Driver Station



The DS must be set to your team number in order to connect to your robot. In order to do this click the Setup tab then enter your team number in the team number box. Press return or click outside the box for the setting to take effect.

PCs will typically have the correct network settings for the DS to connect to the robot already, but if not, make sure your Network adapter is set to DHCP.

### 2.3.5 Confirm Connectivity

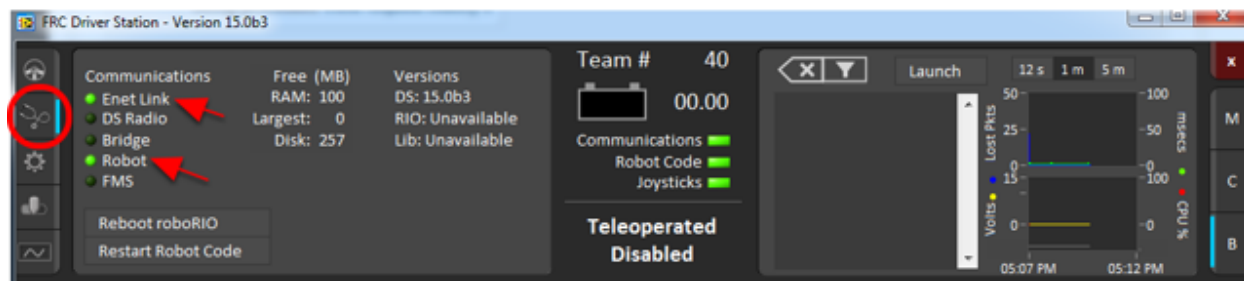


Fig. 1: Tethered

Using the Driver Station software, click Diagnostics and confirm that the Enet Link (or Robot Radio led, if operating wirelessly) and Robot leds are green.

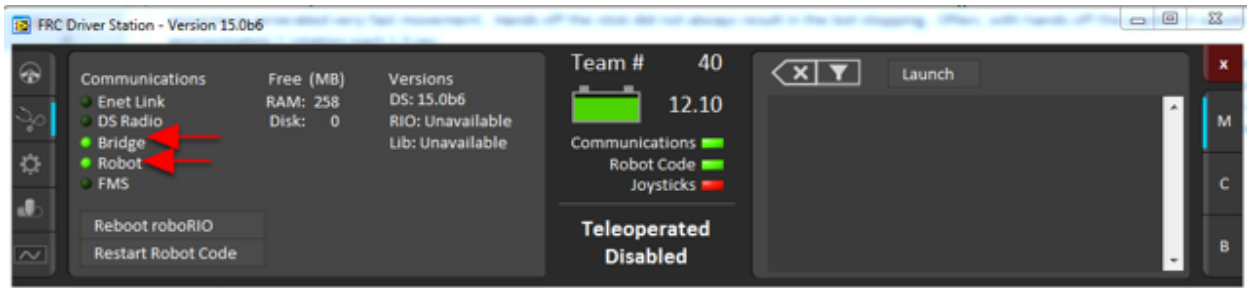
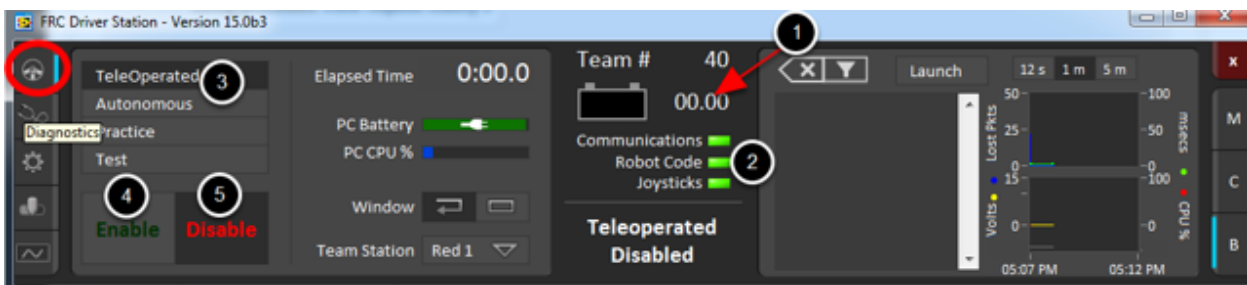


Fig. 2: Wireless

### 2.3.6 Operate the Robot



Click the Operation Tab

1. Confirm that battery voltage is displayed
2. Communications, Robot Code, and Joysticks indicators are green.
3. Put the robot in Teleop Mode
4. Click Enable. Move the joysticks and observe how the robot responds.
5. Click Disable

### 2.3.7 Wireless Operation

Before attempting wireless operation, tethered operation should have been confirmed as described in *Tethered Operation*. Running your benchtop testing program while connected to the Driver Station via WiFi will confirm that the access point is properly configured.

#### Configuring the Access Point

See the article *Programming your radio* for details on configuring the robot radio for use as an access point.

After configuring the access point, connect the driver station wirelessly to the robot. The SSID will be your team number (as entered in the Bridge Configuration Utility). If you set a key when using the Bridge Configuration Utility you will need to enter it to connect to the network. Make sure the computer network adapter is set to DHCP ("Obtain an IP address automatically").

You can now confirm wireless operation using the same steps in **Confirm Connectivity** and **Operate the Robot** above.



## WPILib Overview

### 3.1 Known Issues

This article details known issues (and workarounds) for FRC Control System Software.

#### 3.1.1 Open Issues

##### macOS Simulation fails to launch in Visual Studio Code

The first time launching simulation in VS Code on macOS using the WPILib: Simulate Robot Code on Desktop task will fail with a warning similar to the one below.

```
java.io.IOException: wpiHaljni could not be loaded from path or an embedded resource.  
    attempted to load for platform /osx/x86-64/  
    at edu.wpi.first.wpiutil.RuntimeLoader.loadLibrary(RuntimeLoader.java:78)  
    at edu.wpi.first.hal.JNIWrapper.<clinit>(JNIWrapper.java:38)  
    at edu.wpi.first.wpilibj.RobotBase.startRobot(RobotBase.java:316)  
    at frc.robot.Main.main(Main.java:27)
```

This is a bug in VS Code being tracked by WPILib in [vscode-wpilib#334](#).

**Workaround:** Attempt to launch the simulation once using the WPILib: Simulate Robot Code on Desktop task and let the task fail. Without closing the console that opens at the bottom of the VS Code window, launch the simulator again using the WPILib: Simulate Robot Code on Desktop task. The second time the simulator will launch properly.

##### C++ Intellisense - Files Open on Launch Don't Work Properly

**Issue:** In C++, files open when VS Code launches will have issues with Intellisense showing suggestions from all options from a compilation unit and not just the appropriate ones or not finding header files. This is a bug in VS Code.

**Workaround:**

1. Close all files in VS Code, but leave VS Code open
2. Delete c\_cpp\_properties.json file in the .vscode folder, if it exists

3. Run the “Refresh C++ Intellisense” command in vscode.
4. In the bottom right you should see something that looks like a platform (linuxathena or windowsx86-64 etc). If it’s not linuxathena click it and set it to linuxathena (release)
5. Wait ~ 1 min
6. Open the main cpp file (not a header file). Intellisense should now be working

### SmartDashboard and Simulation fail to launch on Windows N Editions

**Issue:** WPILib code using CScore (dashboards and simulated robot code) will fail to launch on Education N editions of Windows.

**Solution:** Install the [Media Feature Pack](#)

### NetworkTables Interoperability

There is currently an issue with inter-operating C++/Java Network Tables clients (dashboards or co-processors) with LabVIEW servers (LV robot code). In some scenarios users will see updates from one client fail to be replicated across to other clients (e.g. data from a co-processor will not be properly replicated out to a dashboard). Data still continues to return correctly when accessed by code on the server.

**Workaround:** Write code on the server to mirror any keys you wish to see on other clients (e.g. dashboards) to a separate key. For example, if you have a key named `targetX` being published by a co-processor that you want to show up on a dashboard, you could write code on the robot to read the key and re-write it to a key like `targetXDash`.

### 3.1.2 Fixed in 2020.3.2

#### PathWeaver Units

**Issue:** PathWeaver exports paths using the length unit that was used for the project. However, the WPILib trajectory tools expects paths with the length units of meters. If different units are selected in PathWeaver, the paths will be scaled incorrectly.

**Solution:** PathWeaver, starting with version 2020.3.2, can now export export to meters when the units within PathWeaver are set to something else.

### 3.1.3 Fixed in 2020.2.2

#### Java predefined colors are all zero

The predefined (static) colors from the WPILib Color class have all zero red, green, blue values.

This issue is being tracked by WPILib in [allwpilib#2269](#).

## C++ Command Based JoystickButton and POVButton not functioning

C++ JoystickButton and POVButton are both non functioning.

This issue is being tracked by WPILib in [allwpilib#2259](#).

**Workaround:** Use a Button object directly instead of using JoystickButton or POVButton.

```
frc2::Button button{[&] { return m_joy.GetRawButton(1); };
```

## RobotBuilder extensions use the frc namespace (C++)

When using RobotBuilder to create a C++ robot program, extensions will generate code prepended with the `frc::` namespace which will not compile.

**Workaround:** After generating C++ robot code with RobotBuilder, where appropriate, replace `frc::` with the correct namespace for that device.

This issue is being tracked by WPILib in [RobotBuilder#194](#).

### 3.1.4 Fixed in 2020.1.2

#### WPILib Projects created with 2020.1.1 have a project version of Beta2020-2

Any projects created have a project version of *Beta2020-2* set in `wpilib_preferences.json`. This is not an issue, everything will still work properly. This will be fixed and update your projects in the 2nd release.

#### PathWeaver “Build Paths” Doesn’t Work

The “Build Paths” button in PathWeaver currently doesn’t work due to HAL usage reporting in the kinematics classes. This will be resolved in the 2nd release. See [this page](#) for more info on this error.

## 3.2 What is WPILib?

The WPI Robotics Library (WPILib) is the standard software library provided for teams to write code for their FRC robots. A [software library](#) is a collection of code that can be imported into and used by other software. WPILib contains a set of useful classes and subroutines for interfacing with various parts of the FRC control system (such as sensors, motor controllers, and the driver station), as well as an assortment of other utility functions.

### 3.2.1 Supported languages

There are two versions of WPILib, one for each of the two officially-supported text-based languages: WPILibJ for java, and WPILibC for C++. A considerable effort is made to maintain feature-parity between these two languages - library features are not added unless they can be reasonably supported for both Java and C++, and when possible the class and method names are kept identical or highly-similar. While unofficial community-built support is available for

some other languages, notably [python](#), this documentation will only cover Java and C++. Java and C++ were chosen for the officially-supported languages due to their appropriate level-of-abstraction and ubiquity in both industry and high-school computer science classes.

In general, C++ offers better high-end performance, at the cost of increased user effort (memory must be handled manually, and the C++ compiler does not do much to ensure user code will not crash at runtime). Java offers lesser performance, but much greater convenience. New/inexperienced users are strongly encouraged to use Java.

### 3.2.2 Source code and documentation

WPILib is an open-source library - the entirety of its source code is available online on the WPILib Github Page:

- [Official WPILib github](#)

The Java and C++ source code can be found in the WPILibJ and WPILibC source directories:

- [Java source code](#)
- [C++ source code](#)

While users are strongly encouraged to read the source code to resolve detailed questions about library functionality, more-concise documentation can be found on the official documentation pages for WPILibJ and WPILibC:

- [Java documentation](#)
- [C++ documentation](#)

## 3.3 Visual Studio Code Basics and the WPILib Extension

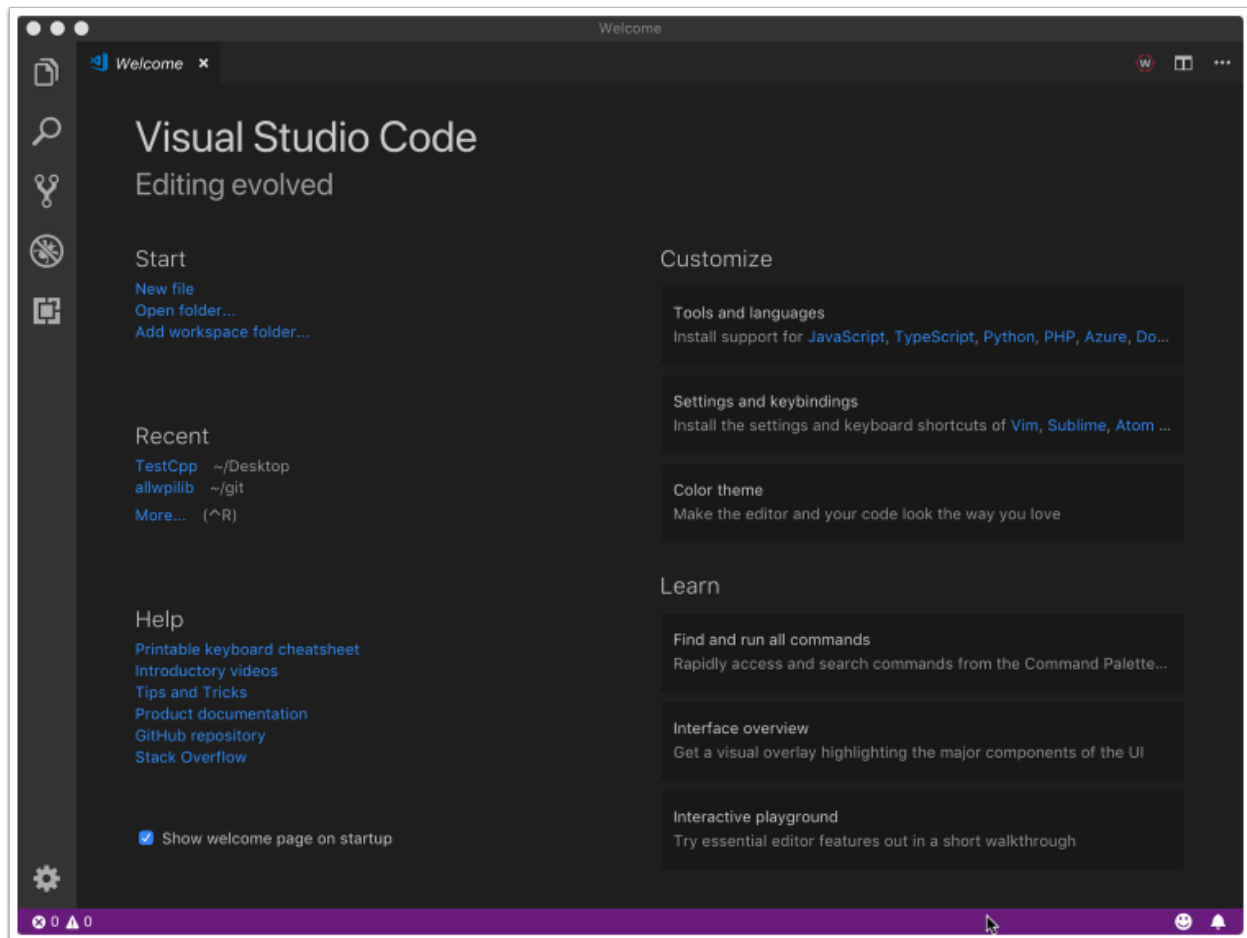
Microsoft's Visual Studio Code is the new supported IDE for C++ and Java development in FRC, replacing the Eclipse IDE used from 2015-2018. This article introduces some of the basics of using Visual Studio Code and the WPILib extension.

---

**Note:** If you used the publicly available Visual Studio Code Alpha or the closed Beta, you should create a new project or re-import your Eclipse project. There were breaking changes made to some of the configuration files (such as build.gradle) between releases.

---

### 3.3.1 Welcome Page



When Visual Studio Code first opens, you are presented with a Welcome page. On this page you will find some quick links that allow you to customize Visual Studio Code as well as a number of links to help documents and videos that may help you learn about the basics of the IDE as well as some tips and tricks.

You may also notice a small WPILib logo way up in the top right corner. This is one way to access the features provided by the WPILib extension (discussed further below).

### 3.3.2 User Interface

The most important link to take a look at is probably the basic User Interface document. This document describes a lot of the basics of using the UI and provides the majority of the information you should need to get started using Visual Studio Code for FRC.

### 3.3.3 Command Palette

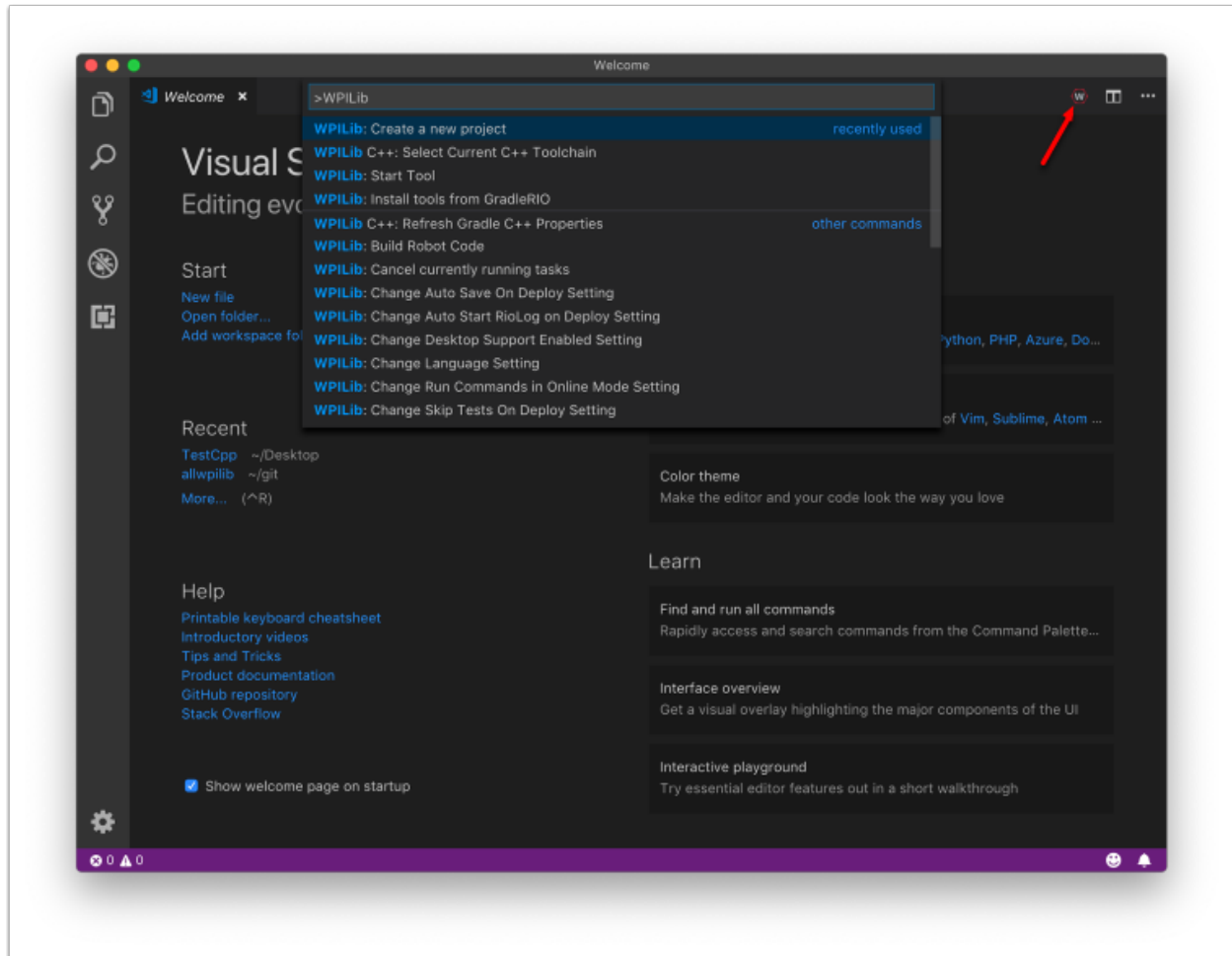
The Command Palette can be used to access or run almost any function or feature in Visual Studio Code (including those from the WPILib extension). The Command Palette can be accessed from the View menu or by pressing `Ctrl+Shift+P` (`Cmd+Shift+P` on macOS). Typing



text into the window will dynamically narrow the search to relevant commands and show them in the dropdown.

In the following example “wpilib” is typed into the search box after activating the Command Palette, and it narrows the list to functions containing WPILib.

### 3.3.4 WPILib Extension



The WPILib extension provides the FRC specific functionality related to creating projects and project components, building and downloading code to the roboRIO and more. You can access the WPILib commands one of two ways:

- By typing “WPILib” into the Command Palette
- By clicking on the WPILib icon in the top right of most windows. This will open the Command Palette with “WPILib” pre-entered

**Note:** It is **not** recommended to install the [Visual Studio IntelliCode](#) plugin with the FRC installation of VS Code as it is known to break IntelliSense in odd ways.

For more information about specific WPILib extension commands, see the other articles in this chapter.

## 3.4 WPILib Commands in Visual Studio Code

This document contains a complete list of the commands provided by the WPILib VS Code Extension and what they do.

To access these commands, press Ctrl+Shift+P to open the Command Palette, then begin typing the command name as shown here to filter the list of commands. Click on the command name to execute it.

- **WPILib: Build Robot Code** - Builds open project using GradleRIO
- **WPILib: Create Project** - Create a new robot project
- **WPILib C++: Refresh C++ Intellisense** - Force an update to the C++ Intellisense configuration.
- **WPILib C++: Select current C++ toolchain** - Select the toolchain to use for Intellisense (i.e. desktop vs. roboRIO vs...). This is the same as clicking the current mode in the bottom right status bar.
- **WPILib: Cancel currently running tasks** - Cancel any tasks the WPILib extension is currently running
- **WPILib: Change Auto Save On Deploy Setting** - Change whether files are saved automatically when doing a Deploy. This defaults to Enabled.
- **WPILib: Change Auto Start RioLog on Deploy Setting** - Change whether RioLog starts automatically on deploy. This defaults to Enabled.
- **WPILib: Change Desktop Support Enabled Setting** - Change whether building robot code on Desktop is enabled. Enable this for test and simulation purposes. This defaults to Desktop Support off.
- **WPILib: Change Language Setting** - Change whether the currently open project is C++ or Java.
- **WPILib: Change Run Commands in Online Mode Setting** - Change whether GradleRIO is running in Online Mode (will attempt to automatically pull dependencies from online). Defaults to disabled (offline mode).
- **WPILib: Change Skip Tests On Deploy Setting** - Change whether to skip tests on deploy. Defaults to disabled (tests are run on deploy)
- **WPILib: Change Stop Simulation on Entry Setting** - Change whether to stop robot code on entry when running simulation. Defaults to disabled (don't stop on entry).
- **WPILib: Check for WPILib Updates** - Check for an update to the WPILib extensions
- **WPILib: Create a new class/command** - Clicking this command in the palette will not do anything. This command is triggered by right-clicking on the desired folder in the Navigation Pane and selecting the appropriate option.
- **WPILib: Debug Robot Code** - Build and deploy robot code to roboRIO in debug mode and start debugging
- **WPILib: Deploy Robot Code** - Build and deploy robot code to roboRIO
- **WPILib: Import a WPILib Eclipse Project** - Open a wizard to help you create a new VS Code project from an existing WPILib Eclipse project from a previous season.
- **WPILib: Import a WPILib 2019 Project** - Open a wizard to help you create a new project from a existing VS Code Gradle project from 2019

- **WPILib: Install tools from GradleRIO** - Install the WPILib Java tools (e.g. SmartDashboard, Shuffleboard, etc.). Note that this is done by default by the offline installer
- **WPILib: Manage Vendor Libraries** - Install/update 3rd party libraries
- **WPILib: Open WPILib Command Palette** - This command is used to open a WPILib Command Palette (equivalent of hitting Ctrl+Shift+P and typing WPILib)
- **WPILib: Open WPILib Help** - This opens a simple page which links to the WPILib documentation (this site)
- **WPILib: Reset Ask for WPILib Updates Flag** - This will clear the flag on the current project, allowing you to re-prompt to update a project to the latest WPILib version if you previously chose to not update.
- **WPILib: Run a command in Gradle** - This lets you run an arbitrary command in the GradleRIO command environment
- **WPILib: Set Team Number** - Used to modify the team number associated with a project. This is only needed if you need to change the team number from the one initially specified when creating the project.
- **WPILib: Set VS Code Java Home to FRC Home** - Set the VS Code Java Home variable to point to the Java Home discovered by the FRC extension. This is needed if not using the offline installer to make sure the intellisense settings are in sync with the WPILib build settings.
- **WPILib: Show Log Folder** - Shows the folder where the WPILib extension stores internal logs. This may be useful when debugging/reporting an extension issue to the WPILib developers
- **WPILib: Simulate Robot Code on Desktop** - This builds the current robot code project on your PC and starts it running in simulation. This requires Desktop Support to be set to Enabled.
- **WPILib: Start RioLog** - This starts the RioLog display used to view console output from a robot program
- **WPILib: Start Tool** - This allows you to launch WPILib tools (e.g. SmartDashboard, Shuffleboard, etc.) from inside VS Code
- **WPILib: Test Robot Code** - This builds the current robot code project and runs any created tests. This requires Desktop Support to be set to Enabled.
- **WPILib: Open Project Information** - Opens a widget with project information (Project version, extension version, etc.)

## 3.5 Creating a Robot Program

Once everything is installed, we're ready to create a robot program. WPILib comes with several templates for robot programs. Use of these templates is highly recommended for new users; however, advanced users are free to write their own robot code from scratch.

### 3.5.1 Choosing a Base Class

To start a project using one of the WPILib robot program templates, users must first choose a base class for their robot. Users subclass these base classes to create their primary Robot

class, which controls the main flow of the robot program. There are three choices available for the base class:

## TimedRobot

Documentation: [Java](#) - [C++](#)

Source: [Java](#) - [C++](#)

The TimedRobot class is the the base class recommended for most users. It provides control of the robot program through a collection of `init()` and `periodic()` methods, which are called by WPILib during specific robot states (e.g. autonomous or teleoperated).

Java

```
import edu.wpi.first.wpilibj.TimedRobot;

public class Robot extends TimedRobot {

    @Override
    public void robotInit() {
        // This is called once when the robot code initializes
    }

    @Override
    public void robotPeriodic() {
        // This is called every period regardless of mode
    }

    @Override
    public void autonomousInit() {
        // This is called once when the robot first enters autonomous mode
    }

    @Override
    public void autonomousPeriodic() {
        // This is called periodically while the robot is in autonomous mode
    }

    @Override
    public void teleopInit() {
        // This is called once when the robot first enters teleoperated mode
    }

    @Override
    public void teleopPeriodic() {
        // This is called periodically while the robot is in teleopreated mode
    }

    @Override
    public void testInit() {
        // This is called once when the robot enters test mode
    }

    @Override
    public void testPeriodic() {
        // This is called periodically while the robot is in test mode
    }
}
```

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```

    }
}

```

C++

```

#include <frc/TimedRobot.h>

class Robot : public frc::TimedRobot {
public:
    void RobotInit() override; // This is called once when the robot code
    ↪initializes
    void RobotPeriodic() override; // This is called every period regardless of
    ↪mode
    void AutonomousInit() override; // This is called once when the robot first
    ↪enters autonomous mode
    void AutonomousPeriodic() override; // This is called periodically while the
    ↪robot is in autonomous mode
    void TeleopInit() override; // This is called once when the robot first
    ↪enters teleoperated mode
    void TeleopPeriodic() override; // This is called periodically while the
    ↪robot is in teleopreated mode
    void TestInit() override; // This is called once when the robot enters test
    ↪mode
    void TestPeriodic() override; // This is called periodically while the robot
    ↪is in test mode
};

```

Periodic methods are called every 20 ms by default. This can be changed by calling the superclass constructor with the new desired update rate.

Java

```

public Robot() {
    super(0.03); // Periodic methods will now be called every 30 ms.
}

```

C++

```

Robot() : frc::TimedRobot(30_ms) {}

```

## IterativeRobotBase

Documentation: [Java](#) - [C++](#)

Source: [Java](#) - [C++](#)

This is identical to `TimedRobot`, except the main robot loop is not run automatically - users are required to implement it inside of the `startCompetition()` method. This gives more freedom for advanced users to handle the loop timing in different ways, but is also less-convenient.

Rather than checking the mode and calling the various `init()` and `periodic()` methods themselves, user implementations can simply call the `loopFunc()` method from their main loop implementation. However, the `robotInit()` method must be called manually.

## RobotBase

Documentation: [Java](#) - [C++](#)

Source: [Java](#) - [C++](#)

The `RobotBase` class is the most minimal base-class offered, and is generally not recommended for direct use. No robot control flow is handled for the user; everything must be written from scratch inside the `startCompetition()` method.

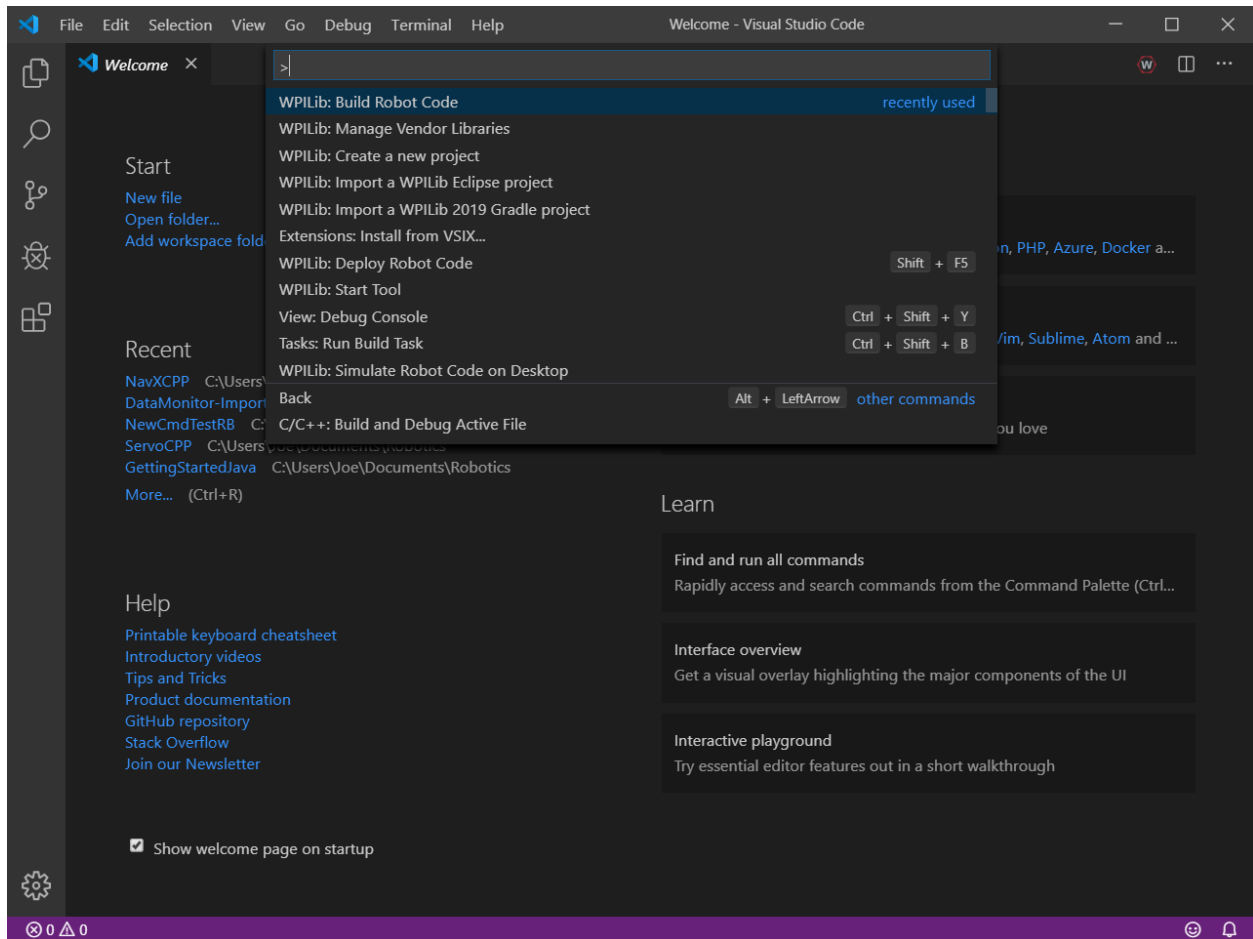
## Not Using a Base Class

If desired, users can omit a base class entirely and simply write their program in a `main()` method, as they would for any other program. This is *highly* discouraged - users should not “reinvent the wheel” when writing their robot code - but it is supported for those who wish to have absolute control over their program flow.

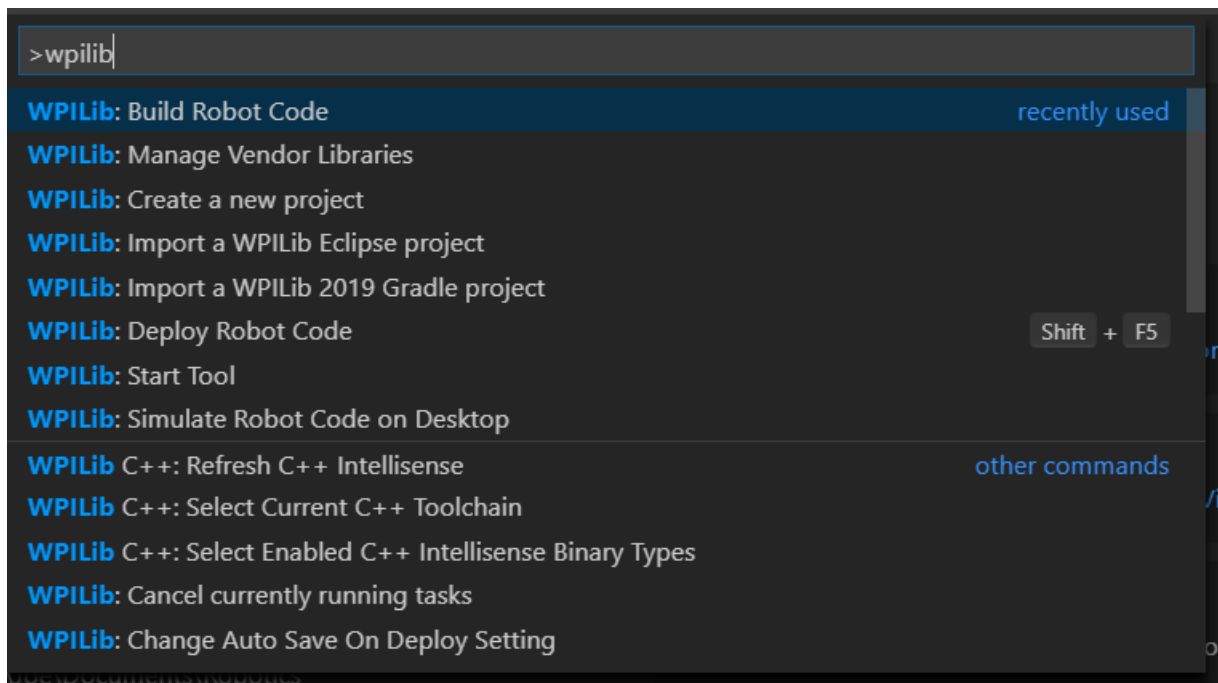
**Warning:** Users should *not* modify the `main()` method of a robot program unless they are absolutely sure of what they are doing.

## 3.5.2 Creating a New WPILib Project

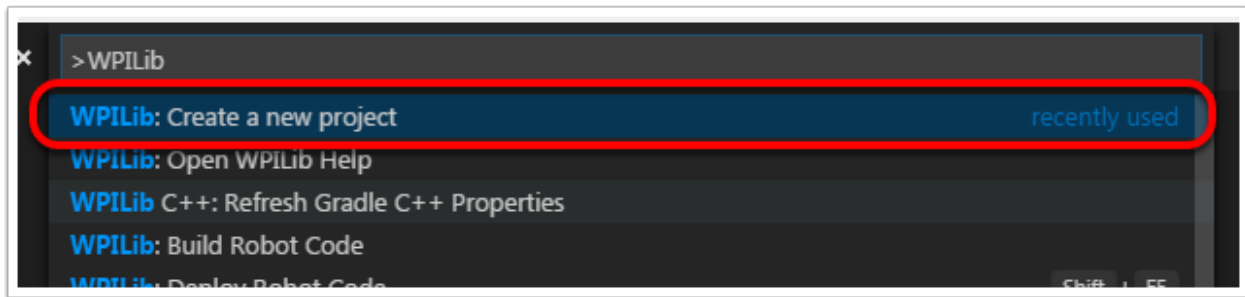
Once we’ve decided on a base class, we can create our new robot project. Bring up the Visual Studio Code command palette with `:kbd:“Control+Shift+P”`:



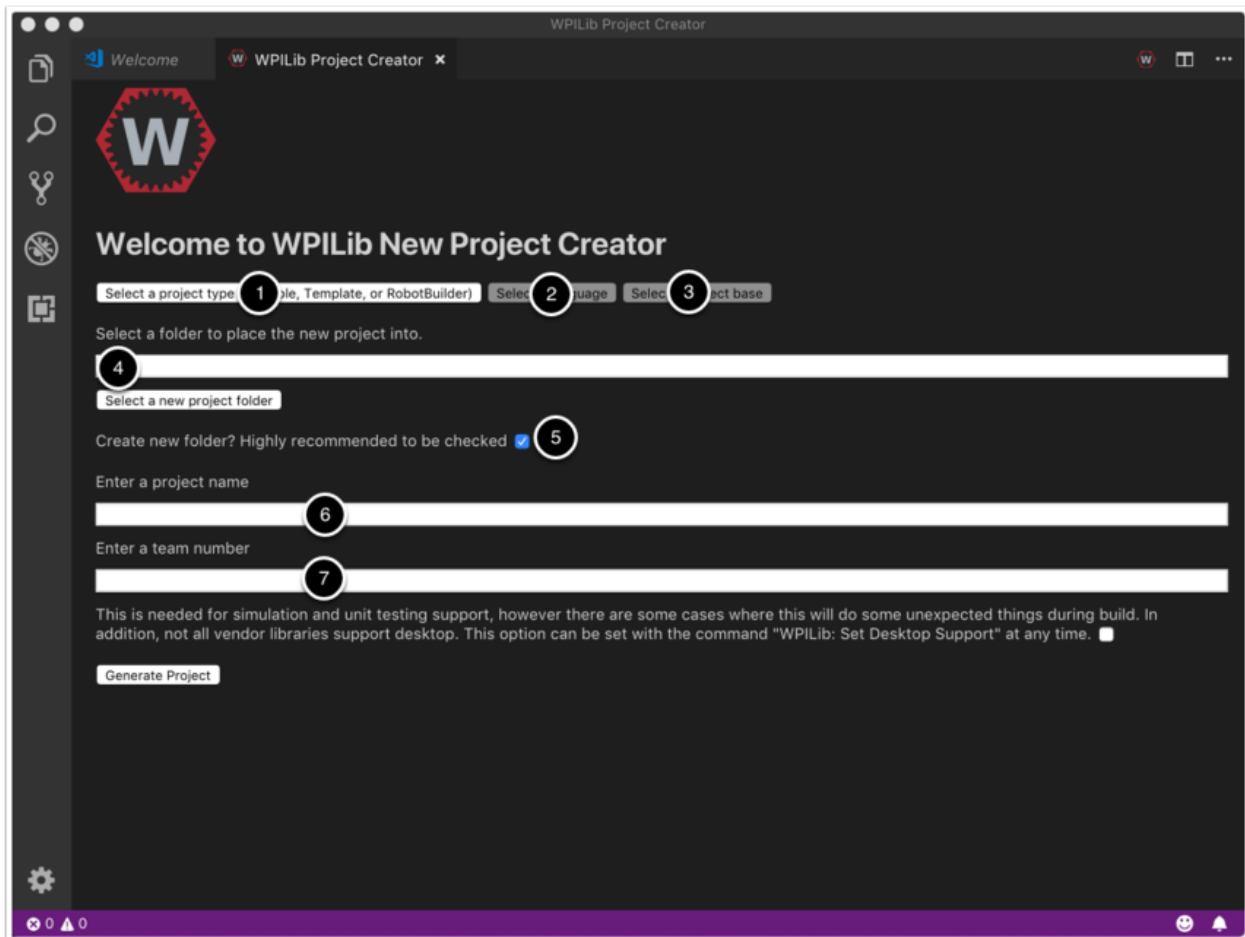
Then, type “WPILib” into the prompt. Since all WPILib commands start with “WPILib,” this will bring up the list of WPILib-specific VS Code commands:



Now, select the “Create a new project” command:



This will bring up the “New Project Creator Window:”



The elements of the New Project Creator Window are explained below:

1. **Project Type:** The kind of project we wish to create. This can be an example project, or one of the project templates provided by WPILib. Templates exist for each of the robot base classes. Additionally, a template exists for *Command-based* projects, which are built on the `TimedRobot` base class but include a number of additional features - this type of robot program is highly recommended for new teams.
2. **Language:** This is the language (C++ or Java) that will be used for this project.
3. **Project Base:** If this is a template project, this specifies the type of template that will be used.



4. **Project Location:** This determines the folder in which the robot project will be located.
5. **Create New Folder:** If this is checked, a new folder will be created to hold the project within the previously-specified folder. If it is *not* checked, the project will be located directly in the previously-specified folder. An error will be thrown if the folder is not empty and this is not checked.
6. **Project Name:** The name of the robot project. This also specifies the name that the project folder will be given if the Create New Folder box is checked.
7. **Team Number:** The team number for the project, which will be used for package names within the project and to locate the robot when deploying code.
8. **Desktop Support:** Enables unit test and simulation. While WPILib supports this, third party software libraries may not. If libraries do not support desktop, then your code may not compile or may crash. It should be left unchecked unless unit testing or simulation is needed and all libraries support it.

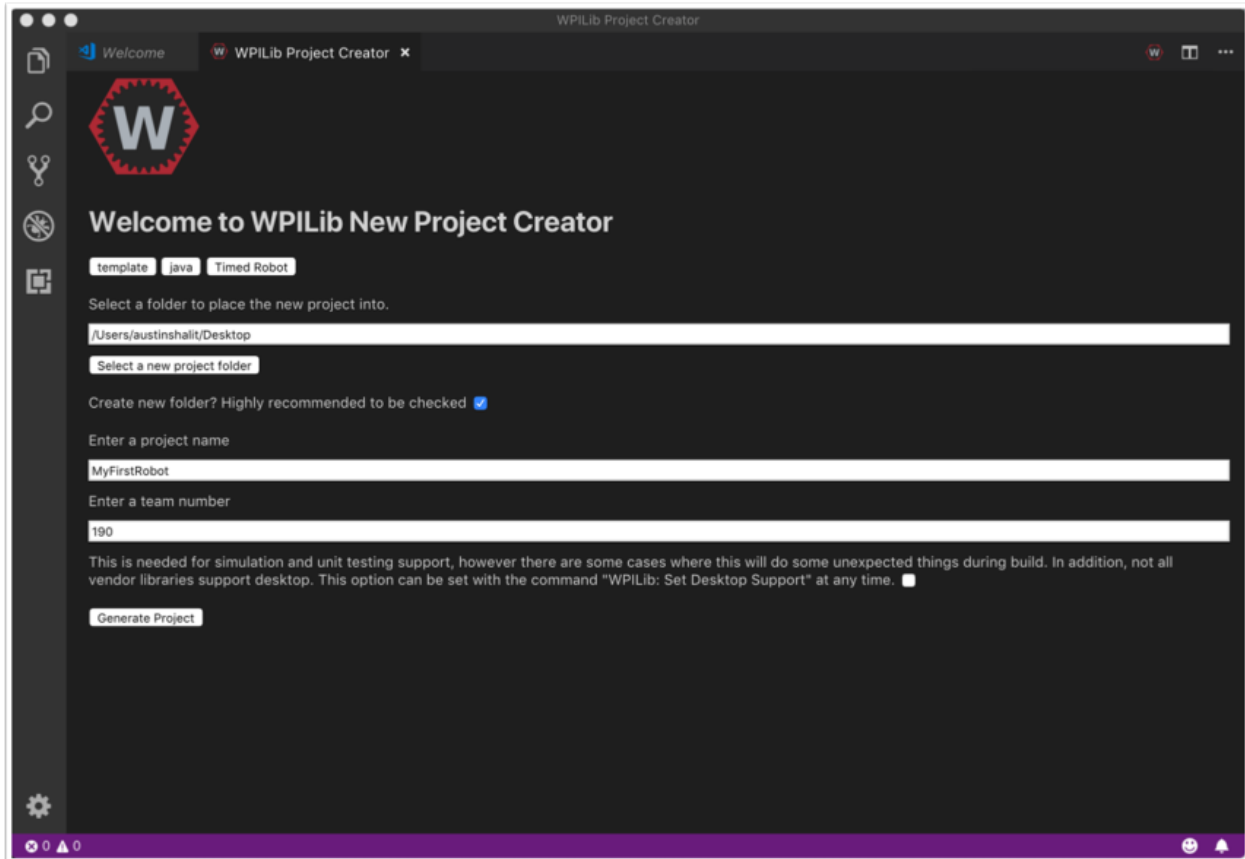
Once all the above have been configured, click “Generate Project” and the robot project will be created.

---

**Note:** Any errors in project generation will appear in the bottom right-hand corner of the screen.

---

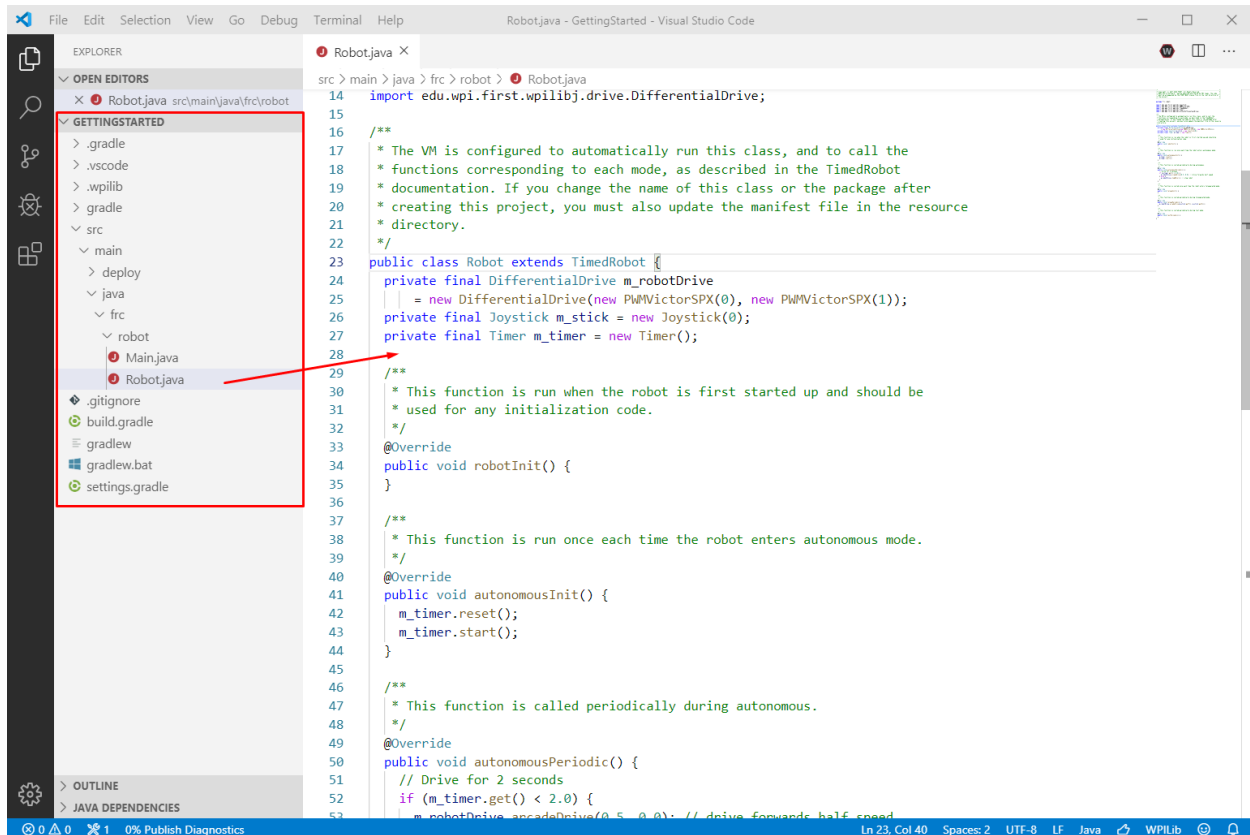
An example after all options are selected is shown below.



### 3.5.3 Opening The New Project

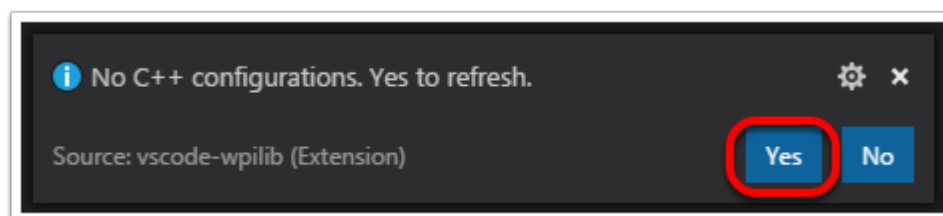
After successfully creating your project, VS Code will give the option of opening the project as shown below. We can choose to do that now or later by typing Ctrl-K then Ctrl-O (or just Command+O on macOS) and select the folder where we saved our project.

Once opened we will see the project hierarchy on the left. Double clicking on the file will open that file in the editor.



### 3.5.4 C++ Configurations (C++ Only)

For C++ projects, there is one more step to set up IntelliSense. Whenever we open a project, we should get a pop-up in the bottom right corner asking to refresh C++ configurations. Click “Yes” to set up IntelliSense.

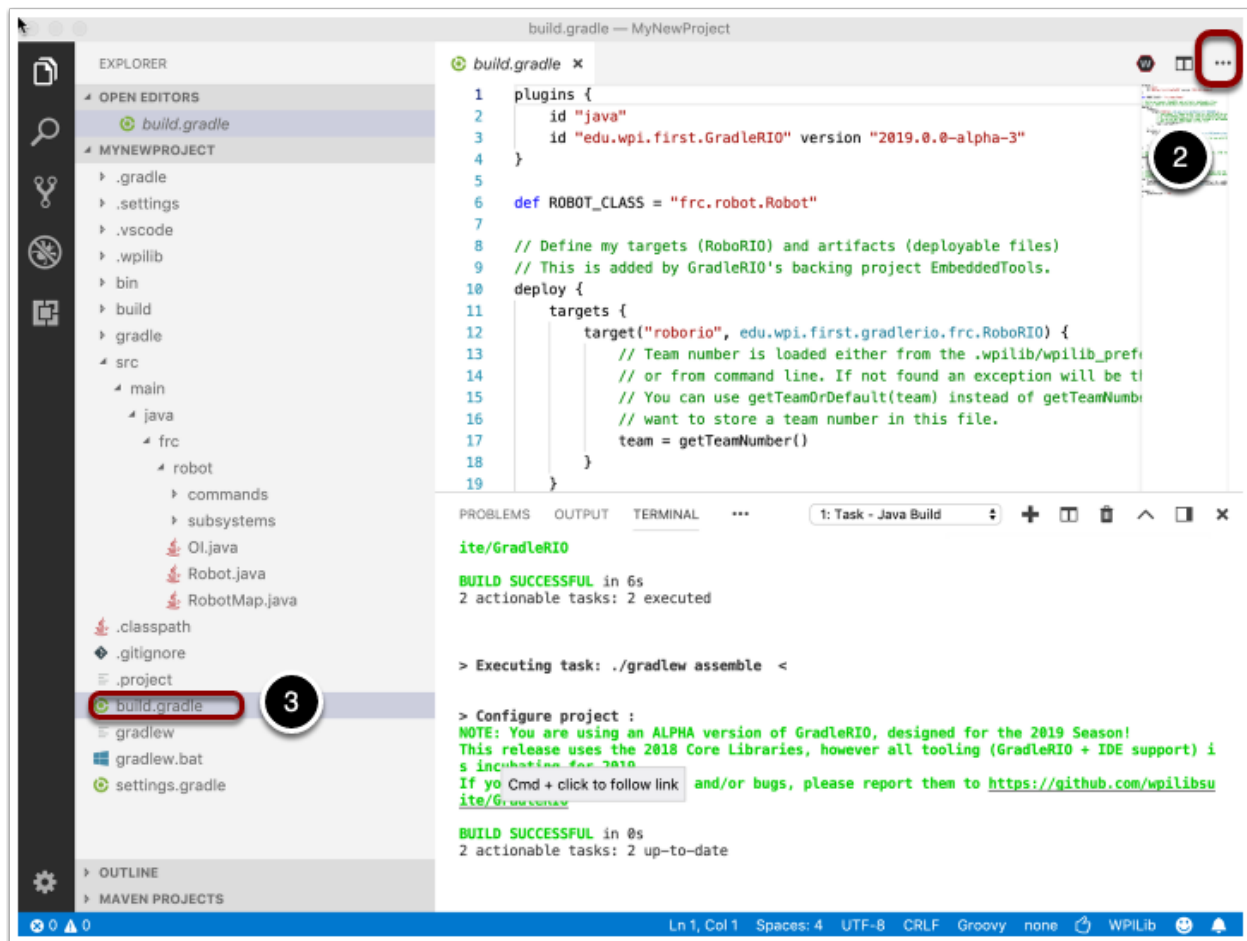


## 3.6 Building and Deploying Robot Code

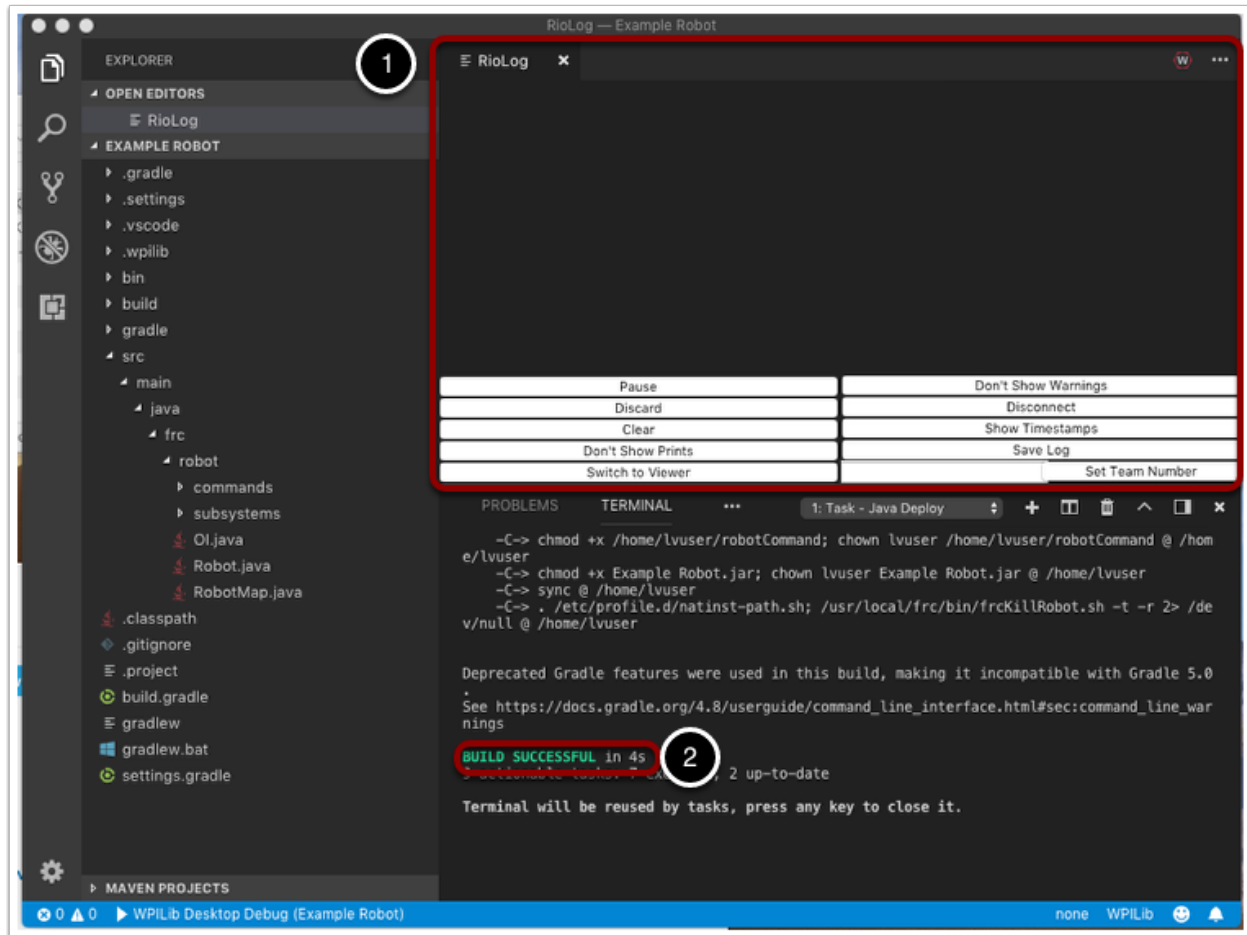
Robot projects must be compiled (“built”) and deployed in order to run on the roboRIO. Since the code is not compiled natively on the robot controller, this is known as “cross-compilation.”

To build and deploy a robot project, do one of:

1. Open the Command Palette and enter/select “Build Robot Code”
2. Open the shortcut menu indicated by the ellipses in the top right corner of the VS Code window and select “Build Robot Code”
3. Right-click on the build.gradle file in the project hierarchy and select “Build Robot Code”



Deploy robot code by selecting “Deploy Robot Code” from any of the three locations from the previous instructions. That will build (if necessary) and deploy the robot program to the roboRIO. If successful, we will see a “Build Successful” message (2) and the RioLog will open with the console output from the robot program as it runs (1).



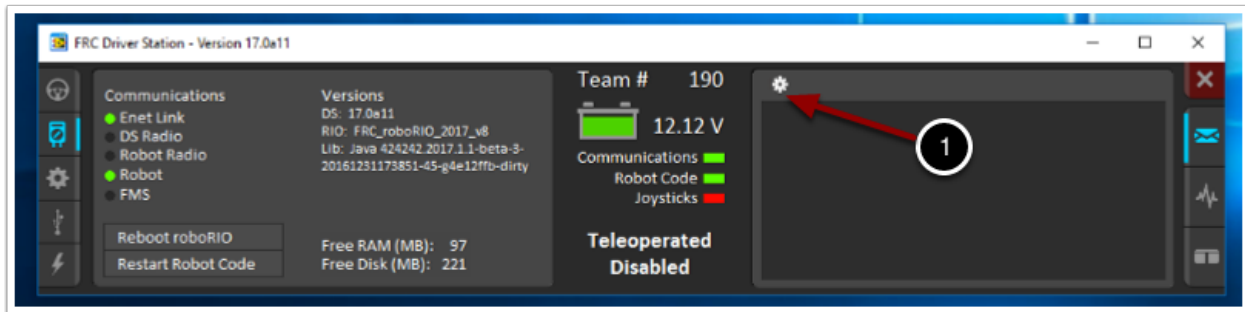
## 3.7 Viewing Console Output

For viewing the console output of text based programs the roboRIO implements a NetConsole. There are two main ways to view the NetConsole output from the roboRIO: The Console Viewer in the FRC Driver Station and the RioLog plugin in VS Code.

**Note:** On the roboRIO, the NetConsole is only for program output. If you want to interact with the system console you will need to use SSH or the Serial console.

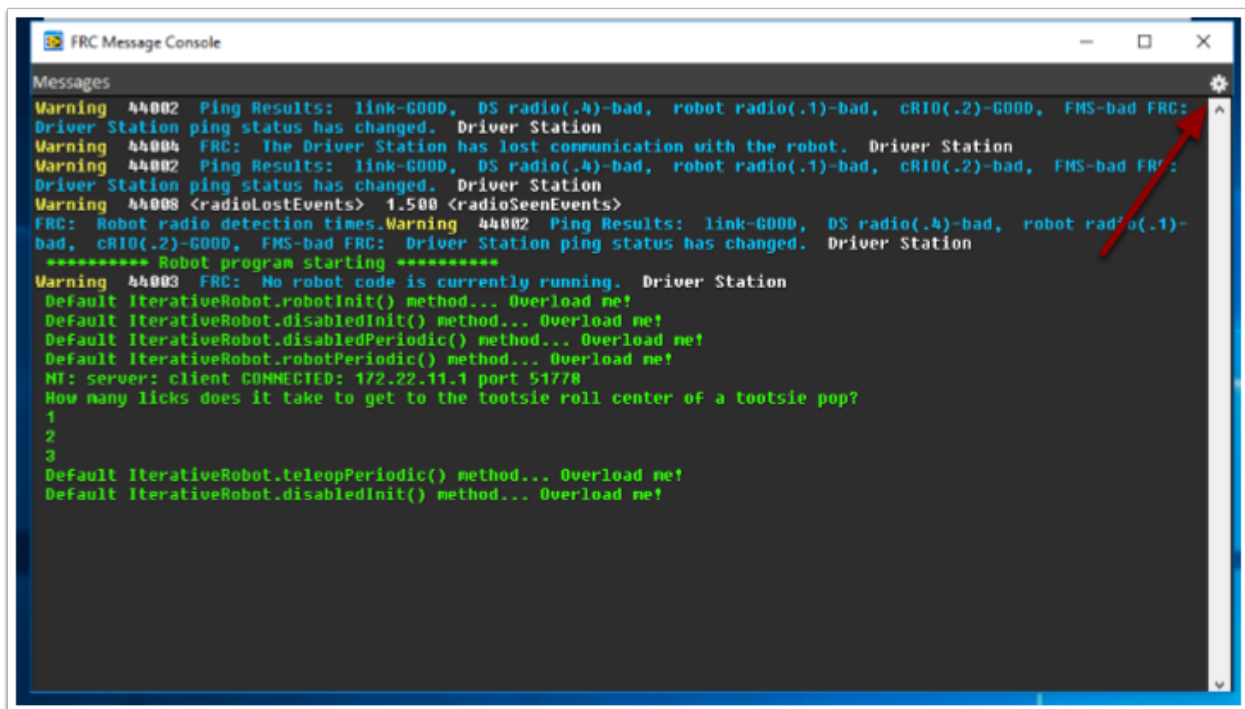
### 3.7.1 Console Viewer

### Opening the Console Viewer



To open Console Viewer, first open the FRC Driver Station. Then, click on the gear at the top of the message viewer window (1) and select “View Console”.

### Console Viewer Window

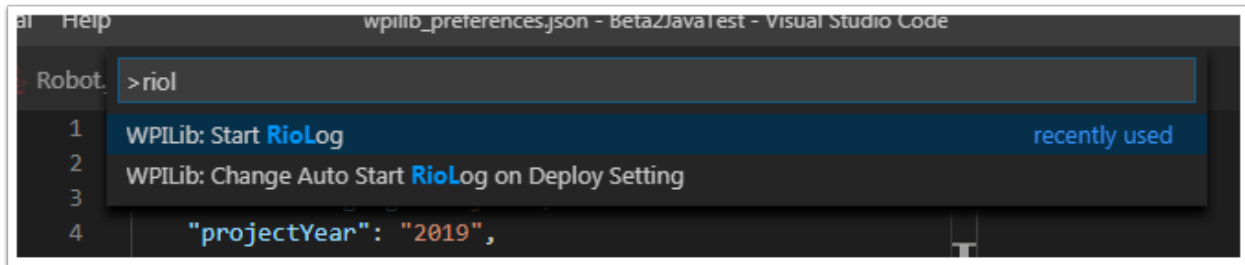


The Console Viewer window displays the output from our robot program in green. The gear in the top right can clear the window and set the level of messages displayed.

### 3.7.2 Riolog VS Code Plugin

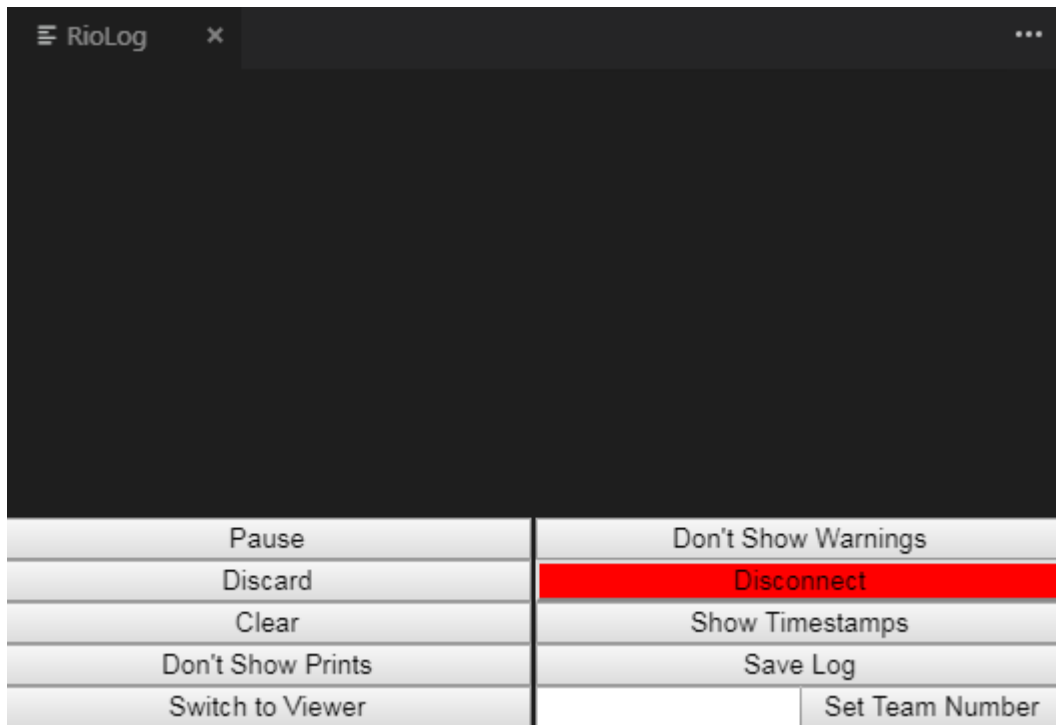
The Riolog plugin is a VS Code view that can be used to view the NetConsole output in VS Code (credit for the original Eclipse version: Manuel Stoeckl, FRC1511).

## Opening the RioLog View



By default, the RioLog view will open automatically at the end of each roboRIO deploy. To launch the RioLog view manually, press Ctrl+Shift+P to open the command palette and start typing “RioLog”, then select the WPILib: Start RioLog option.

## RioLog Window



The RioLog view should appear in the top pane. The Riolog contains a number of controls for manipulating the console:

- **Pause/Resume Display** - This will pause/resume the display. In the background, the new packets will still be received and will be displayed when the resume button is clicked.
- **Discard/Accept Incoming** - This will toggle whether to accept new packets. When packets are being discarded the display will be paused and all packets received will be discarded. Clicking the button again will resume receiving packets.
- **Clear** - This will clear the current contents of the display.
- **Don't Show/Show Prints** - This shows or hides messages categorized as print statements

- **Switch to Viewer** - This switches to viewer for saved log files
- **Don't Show/Show Warnings** - This shows or hides messages categorized as warnings
- **Disconnect/Reconnect** - This disconnects or reconnects to the console stream
- **Show/Don't Show Timestamps** - Shows or hides timestamps on messages in the window
- **Save Log** - Copies the log contents into a file you can save and view or open later with the RioLog viewer (see Switch to Viewer above)
- **Set Team Number** - Sets the team number of the roboRIO to connect to the console stream on, set automatically if RioLog is launched by the deploy process

## 3.8 Debugging a Robot Program

Inevitably, a program will not behave in the way we expect it to behave. When this occurs, it becomes necessary to figure out why the program is doing what it is doing, so that we can make it do what we want it to do, instead. Such an undesired program behavior is called a “bug,” and this process is called “debugging.”

A debugger is a tool used to control program flow and monitor variables in order to assist in debugging a program. This section will describe how to set up a debug session for an FRC robot program.

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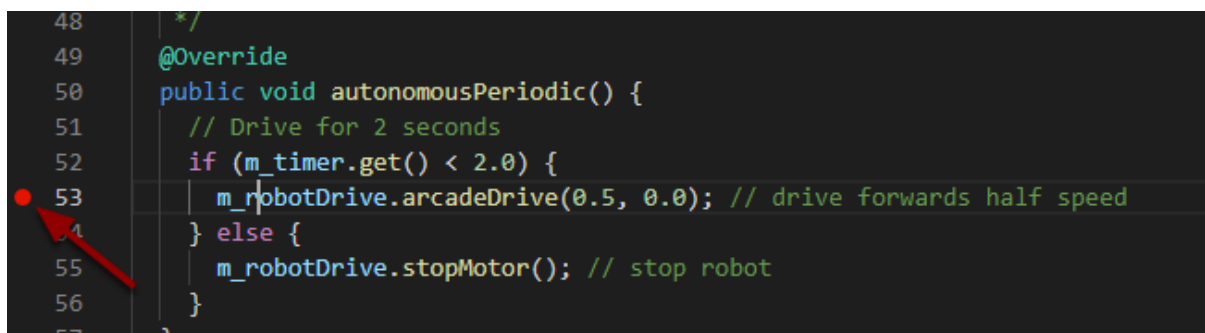
**Note:** For beginning users who need to debug their programs but do not know/have time to learn how to use a debugger, it is often possible to debug a program simply by printing the relevant program state to the console. However, it is strongly recommended that students eventually learn to use a debugger.

---

### 3.8.1 Breakpoints

A “breakpoint” is a line of code at which the debugger will stop the program execution so that the user can examine the program state. This is extremely useful while debugging, as it allows the user to pause the program at specific points in problematic code to determine where exactly the program is deviating from the expected behavior.

#### Setting a Breakpoint



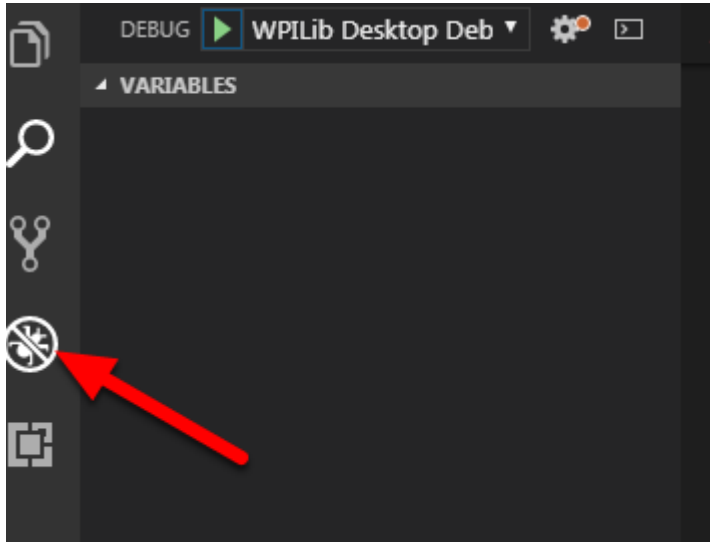
The screenshot shows a code editor with a dark background. The code is as follows:

```
48  */
49  @Override
50  public void autonomousPeriodic() {
51      // Drive for 2 seconds
52      if (m_timer.get() < 2.0) {
53          m_robotDrive.arcadeDrive(0.5, 0.0); // drive forwards half speed
54      } else {
55          m_robotDrive.stopMotor(); // stop robot
56      }
57  }
```

A red dot, representing a breakpoint, is placed on the left margin next to line 53. A red arrow points from this dot to the line of code.

Double-click in the left margin of the source code window to set a breakpoint in your user program: A small red circle indicates the breakpoint has been set on the corresponding line.

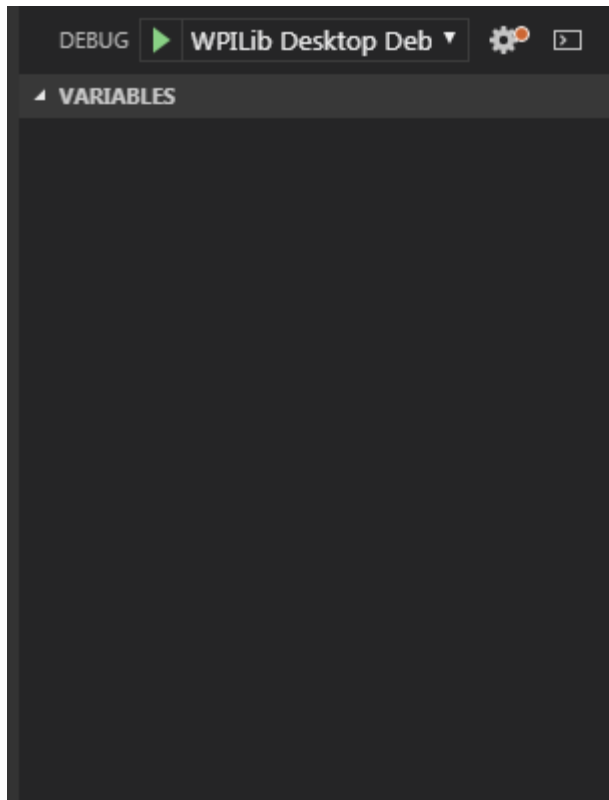
### Viewing Program State



When the program is stopped at a breakpoint, various pieces of program state can be viewed from the debug tab. The Debug tab is accessed by clicking on the debug icon on the far left pane. Within the debug tab, the program state can be viewed from an assortment of “panes.”

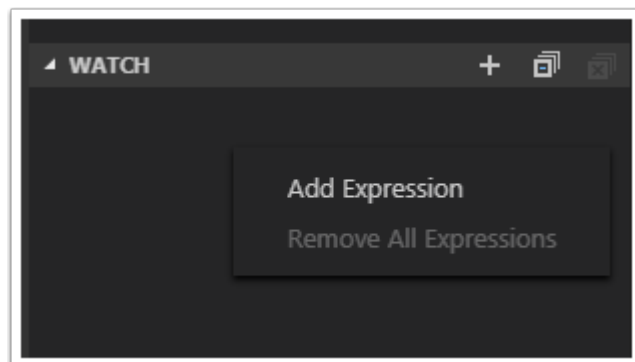


## The Variables Pane



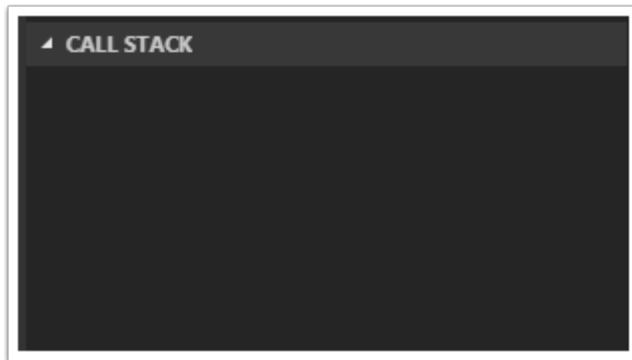
The Variables view shows the current values of variables. To see a variable that is not displayed, select the “Watch” pane and enter the variable name. This will show the variable’s value if it’s in-scope. Clicking on the arrows next to a variable name will expand the tree and show its [fields](#).

## Watch Pane



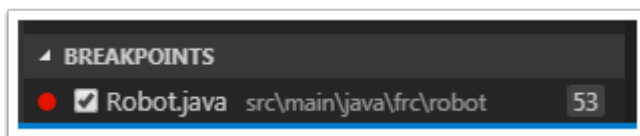
The Watch Pane can be used to monitor specific variables or expressions while debugging. To add an expression, right-click and select Add Expression.

## Call Stack



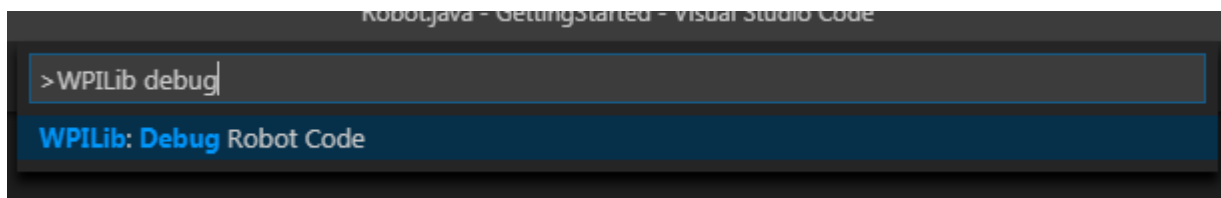
The Call Stack pane is used to display the current [call stack](#) of the running program. This can be used to monitor the current call hierarchy of the program while debugging.

## Breakpoint Pane



The Breakpoint Pane displays all of the current breakpoints. To temporarily disable a breakpoint without permanently removing it, click the corresponding checkbox.

## 3.8.2 Running the Debugger



Press Ctrl+Shift+P and type WPILib or click on the WPILib Menu item to open the Command palette with WPILib pre-populated. Type Debug and select the Debug Robot Code menu item to start debugging. The code will download to the roboRIO and begin debugging.

The debugger will automatically pause at the first breakpoint it encounters. The user can then tell the debugger when to proceed to the next breakpoint.

## 3.8.3 Debugging with Console

Another way to debug your program is to use `System.out.println` statements in your code and receive them using the RioLog in Visual Studio Code.

## 3.9 3rd Party Libraries

A number of software components were broken out of WPILib starting in 2017 and are now maintained by the third parties who produce the hardware. See [this](#) blog for more details.

### 3.9.1 Libraries

**Warning:** These are **not** links to directly plug in to the VS Code -> Install New Libraries (online) feature. Click these links to visit the vendor site to see whether they offer online installers, offline installers, or both.

[Analog Devices ADIS16448 IMU](#) - Driver for ADIS16448 IMU. More info [here](#)

[Analog Devices ADIS16470 IMU](#) - Driver for ADIS16470 IMU. More info [here](#)

[Copperforge LibCu Software Library](#) - Library for all Copperforge devices including the Laser-shark

[CTRE Phoenix Toolsuite](#) - Contains CANCoder, Canifier, Pigeon, Talon FX, Talon SRX, and Victor SPX Libraries and Phoenix Tuner program for configuring CTRE CAN devices

[Digilent](#) - DMC-60C library

[Playing With Fusion Driver](#) - Library for all PWF devices including the Venom motor/controller

[Kauai Labs](#) - Libraries for NavX-MXP, NavX-Micro, and Sensor Fusion

[Rev Robotics Color Sensor V3](#) - Library for Rev Robotics Color Sensor included in 2020 Kit of Parts

[Rev Robotics SPARK MAX](#) - SPARK MAX Library

### 3.9.2 WPILib Command Libraries

The WPILib *old* and *new* command libraries have been split into vendor libraries in order to reduce the chances of mixing the two which will not work correctly. They are both installed by the wpilib installer for offline installation. They may also be installed with the following online links:

[Old Command Library](#)

[New Command Library](#)

### 3.9.3 The Mechanism

In support of this effort NI (for LabVIEW) and FIRST/WPI (for C++/Java) have developed mechanisms that should make it easy for vendors to plug their code into the WPILib software and for teams to use that code once it has been installed. A brief description of how the system works for each language can be found below.

## The Mechanism - LabVIEW

For LabVIEW teams, you may notice a few new Third Party items on various palettes (specifically, one in Actuators, one in Actuators->Motor Control labeled “CAN Motor”, and one in “Sensors”). These correspond to folders in C:\Program Files\National Instruments\LabVIEW 2016\vi.lib\Rock Robotics\WPI\Third Party.

For a library to insert VI’s in these palettes, they simply make a subfolder in one of these three Third Party folders containing their VIs and they will be added automatically. To control the appearance of the palette (have some VI’s not show up, set the Icon for the folder, etc.) there is a process to create a dir.mnu file for your directory. We will be working on documenting that process shortly.

To use installed Third Party libraries, simply locate the VIs in one of these 3 locations and drag them into your project as you would with any other VI.

## The Mechanism - C++/Java

For C++ and Java a JSON file describing the vendor library is installed on your system to ~\wpilib/YYYY/vendordeps (where YYYY is the year and ~ is C:\Users\Public on Windows). This can either be done by an offline installer or the file can be fetched from an online location using the menu item in Visual Studio Code. This file is then used from VS Code to add to the library to each individual project. Vendor library information is managed on a per-project basis to make sure that a project is always pointing to a consistent version of a given vendor library. The libraries themselves are placed in the Maven cache at C:\Users\Public\wpilib\YYYY\maven. Vendors can place a local copy here with an offline installer (recommended) or require users to be online for an initial build to fetch the library from a remote Maven location.

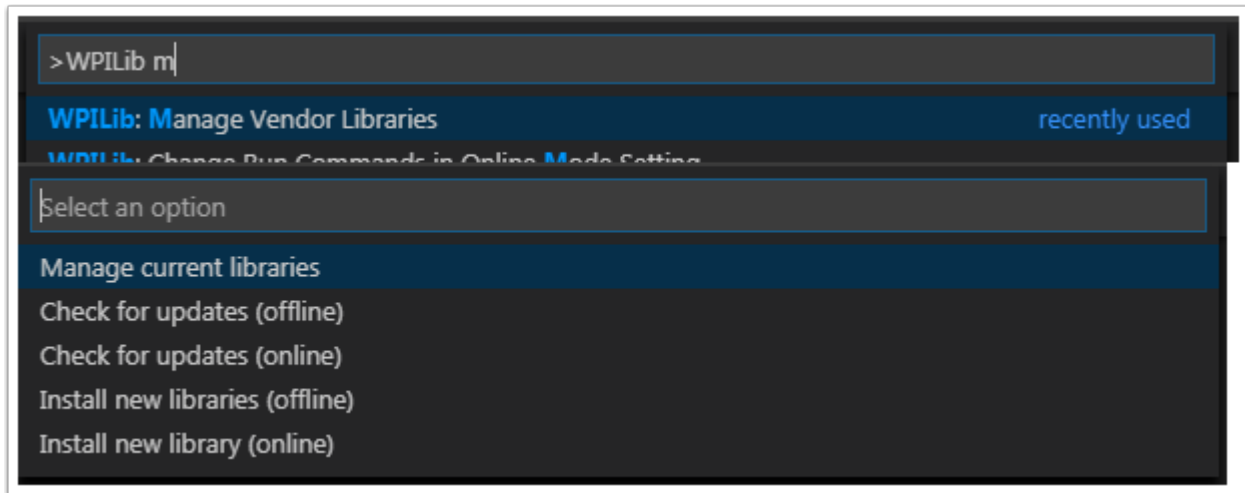
The JSON file allows specification of complex libraries with multiple components (C++, Java, JNI, etc.) and also helps handle some complexities related to simulation. Vendors choosing to provide a remote URL in the JSON also enable users to check for updates from within VS Code.

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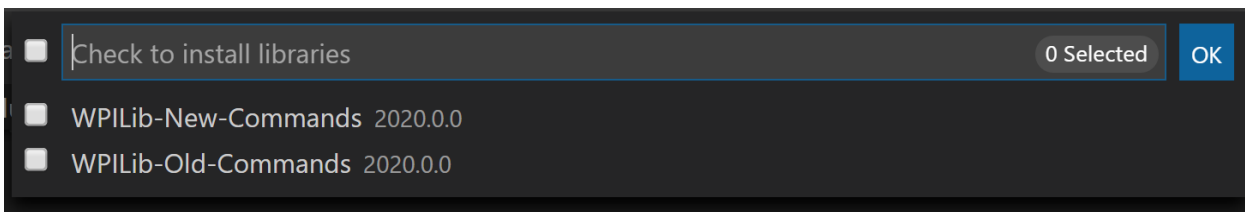
**Note:** The vendor JSON files are actually processed by GradleRIO once they are in your projects vendordeps folder. If you are using another IDE, you will need to manually create a “vendordeps” folder in your project and copy any desired vendor JSON files from the “wpilib/YYYY” folder (where they should be placed by an offline installer) or download them directly from the vendor and place them into the folder in the project.

---

## Adding an Offline-Installed Library



To add a vendor library that has been installed by an offline installer, press **Ctrl+Shift+P** and type WPILib or click on the WPILib icon in the top right to open the WPILib Command Palette and begin typing **Manage Vendor Libraries**, then select it from the menu. Select the option to **Install new libraries (offline)**.



Select the desired libraries to add to the project by checking the box next to each, then click OK. The JSON file will be copied to the **vendordeps** folder in the project, adding the library as a dependency to the project.

## Checking for Updates (Offline)

Remember: Dependencies are now version managed and done on a per-project bases. Even if you have installed an updated library using an offline installer, you will need to Manage Vendor Libraries and select **Check for updates (offline)** for each project you wish to update.

## Checking for Updates (Online)

Part of the JSON file that vendors may optionally populate is an online update location. If a library has an appropriate location specified, running **Check for updates (online)** will check if a newer version of the library is available from the remote location.

## Removing a Library Dependency

To remove a library dependency from a project, select **Manage Current Libraries** from the **Manage Vendor Libraries** menu, check the box for any libraries to uninstall and click OK. These libraries will be removed as dependencies from the project.

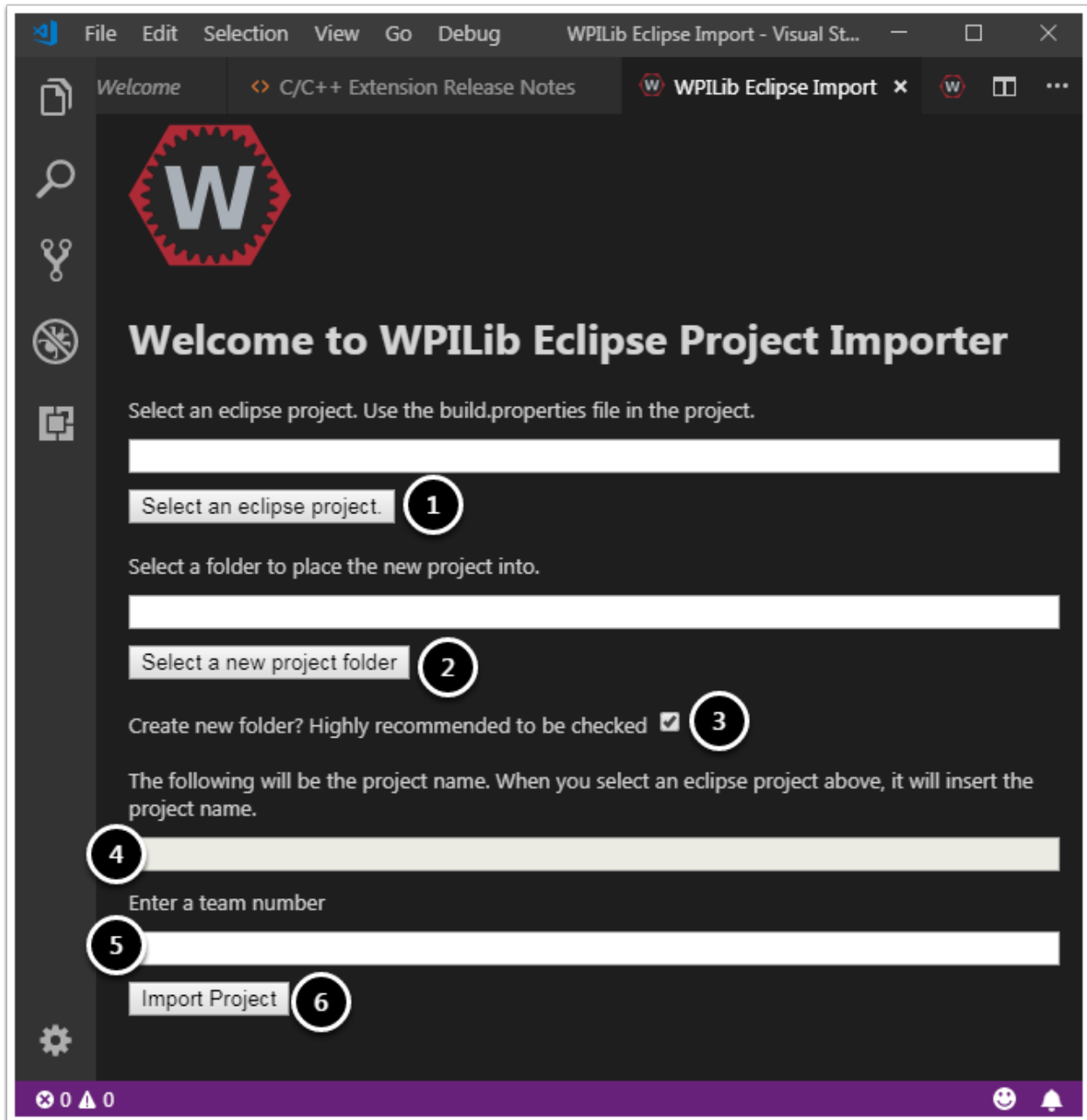
## 3.10 Importing an Eclipse project into VS Code

To make it easy for teams to use existing projects with the new IDE, WPILib includes a wizard for importing Eclipse projects into VS Code. This will generate the necessary Gradle components and load the project into VS Code. The importer automatically imports the old command framework 3rd party library.

### 3.10.1 Launching the Import Wizard



Press Ctrl+Shift+P and type “WPILib” or click the WPILib icon to locate the WPILib commands. Begin typing “Import a WPILib Eclipse project” and select it from the dropdown.



You'll be presented with the WPILib Eclipse Project Upgrade window. This is similar to the process of creating a new project and the window and the steps are shown below. This window contains the following elements:

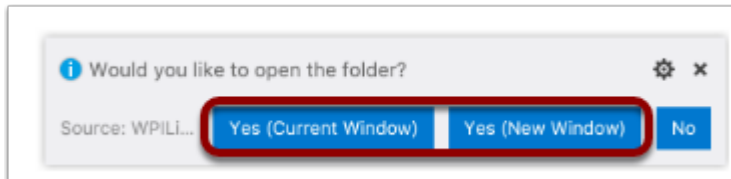
1. **Eclipse Project Selection:** Selects the Eclipse project to be imported. Users should select the build.properties file in the root directory of the eclipse project.
2. **Project Location:** This determines the folder in which the robot project will be located.
3. **Create New Folder:** If this is checked, a new folder will be created to hold the project within the previously-specified folder. If it is *not* checked, the project will be located directly in the previously-specified folder. An error will be thrown if the folder is not empty and this is not checked.
4. **Project Name:** The name of the robot project. This also specifies the name that the

project folder will be given if the Create New Folder box is checked.

5. **Team Number:** The team number for the project, which will be used for package names within the project and to locate the robot when deploying code.

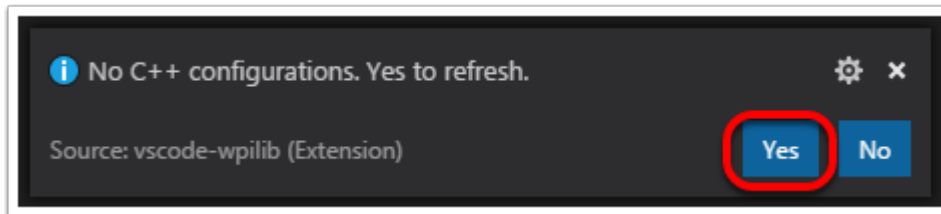
Click “Upgrade Project” to begin the upgrade.

The eclipse project will be upgraded and copied into the new project directory. You can then either open the new project immediately (the pop-up shown below should appear in the bottom right) or open it later using the Ctrl-O (or Command-O for macOS) shortcut.



### 3.10.2 C++ Configurations (C++ Only)

For C++ projects, there is one more step to set up IntelliSense. Whenever you open a project, you should get a pop-up in the bottom right corner asking to refresh C++ configurations. Click “Yes” to set up IntelliSense.



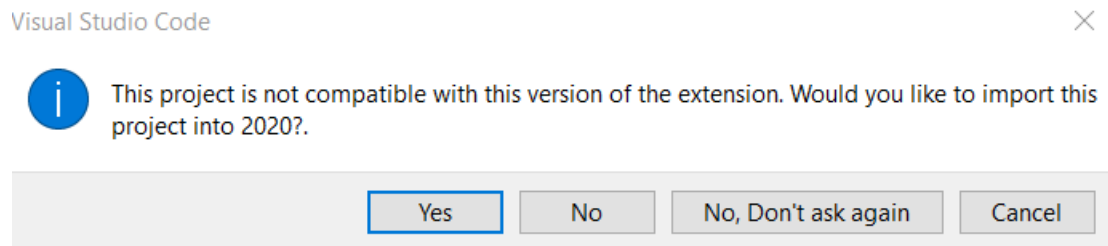
## 3.11 Importing a Gradle Project

Due to changes in the project, it is necessary to update the build files for a previous years Gradle project. To make it easy for teams to import previous years gradle projects into the current year’s framework, WPILib includes a wizard for importing previous years projects into VS Code. This will generate the necessary gradle components and load the project into VS Code. In place upgrades are not supported. The importer automatically imports the old command framework 3rd party library.

**Important:** The import process copies your project from the current directory to a new directory and completely regenerates the gradle files. If you made non-standard updates to the build.gradle, you will need to make those changes again. For this reason, in place upgrades are not supported. It is also necessary to import vendor libraries again, since last year’s vendor libraries must be updated to be compatible with this year’s projects.

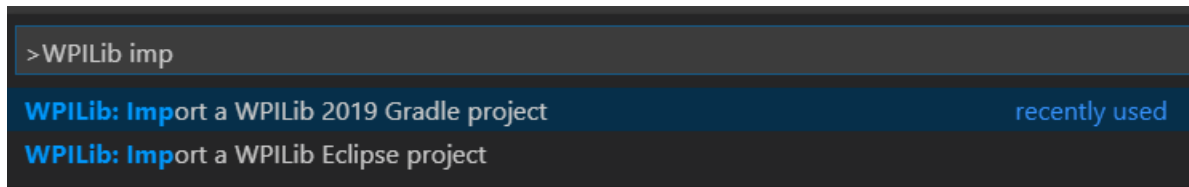


### 3.11.1 Launching the Import Wizard



When you open a previous year's project, you will be prompted to import that project. Click yes.

Alternately, you can choose to import it from the menu. Press Ctrl+Shift+P and type "WPILib" or click the WPILib icon to locate the WPILib commands. Begin typing "Import a WPILib 2019 Gradle project" and select it from the dropdown as shown below.





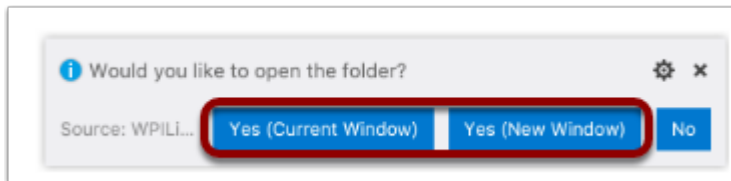
You'll be presented with the WPILib Project Importer window. This is similar to the process of creating a new project and the window and the steps are shown below. This window contains the following elements:

1. **Gradle Project:** Selects the project to be imported. Users should select the build.gradle file in the root directory of the gradle project.

2. **Project Location:** This determines the folder in which the robot project will be located.
3. **Create New Folder:** If this is checked, a new folder will be created to hold the project within the previously-specified folder. If it is *not* checked, the project will be located directly in the previously-specified folder. An error will be thrown if the folder is not empty and this is not checked.
4. **Project Name:** The name of the robot project. This also specifies the name that the project folder will be given if the Create New Folder box is checked. This must be a different directory from the original location.
5. **Team Number:** The team number for the project, which will be used for package names within the project and to locate the robot when deploying code.

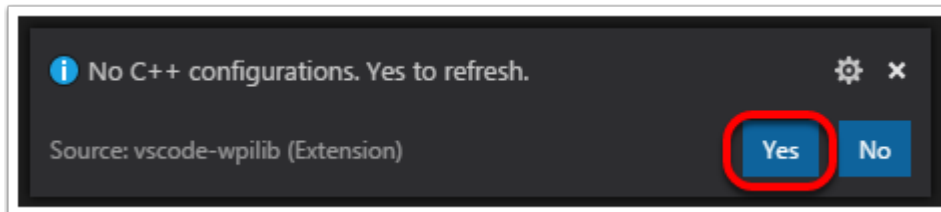
Click “Upgrade Project” to begin the upgrade.

The gradle project will be upgraded and copied into the new project directory. You can then either open the new project immediately (the pop-up shown below should appear in the bottom right) or open it later using the Ctrl-O (or Command-O for macOS) shortcut.



### 3.11.2 C++ Configurations (C++ Only)

For C++ projects, there is one more step to set up IntelliSense. Whenever you open a project, you should get a pop-up in the bottom right corner asking to refresh C++ configurations. Click “Yes” to set up IntelliSense.



### 3.11.3 3rd Party Libraries

It is necessary to update and re-import 3rd party libraries. See [3rd Party Libraries](#) for details.

## 3.12 Using Test Mode

Test mode is designed to enable programmers to have a place to put code to verify that all systems on the robot are functioning. In each of the robot program templates there is a place to add test code to the robot. If you use the TimedRobot template, or use command-based programming you can easily see the operation of all the motors and sensors through the LiveWindow.

### 3.12.1 Enabling Test Mode

Test mode on the robot can be enabled from the Driver Station just like autonomous or teleop. When in test mode, the `testInit` method is run once, and the `testPeriodic` method is run once per tick, in addition to `robotPeriodic`, the same as teleop and autonomous control modes. To enable test mode in the Driver Station, select the “Test” button and enable the robot. The test mode code will then run.

### 3.12.2 Adding Test mode code to your robot code

Adding test mode can be as painless as calling your already written Teleop methods from Test. This will allow you to use the LiveWindow tuning features for classes such as `PIDBase` and `PIDController`, as well as `PIDSubsystems` and `PIDCommands`, to change PID constants and setpoints. Make sure to add your subsystems to SmartDashboard with the `putData(subsystem)` or `PutData(subsystem)` method.

Java

```
public class Robot extends TimedRobot {

    @Override
    public void robotInit() {
        SmartDashboard.putData(m_aSubsystem);
    }

    @Override
    public void testInit() {
        teleopInit();
    }

    @Override
    public void testPeriodic() {
        teleopPeriodic();
    }

}
```

C++

```
void Robot::RobotInit() {
    SmartDashboard::PutData(m_aSubsystem);
}

void Robot::TestInit() {
    TestInit();
}

void Robot::TestPeriodic() {
    TeleopPeriodic();
}
```

### 3.12.3 Test Mode in SmartDashboard

The above sample code produces the following output when the Driver Station is put into Test mode then enabled. You can operate the motors by moving the sliders and read the values of

sensors such as the wrist potentiometer.

Notice that the values are grouped by the subsystem names to group related actuators and sensors for easy testing. The subsystem names are specified by supplying a name to the `putData()` method, or by calling `SendableRegistry.setName()`. This grouping, while not required, makes it much easier to test one subsystem at a time and have all the values next to each other on the screen.

### Using Test Mode with the TimedRobot Template

The TimedRobot template lends itself quite nicely to testing since it will periodically call the `testPeriodic()` method (or `TestPeriodic()` in C++) in your robot program. The `testPeriodic()` method will be called every 20ms and it is a good place to test commands or have LiveWindow update. The LiveWindow updating is built into the TimedRobot template so there is very little work to use LiveWindow.

---

**Note:** This works even if you are using the TimedRobot template and not doing Command-based programming.

---

In this example the sensors are registered with the LiveWindow and during the `testPeriodic` method, simply update all the values by calling the LiveWindow `run()` method. If your program is causing too much network traffic you can call the `run` method less frequently by, for example, only calling it every 5 updates for a 100ms update rate.

### 3.12.4 PID Tuning in Test Mode

Tuning PID loops is often a challenging prospect with frequent recompiles of the program to get the correct values. When using the command based programming model, subclassing `PIDSubsystem` or `PIDCommand` in your PID commands allows the adjustment of PID constants with immediate feedback of the results.

## 3.13 New for 2020

A number of improvements have been made to FRC Control System software for 2020. This article will describe and provide a brief overview of the new changes and features as well as a more complete changelog for C++/Java WPILib changes.

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**Important:** Due to internal GradleRIO changes, it is necessary to update previous years projects. After *Installing WPILib for 2020*, any 2019 projects must be *imported* to be compatible.

---

### 3.13.1 Major Features - All Languages

- **Addressable LEDs** - The roboRIO FPGA has been enhanced to be able to control individually addressable LEDs (WS2812 or compatible protocol) from the roboRIO PWM

ports (non-MXP). Teams can connect the signal line of these LEDs directly to the roboRIO PWM signal line and control them from APIs in all three languages. Depending on the length of the LED string and whether any servos are also being powered from the PWM ports, teams may be able to power the string directly from the PWM port or may need to use an external supply.

- **Duty Cycle Encoder** - The roboRIO FPGA has been enhanced to be able to decode the signals from Duty Cycle encoders (this includes devices like the US Digital MA3, CTRE Mag Encoder, and REV Robotics Through Bore Encoder). Teams can connect these devices to the DIO ports on the roboRIO and access the encoder data via APIs in all three languages.
- **CAN Bus Internal Restructure** - The internal implementation of the CAN bus has changed to reduce the latency incurred by CAN bus calls from robot programs. Team programs, particularly those with many CAN calls, should see reduced and more consistent loop timing with the new implementation. No team action is needed to take advantage of this change, the changes are limited to internal implementation. Users may notice changes in how some tools like the CTRE Phoenix Tuner work as a consequence of the restructure.
- **Control Packet Caching** - A change has been made to the internals of how control packet data (such as Joystick data, current mode, etc.) is retrieved, resulting in reduced latency in these calls. The user-facing API has not changed, users will see this benefit without making any changes to their programs.
- **Documentation** - If you're on this page, you're likely aware that the software documentation has moved from Screensteps to this new FRC-Docs page. This open source documentation, hosted on Read the Docs, allows for a greater number of contributors (including community contribution) as well as new features such as testable example code (to ensure example code remains correct as library changes are made), better support for localization, and more. For the 2020 season, KOP part documentation can still be found on [Screensteps](#)

### 3.13.2 Major Features - C++/Java

More complete details on all of these changes can be found in the changelog below (under WPILib).

- **Command Based Framework Rewrite** - A new version of the Command Based framework has been written from the ground up based on the years of experience with the previous framework. Both frameworks will be available as options in 2020 and have been split out as "vendor libraries" (though they are still included in the WPILib installer) in order to reduce the chances of mixing the two which will not work correctly.
- **PID Controller Rewrite** - A new synchronous PID controller class has been written that is structured in a way that makes it simpler to compose with other higher level classes such as filters, motion profiles, kinematics and more. The new PID Controller is located in a new package to maintain separation from the existing implementation.
- **High level controls & Trajectory generation** - A number of new classes have been added to assist teams with higher level controls including kinematics, odometry, and trajectory generation. In addition to the characterization GUI mentioned below this should allow teams a much easier entry to high level control of mechanisms included drivetrains (with smooth trajectories), arms, and elevators.
- **Robot Characterization Tool** - This new tool helps teams characterize their mechanical systems (currently supports drivetrains, elevators, and arms) to help tune control loops.

Combined with the new controls classes this should enable teams to follow an end-to-end solution for autonomous trajectory following.

- **Simulation GUI** - A basic simulation GUI has been implemented allowing teams to visualize outputs and control basic inputs when simulating code on their desktop. While vendor support at Kickoff is expected to be limited, we hope this will expand in the future.

### 3.13.3 WPILib

There are many changes and additions to the main WPILib library for 2020. Most notably, there is a new version of the command-based framework with several major enhancements, a new (synchronous) PIDController, a GUI simulator, and kinematics classes have been added for closed loop driving. The full change log can be read below.

- The command-based framework has been rewritten. The design rationale behind the rewrite can be found [here](#). The new version of the framework is located in the `frc2` namespace (C++) and the `edu.wpi.first.wpilibj2` package (Java).
- The command-based frameworks are now separate vendor libraries, rather than built into WPILib itself.
- `LinearDigitalFilter` has been renamed to `LinearFilter`, and now has a `Calculate()` method which returns the filtered value
  - Takes a double in the `Calculate()` method instead of a `PIDSource` in the constructor
  - `PIDGet()` was replaced with `Calculate()`
  - Both of these changes make it easy to compose the `LinearFilter` class with the new `PIDController` class
- `PIDController` has been rewritten; the old `PIDController` along with `PIDSource` and `PIDOutput` have been deprecated. The new version of `PIDController` is located in the `frc2` namespace (C++) and the `edu.wpi.first.wpilibj2` package (Java) while the deprecated version remains in the old namespace and package.
  - The new `PIDController` no longer runs asynchronously in a separate thread. This eliminates a major source of bugs for teams. Instead, teams should run the controller as part of their main periodic `TimedRobot` loop by calling `Calculate()` and passing the result to the motor's `Set()` function. Note this means that the controller will run at the `TimedRobot` periodic rate.
  - Input range was replaced with `EnableContinuousInput()` and output range was replaced with integrator range. If it's necessary to clamp inputs or outputs to a range, use `std::clamp()` or `wpiutil.MathUtils.clamp()` on either the input or output of `Calculate()` as appropriate. To deal with steady-state error, use `ProfiledPIDController` instead of reducing the output range or having an integral term.
  - `PIDSource` is no longer used. Instead, pass the sensor value directly to `Calculate()`.
  - `PIDOutput` is no longer used. Instead, call `Set()` with the output of `Calculate()`.
  - Percent tolerance has been removed. Absolute tolerance is provided via `SetTolerance()`.
- Added kinematics classes for Swerve, Mecanum, and DifferentialDrive. These classes can be used to implement closed loop driving of these drive types.

- Added odometry classes for Swerve, Mecanum, and DifferentialDrive. These are needed for closed loop feedback control on global pose (as opposed to just PID on the two drive-train sides, which can accrue error since there are multiple ending positions a robot can be in for a given set of encoder measurements)
- Add RamseteController for closed loop feedback control on global pose for unicycles (the DifferentialDriveKinematics class can convert the chassis speeds to that of a differential drive)
- (C++) Add frc2::Timer which is unit safe
- Real-time trajectory generation for 2 DOF trajectories (e.g., x and y position for a drive-train)
- Added a PortForwarding class to allow forwarding ports from a remote, to a client. This can be used when connecting to the roboRIO from USB and needing to access Ethernet content.
- Added an interactive GUI for desktop simulation of robot code. The GUI provides DS-like controls for operating mode and joystick input and provides live display/control of virtual hardware inputs and outputs.
- Removed SampleRobot
- Made null checks on Java parameters more descriptive
- Removed deprecated LiveWindow functions
- Deprecated frc/WPILib.h. Instead, include only what you use.
- Removed deprecated shim header files for wpilibc and llvm.
- Added low-level geometry classes: Pose2d, Rotation2d, Transform2d, Translation2d
- Added C++ units library. This library provides type safety, which makes it impossible to mix up units (e.g. pass seconds as meters) and also provides automatic unit conversion. The units can be specified in literals using a suffix, e.g. 1.0\_s for 1 second.
- Added Java units utility functions for unit conversions. This provides a set of common unit conversions (e.g. feet to meters). Unlike C++, the Java library does not provide type safety; this was done for performance reasons.
- Added TrapezoidProfile class for 1 degree-of-freedom (DOF) trajectories
- Added ProfiledPIDController class. Given a goal, this class constrains the setpoint movement over time to a max velocity and acceleration.
- Moved the CircularBuffer/circular\_buffer classes from wpilib to wpiutil
- Deprecated the GearTooth class. Based on usage reporting, no teams have used this class in the last several years. The Counter class can be used directly instead.
- Deprecated the Filter class. Since PIDSource is deprecated, it no longer serves a purpose. Teams should use the derived classes of Filter directly rather than using polymorphism.
- Added the PWMSparkMax class for PWM control of the REV Robotics SPARK MAX Motor Controller
- Simplified the Sendable interface and deprecated SendableBase. The name and subsystem have been removed from individual objects, and instead this data is stored in a new singleton class, SendableRegistry. Much of LiveWindow has been refactored into SendableRegistry.



- In C++, a new CRTP helper class, `SendableHelper`, has been added to provide move and destruction functionality.
- Shims for `GetName`, `SetName`, `GetSubsystem`, and `SetSubsystem` have been added to `Command` and `Subsystem` (both old and new), and also to `SendableHelper` to prevent code breakage.
- Update to GCC 7, and use C++17
- Use OS for serial port instead of the NI driver
- `IterativeRobot` template has been removed
- Add support for Addressable LEDs, such as WS2812's and NeoPixels
- Add support for DutyCycle inputs, such as the absolute output on many FRC encoders
- Eigen has been added to C++, and EJML has been added to Java to support linear algebra and matrix calculations. These are included by default, with no need to add anything to your robot project to use them.
- Jackson has been added to Java for JSON support. C++ support already existed with json library in the wpi header root. These can be used with no need to add anything to your robot project.
- The location that maven artifacts are published has changed to: <https://frcmaven.wpi.edu/artifactory/release/>

### 3.13.4 Shuffleboard

- Ignore whitespace and capitalization for remotely defined settings
- Components in grids can now have location specified remotely
- Upper and lower bounds on graph X and Y axis can now be manually specified
- Small numbers will properly be shown in number fields using scientific notation.
- Allow widget titles to be hidden
- Added a documentation link in the about dropdown

### 3.13.5 FRC Raspberry Pi Image

- Updated to work on Raspberry Pi 4
- Updated to use Raspbian Buster
- Added CPU temperature to system status screen

### 3.13.6 SmartDashboard

- Properly parses special characters in MJPEG urls

### 3.13.7 PathWeaver

- Updated to output WPILib splines
- Now shows an error alert when configuration screen is invalid

### 3.13.8 OutlineViewer

- Fixed the initial settings dialog (it was too small on some platforms)
- Fixed array editor

### 3.13.9 GradleRIO

- Fixed JRE slowdown when using `concat()` on Strings.
- Fixed JRE slowdown on garbage collection.

### 3.13.10 CScore

- Fixed cscore compatibility with OpenCV 4 (mainly useful for coprocessors)
- Fixed setting exposure on PS3eye cameras

### 3.13.11 WPILib All in One Installer

- Use `wplib\2020\` instead of `frc2020\`. This prevents cluttering the user's home directory when installing alongside previous years' installation.
- Fixed an issue where shortcuts would get created for installed tools, even if it was unchecked.
- Installing for **All Users** will now create shortcuts for all users, instead of only the current one.
- Update to latest Visual Studio Code and C++/Java extensions

### 3.13.12 Visual Studio Code Extension

- Added a 2019 to 2020 project importer
- Add a window for a simple way to grab all project information
- Add built in way to open and display API docs

### 3.13.13 RobotBuilder

- Use individual includes instead of `wplib.h` for C++
- Add export of `PWMSparkMax`, `PWMTalonFX`, `PWMVenom`
- Extensions are now stored in `~/wplib/2020/Robotbuilder/extensions`

- GUI for defining Command Groups was removed for maintainability reasons. Commands can be added in VS Code.

### 3.13.14 Robot Characterization

- Introduced the robot characterization toolsuite.

## 3.14 2020 Game Data Details

In the 2020 *FIRST*® Robotics Competition game, the Position Control objective requires alliances to select a specific color transmitted to them when specific pre-requisites have been met. The field will transmit the selected color to teams using Game Data. This page details the timing and structure of the sent data and provides examples of how to access it in the three supported programming languages.

### 3.14.1 The Data

#### Timing

Color assignment data is sent to both alliances simultaneously once the first alliance in a match has reached Capacity on Stage 3 of the Shield Generator (see the Game Manual for more complete details). Between the beginning of the match and this point, the Game Data will be an empty string.

#### Data format

The selected color for an alliance will be provided as a single character representing the color (i.e. 'R' = red, 'G' = green, 'B' = blue, 'Y' = yellow). This color indicates the color that must be placed underneath the Control Panel's color sensor in order to complete the Position Control objective (see the Game Manual for information about the location of the Control Panel sensor).

### 3.14.2 Accessing the Data

The data is accessed using the Game Data methods or VIs in each language. Below are descriptions and examples of how to access the data from each of the three languages. As the data is provided to the Robot during the Teleop period, teams will likely want to query the data in Teleop periodic code, or trigger reading it off a button press or other action after they have reached Stage 3 capacity.

#### C++/Java

In C++ and Java the Game Data is accessed by using the `GetGameSpecificMessage` method of the `DriverStation` class. Teams likely want to query the data in a Teleop method such as `Teleop Periodic` in order to receive the data after it is sent during the match. Make sure to

handle the case where the data is an empty string as this is what the data will be until the criteria are reached to enable Position Control for either alliance.

Java

```
import edu.wpi.first.wpilibj.DriverStation;

String gameData;
gameData = DriverStation.getInstance().getGameSpecificMessage();
if(gameData.length() > 0)
{
    switch (gameData.charAt(0))
    {
        case 'B' :
            //Blue case code
            break;
        case 'G' :
            //Green case code
            break;
        case 'R' :
            //Red case code
            break;
        case 'Y' :
            //Yellow case code
            break;
        default :
            //This is corrupt data
            break;
    }
} else {
    //Code for no data received yet
}
```

C++

```
#include <frc/DriverStation.h>

std::string gameData;
gameData = frc::DriverStation::GetInstance().GetGameSpecificMessage();
if(gameData.length() > 0)
{
    switch (gameData[0])
    {
        case 'B' :
            //Blue case code
            break;
        case 'G' :
            //Green case code
            break;
        case 'R' :
            //Red case code
            break;
        case 'Y' :
            //Yellow case code
            break;
        default :
            //This is corrupt data
            break;
    }
}
```

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```

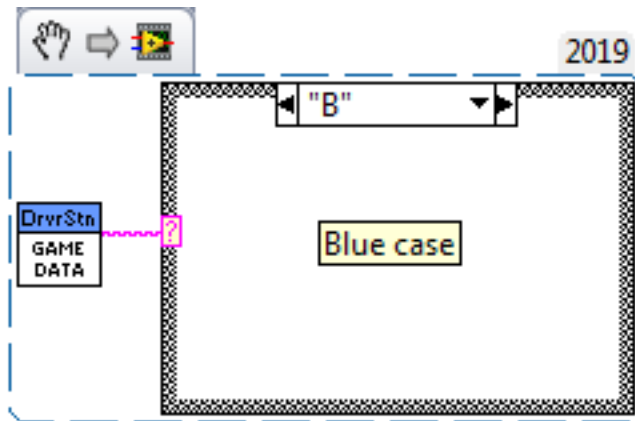
}
} else {
    //Code for no data received yet
}

```

## LabVIEW

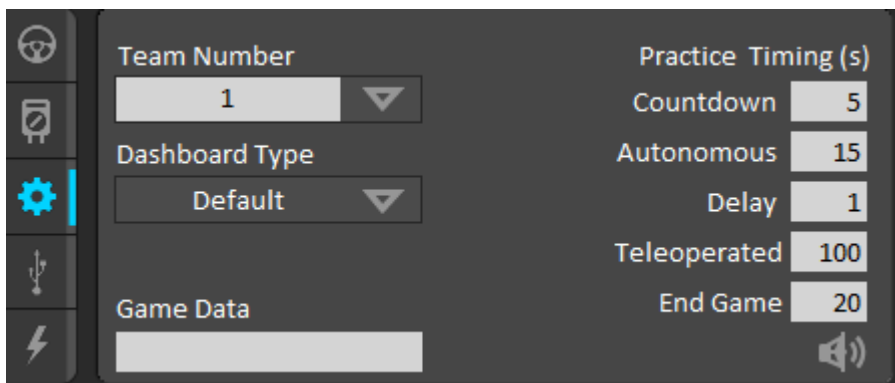
The Game Data in LabVIEW is accessed from the Game Specific Data VI. This VI can be found in the WPI Robotics Library -> Driver Station palette.

LabVIEW teams will likely want to query the data in the Teleop or PeriodicTasks VIs and may choose to gate the query behind a button press or other action. The code below reads the data and then uses a case structure to react differently to each of the 5 possible cases (empty, or any of the 4 letters).



### 3.14.3 Testing Game Specific Data

You can test your Game Specific Data code without FMS by using the Driver Station. Click on the Setup tab of the Driver Station, then enter the desired test string into the Game Data text field. The data will be transmitted to the robot in one of two conditions: Enable the robot in Teleop mode, or when the DS reaches the End Game time in a Practice Match (times are configurable on the Setup tab). It is recommended to run at least one match using the Practice functionality to verify that your code works correctly in a full match flow.



## FRC LabVIEW Programming

### 4.1 Creating Robot Programs

#### 4.1.1 Creating, Building and Loading your Benchtop Test Program



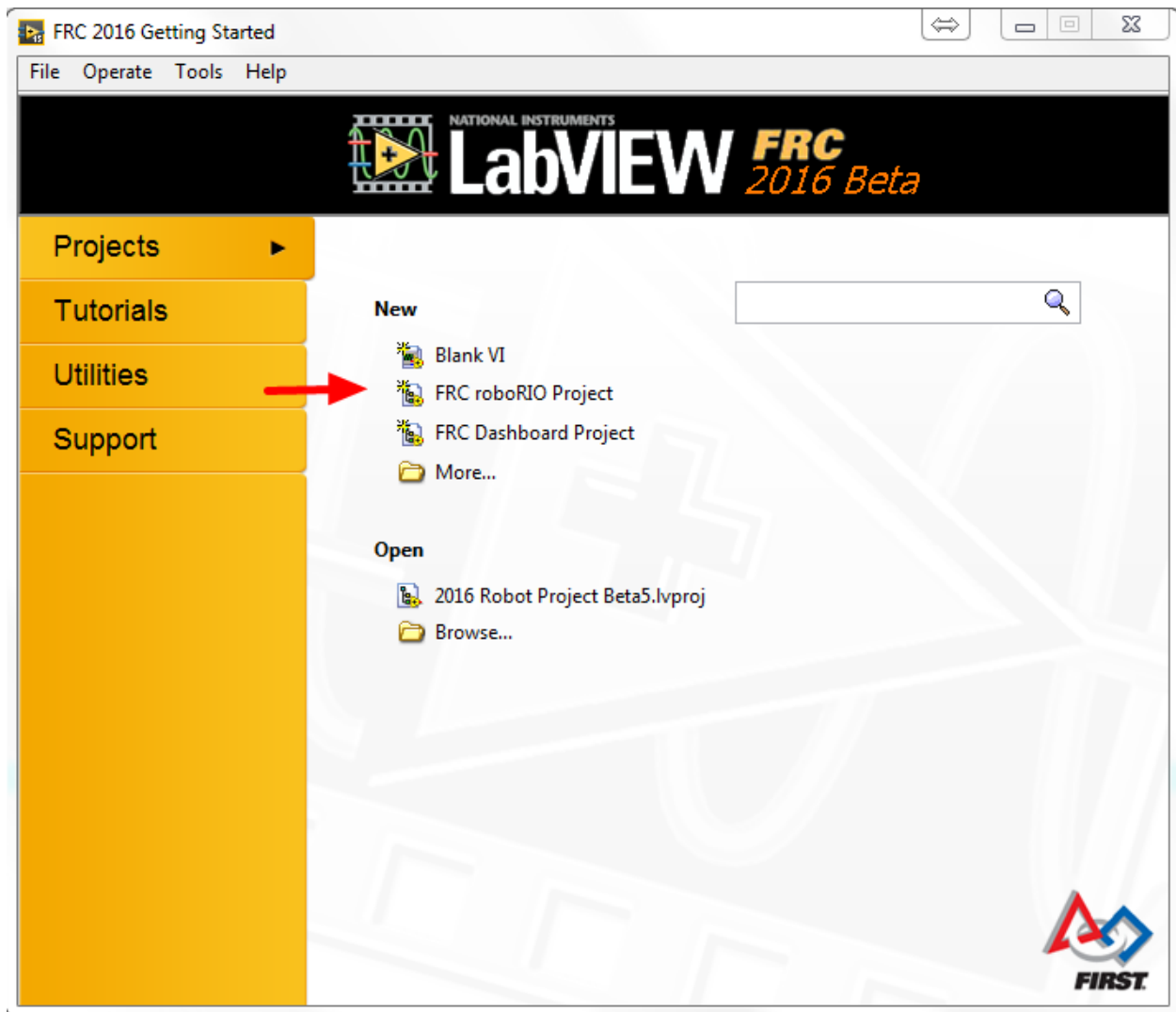
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**Note:** This document covers how to create, build and load an FRC LabVIEW program onto a roboRIO. Before beginning, make sure that you have installed LabVIEW for FRC and the FRC Driver Station and that you have configured and imaged your roboRIO as described in the *Getting Started with the Control System section*.

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#### Creating a Project

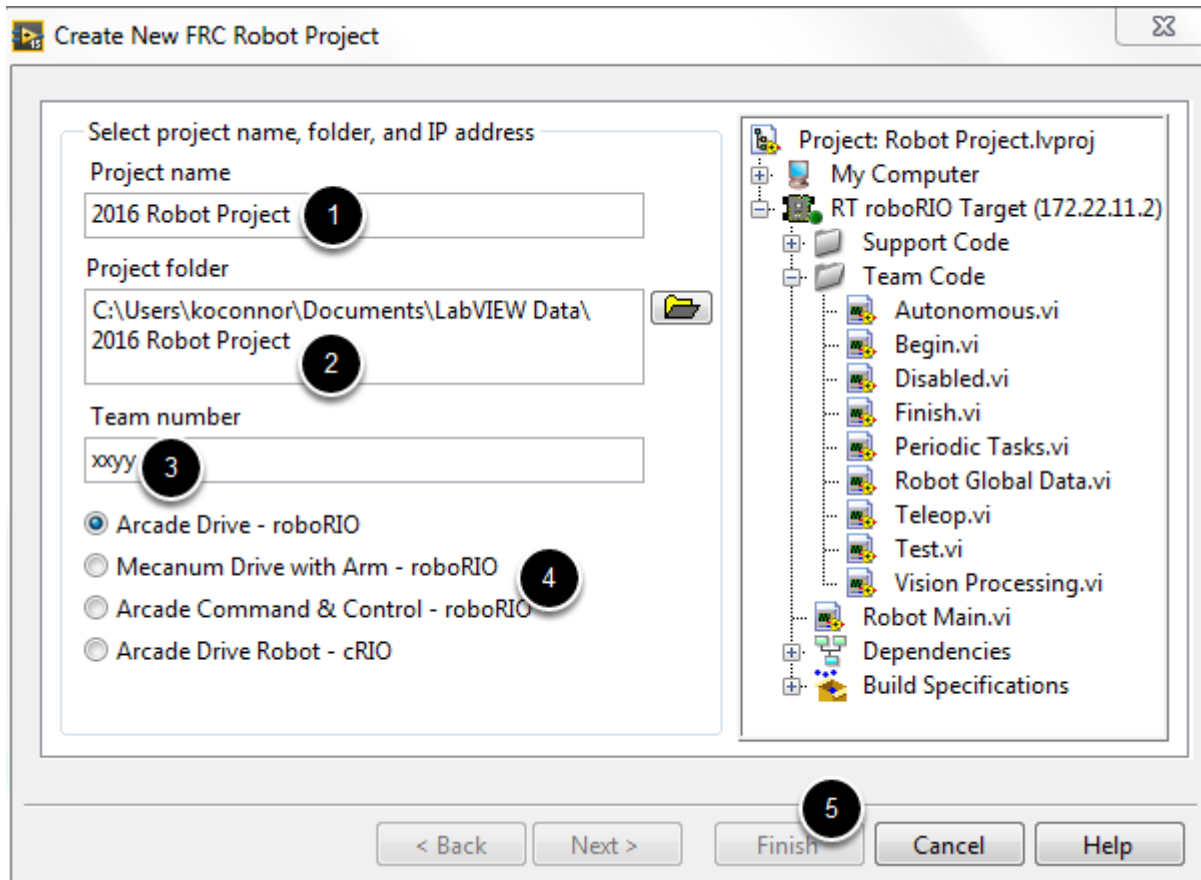
Launch LabVIEW and click the FRC roboRIO Robot Project link in the Projects window to display the Create New FRC Robot Project dialog box.



### Configuring Project

Fill in the Create New FRC Project Dialog:

1. Pick a name for your project
2. Select a folder to place the project in.
3. Enter your team number
4. Select a project type. If unsure, select Arcade Drive - roboRIO.
5. Click Finish

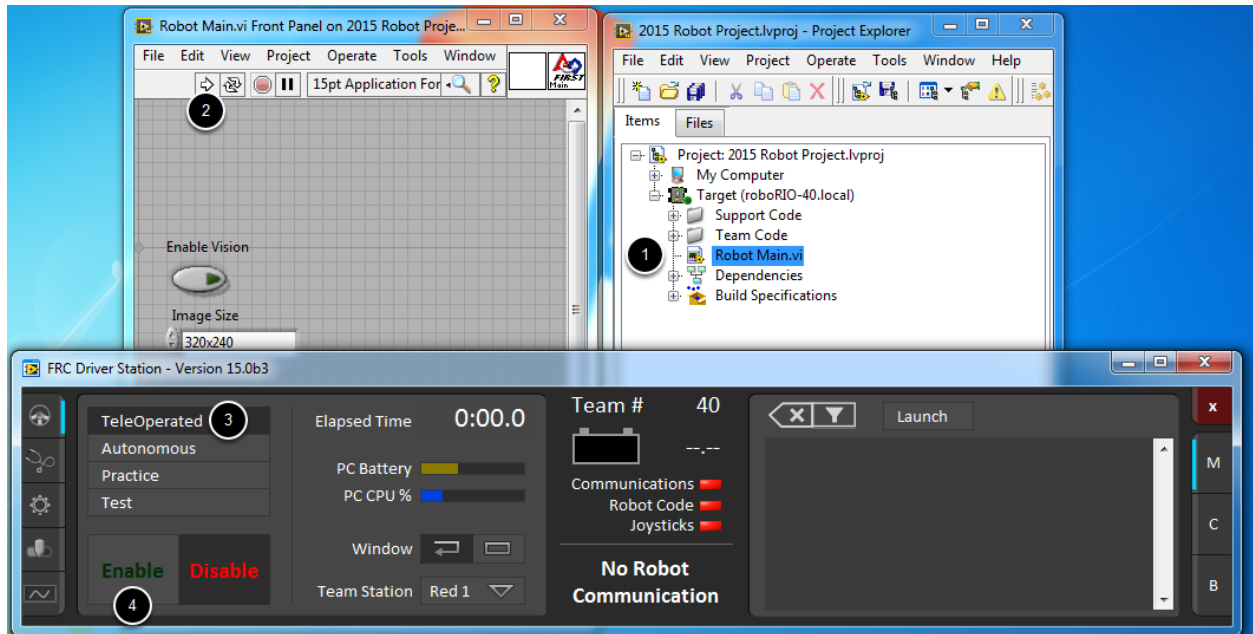


## Running the Program

**Note:** Note that a program deployed in this manner will not remain on the roboRIO after a power cycle. To deploy a program to run every time the roboRIO starts follow the next step, Deploying the program.

1. In the Project Explorer window, double-click the Robot Main.vi item to open the Robot Main VI.
2. Click the Run button (White Arrow on the top ribbon) of the Robot Main VI to deploy the VI to the roboRIO. LabVIEW deploys the VI, all items required by the VI, and the target settings to memory on the roboRIO. If prompted to save any VIs, click Save on all prompts.
3. Using the Driver Station software, put the robot in Teleop Mode. For more information on configuring and using the Driver Station software, see the FRC Driver Station Software article.
4. Click Enable.
5. Move the joysticks and observe how the robot responds.
6. Click the Abort button of the Robot Main VI. Notice that the VI stops. When you deploy a program with the Run button, the program runs on the roboRIO, but you can manipulate the front panel objects of the program from the host computer.

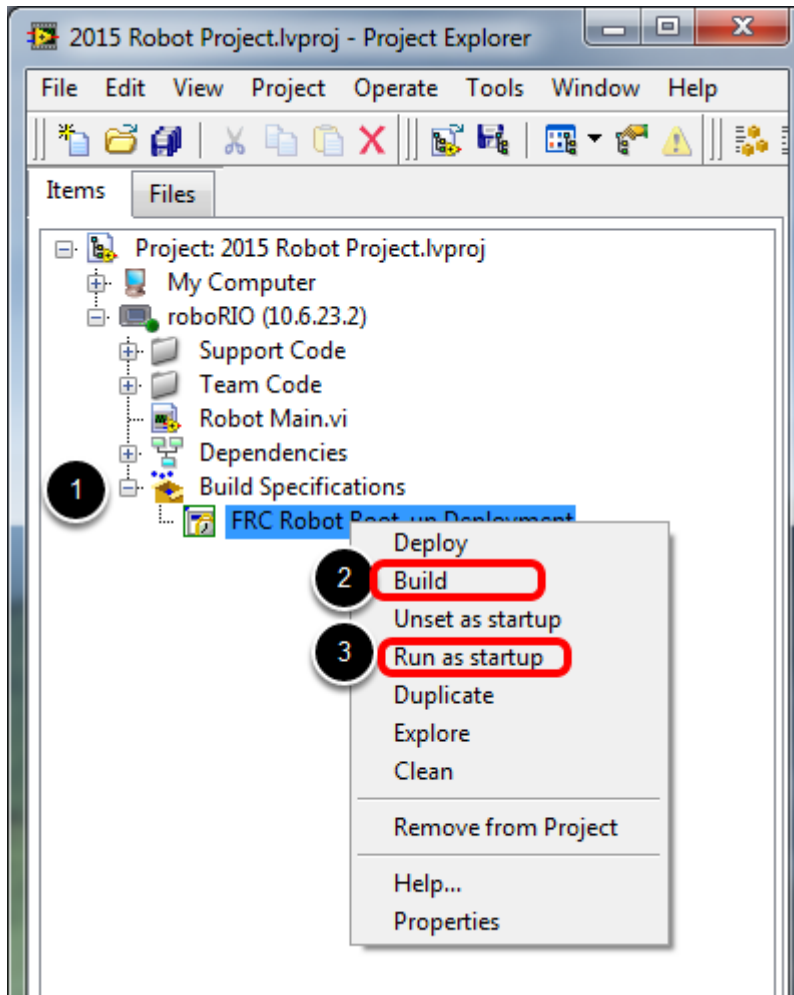




### Deploying the Program

To run in the competition, you will need to deploy a program to your roboRIO. This allows the program to survive across reboots of the controller, but doesn't allow the same debugging features (front panel, probes, highlight execution) as running from the front panel. To deploy your program:

1. In the Project Explorer, click the + next to Build Specifications to expand it.
2. Right-click on FRC Robot Boot-up Deployment and select Build. Wait for the build to complete.
3. Right-click again on FRC Robot Boot-Up Deployment and select Run as Startup. If you receive a conflict dialog, click OK. This dialog simply indicates that there is currently a program on the roboRIO which will be terminated/replaced.
4. Either check the box to close the deployment window on successful completion or click the close button when the deployment completes.
5. The roboRIO will automatically start running the deployed code within a few seconds of the dialog closing.



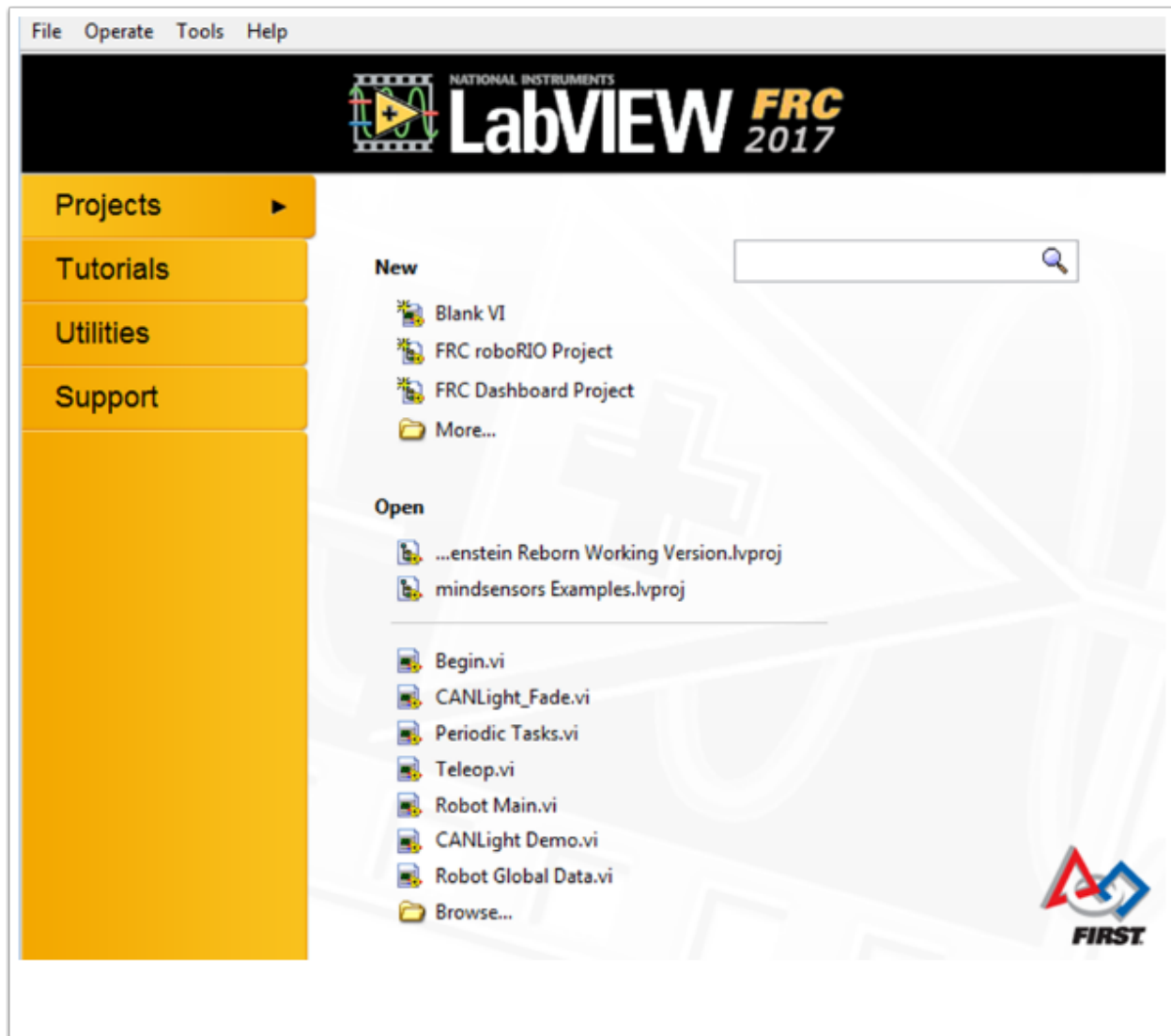
#### 4.1.2 Tank Drive Tutorial



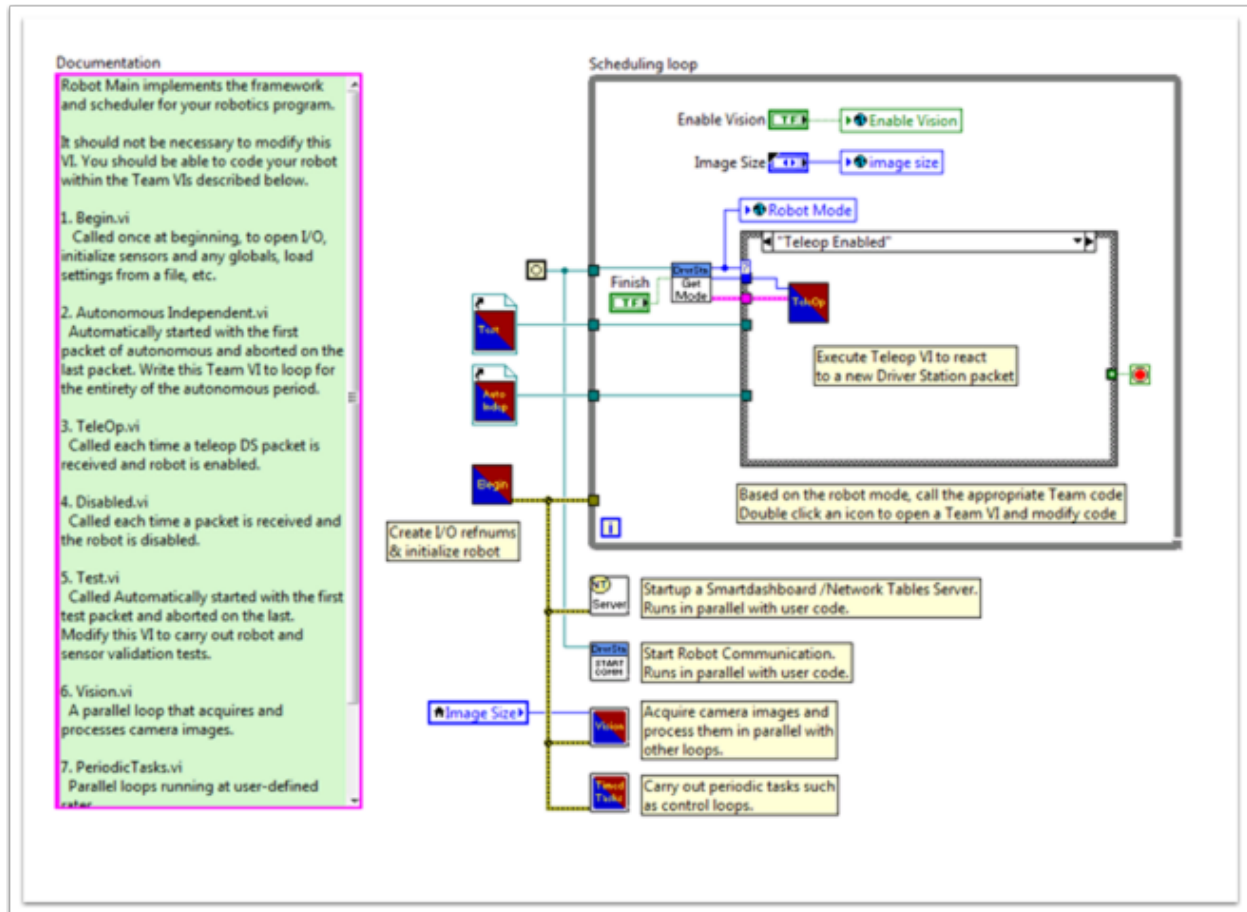
**Question:** How do I get my robot to drive with two joysticks using tank drive?

**Solution:** There are four components to consider when setting up tank drive for your robot. The first thing you will want to do is make sure the tank drive.vi is used instead of the arcade drive.vi or whichever drive VI you were utilizing previously. The second item to consider is how you want your joysticks to map to the direction you want to drive. In tank drive, the left joystick is used to control the left motors and the right joystick is used to control the right motors. For example, if you want to make your robot turn right by pushing up on the left joystick and down on the right joystick you will need to set your joystick's accordingly in LabVIEW (this is shown in more detail below). Next, you will want to confirm the PWM lines that you are wired into, are the same ones your joysticks will be controlling. Lastly, make sure your motor controllers match the motor controllers specified in LabVIEW. The steps below will discuss these ideas in more detail:

1. Open LabVIEW and double click FRC roboRIO Project.

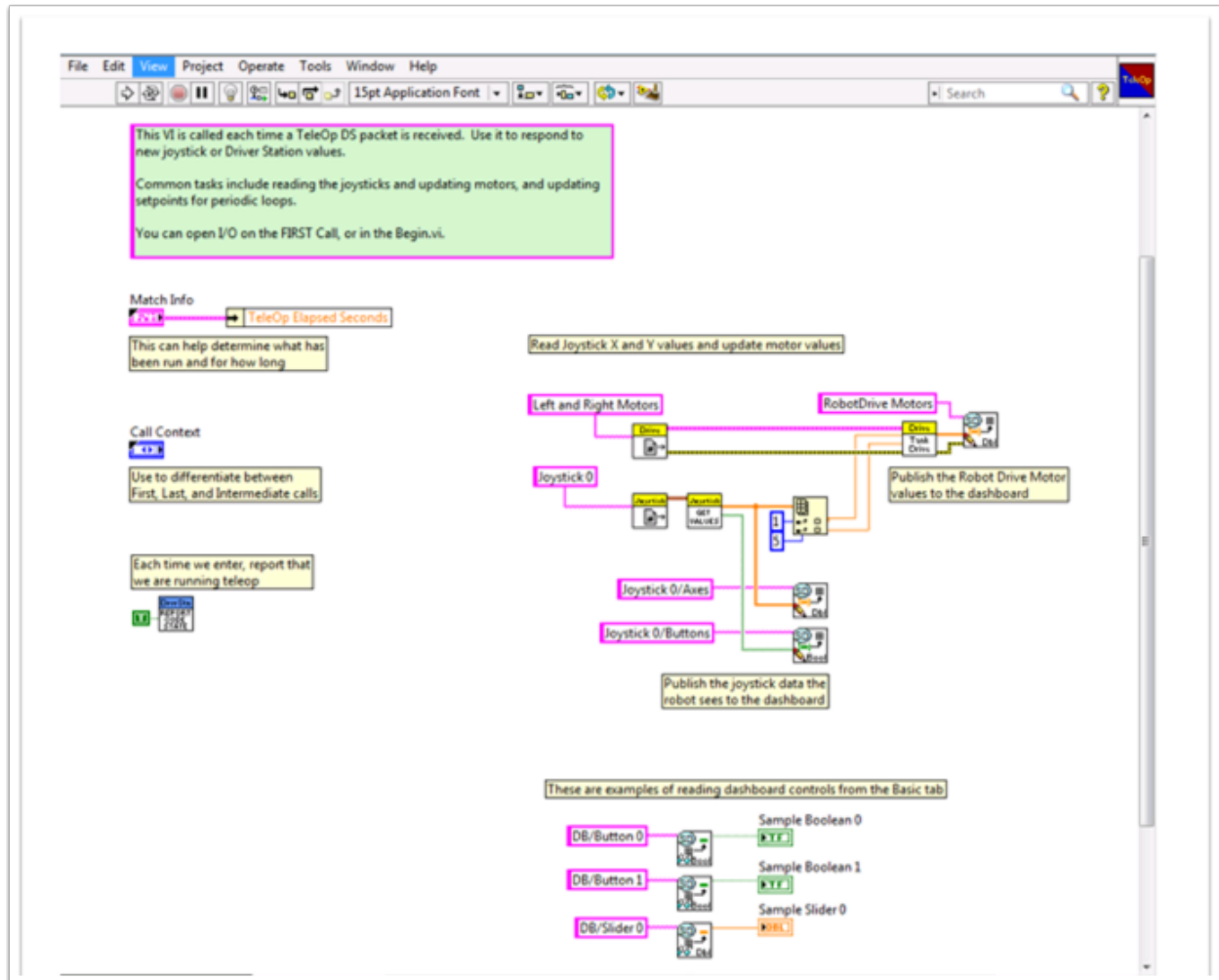


2. Give your project a name, add your team number, and select Arcade Drive Robot roboRIO. You can select another option, however, this tutorial will discuss how to setup tank drive for this project.
3. In the Project Explorer window, open up the Robot Main.vi.
4. Push Ctrl + E to see the block diagram. It should look like the following image:



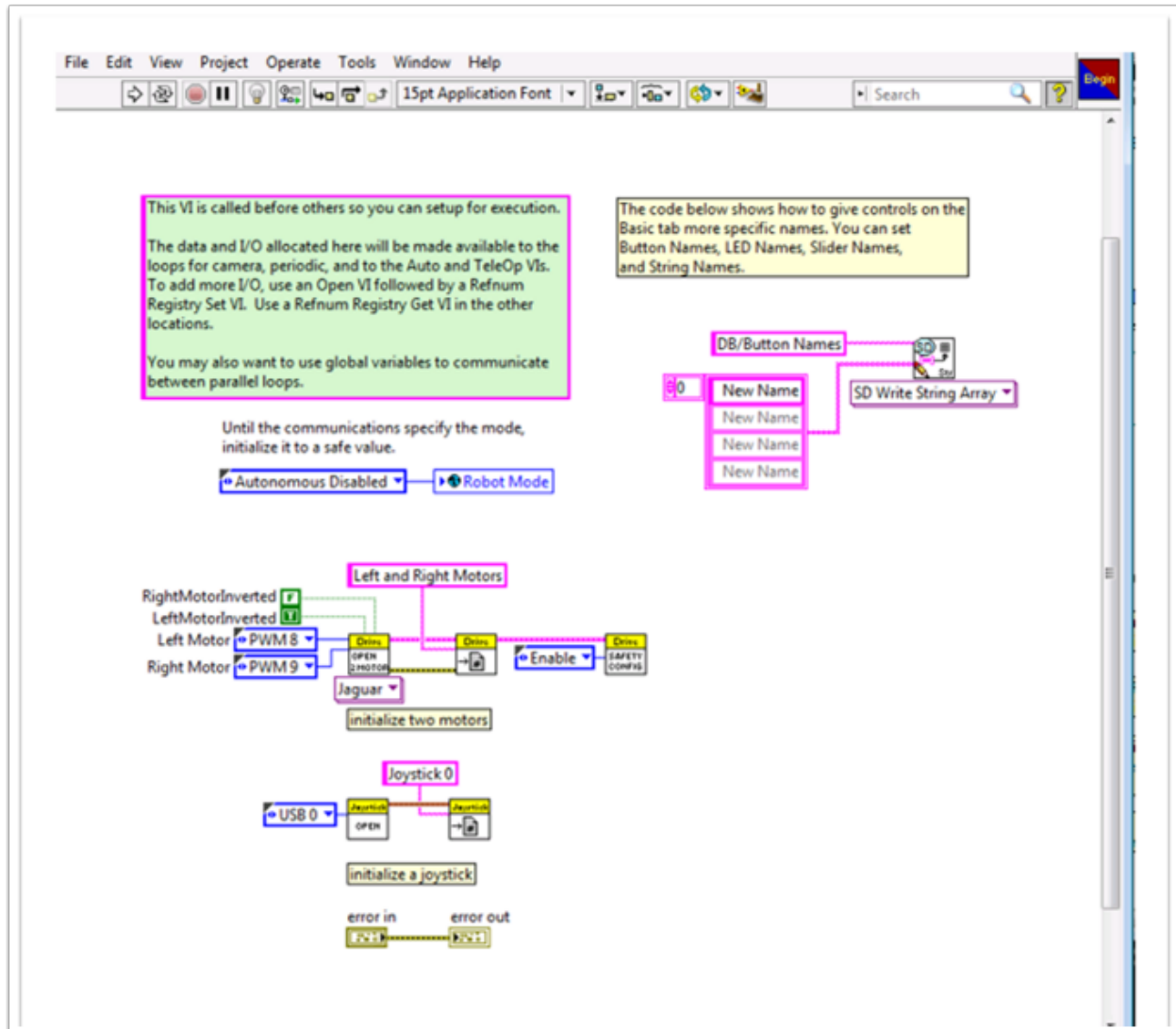
5. Double click the “Teleop” vi inside of the Teleop Enabled case structure. Look at its block diagram. You will want to make two changes here:

- Replace Arcade Drive with the tank drive.vi. This can be found by right clicking on the block diagram >> WPI Robotics Library >> Robot Drive >> and clicking the Tank Drive VI.
- Find the Index Array function that is after the Get Values.vi. You will need to create two numeric constants and wire each into one of the index inputs. You can determine what the values of each index should be by looking at the USB Devices tab in the FRC Driver Station. Move the two joysticks to determine which number (index) they are tied to. You will likely want to use the Y-axis index for each joystick. This is because it is intuitive to push up on the joystick when you want the motors to go forward, and down when you when them to go in reverse. If you select the X-axis index for each, then you will have to move the joystick left or right (x-axis directions) to get the robot motors to move. In my setup, I’ve selected index 1 for my left motors Y-axis control and index 5 as the right motors Y-axis control. You can see the adjustments in LabVIEW in the following image:



6. Next you will want to go back to your “Robot Main.vi” and double click on the “Begin.vi.”
7. The first thing to confirm in this VI is that your left and right motors are connected to the same PWM lines in LabVIEW as they are on your PDP (Power Distribution Panel).
8. The second thing to confirm in this VI is that the “Open 2 Motor.vi” has the correct motor controller selected (Talon, Jaguar, Victor, etc.).

For example, I am using Jaguar motor controllers and my motors are wired into PWM 8 and 9. The image below shows the changes I need to make:



9. Save all of the Vis that you have made adjustments to and you are now able to drive a robot with tank drive!

### 4.1.3 Command and Control Tutorial



#### Introduction

Command and Control is a new LabVIEW template added for the 2016 season which organizes robot code into commands and controllers for a collection of robot-specific subsystems. Each subsystem has an independent control loop or state machine running at the appropriate rate

for the mechanism and high-level commands that update desired operations and set points. This makes it very easy for autonomous code to build synchronous sequences of commands. Meanwhile, TeleOp benefits because it can use the same commands without needing to wait for completion, allowing for easy cancellation and initiation of new commands according to the drive team input. Each subsystem has a panel displaying its sensor and control values over time, and command tracing to aid in debugging.

### What is Command and Control?

Command and Control recognizes that FRC robots tend to be built up of relatively independent mechanisms such as Drive, Shooter, Arm, etc. Each of these is referred to as a subsystem and needs code that will coordinate the various sensors and actuators of the subsystem in order to complete requested commands, or actions, such as “Close Gripper” or “Lower Arm”. One of the key principles of this framework is that subsystems will each have an independent controller loop that is solely responsible for updating motors and other actuators. Code outside of the subsystem controller can issue commands which may change the robot’s output, but should not directly change any outputs. The difference is very subtle but this means that outputs can only possibly be updated from one location in the project. This speeds up debugging a robot behaving unexpectedly by giving you the ability to look through a list of commands sent to the subsystem rather than searching your project for where an output may have been modified. It also becomes easier to add an additional sensor, change gearing, or disable a mechanism without needing to modify code outside of the controller.

Game code, primarily consisting of Autonomous and TeleOp, will typically need to update set points and react to the state of certain mechanisms. For Autonomous, it is very common to define the robot’s operation as a sequence of operations – drive here, pick that up, carry it there, shoot it, etc. Commands can be wired sequentially with additional logic to quickly build complex routines. For teleOp, the same commands can execute asynchronously, allowing the robot to always process the latest driver inputs, and if implemented properly, new commands will interrupt, allowing the drive team to quickly respond to field conditions while also taking advantage of automated commands and command sequences.

### Why should I use Command and Control?

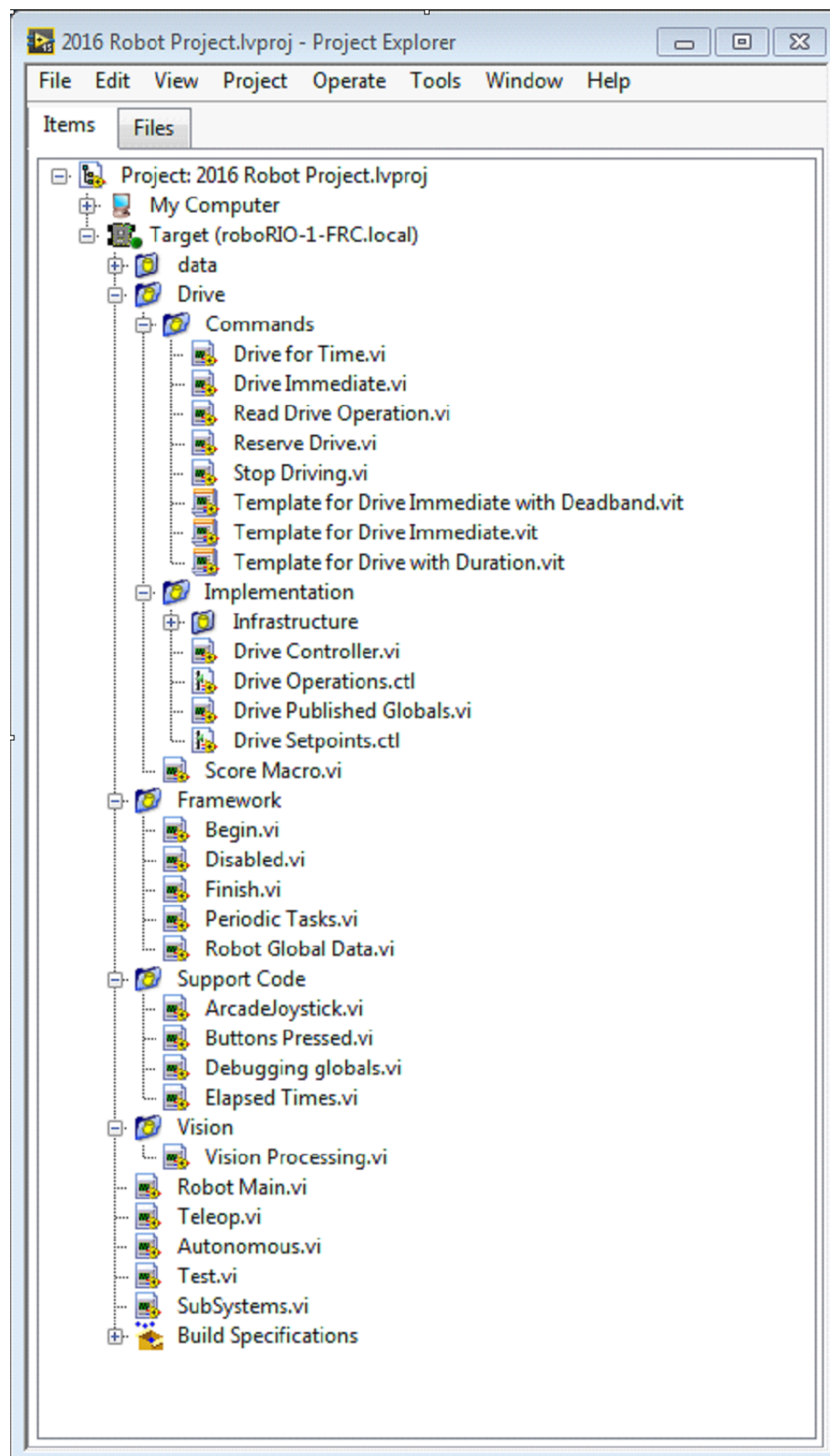
Command and Control adds functionality to the existing LabVIEW project templates, allowing code to scale better with more sophisticated robots and robot code. Subsystems are used to abstract the details of the implementation, and game code is built from sequences of high level command VIs. The commands themselves are VIs that can update set points, perform numerical scaling/mapping between engineering units and mechanism units, and offer synchronization options. If physical changes are made to the robot, such as changing a gearing ratio, changes can be made to just a few command VIs to reflect this change across the entire code base.

I/O encapsulation makes for more predictable operation and quicker debugging when resource conflicts do occur. Because each command is a VI, you are able to single step through commands or use the built in Trace functionality to view a list of all commands sent to each subsystem. The framework uses asynchronous notification and consistent data propagation making it easy to program a sequence of commands or add in simple logic to determine the correct command to run.

## **Part 1: Project Explorer**

The Project Explorer provides organization for all of the Vis and files you will use for your robot system. Below is a description of the major components in the Project Explorer to help with the expansion of our system. The most frequently used items have been bolded.





**My Computer** The items that define operation on the computer that the project was loaded on. For a robot project, this is used as a simulation target and is populated with simulation files.

**Sim Support Files** The folder containing 3D CAD models and description files for the simulated robot.

**Robot Simulation Readme.html** Documents the PWM channels and robot info you will need in order to write robot code that matches the wiring of the simulated robot.

**Dependencies** Shows the files used by the simulated robot's code. This will populate when you designate the code for the simulated robot target.

**Build Specifications** This will contain the files that define how to build and deploy code for the simulated robot target.

**Target (roboRIO-TEAM-FRC.local)** The items that define operation on the roboRIO located at (address).

**Drive** The subsystem implementation and commands for the robot drive base. This serves as a custom replacement for the WPILib RobotDrive VIs.

**Framework** VIs used for robot code that is not part of a subsystem that are not used very often.

**Begin** Called once when robot code first starts. This is useful for initialization code that doesn't belong to a particular subsystem.

**Disabled** Called once for each disabled packet and can be used to debug sensors when you don't want the robot to move.

**Finish** During development, this may be called when robot code finishes. Not called on abort or when power is turned off.

**Periodic Tasks** A good place for ad hoc periodic loops for debugging or monitoring

**Robot Global Data** Useful for sharing robot information that doesn't belong to a subsystem.

**Support Code** Debugging and code development aids.

**Vision** Subsystem and commands for the camera and image processing.

**Robot Main.vi** Top level VI that you will run while developing code.

**Autonomous.vi** VI that runs during autonomous period.

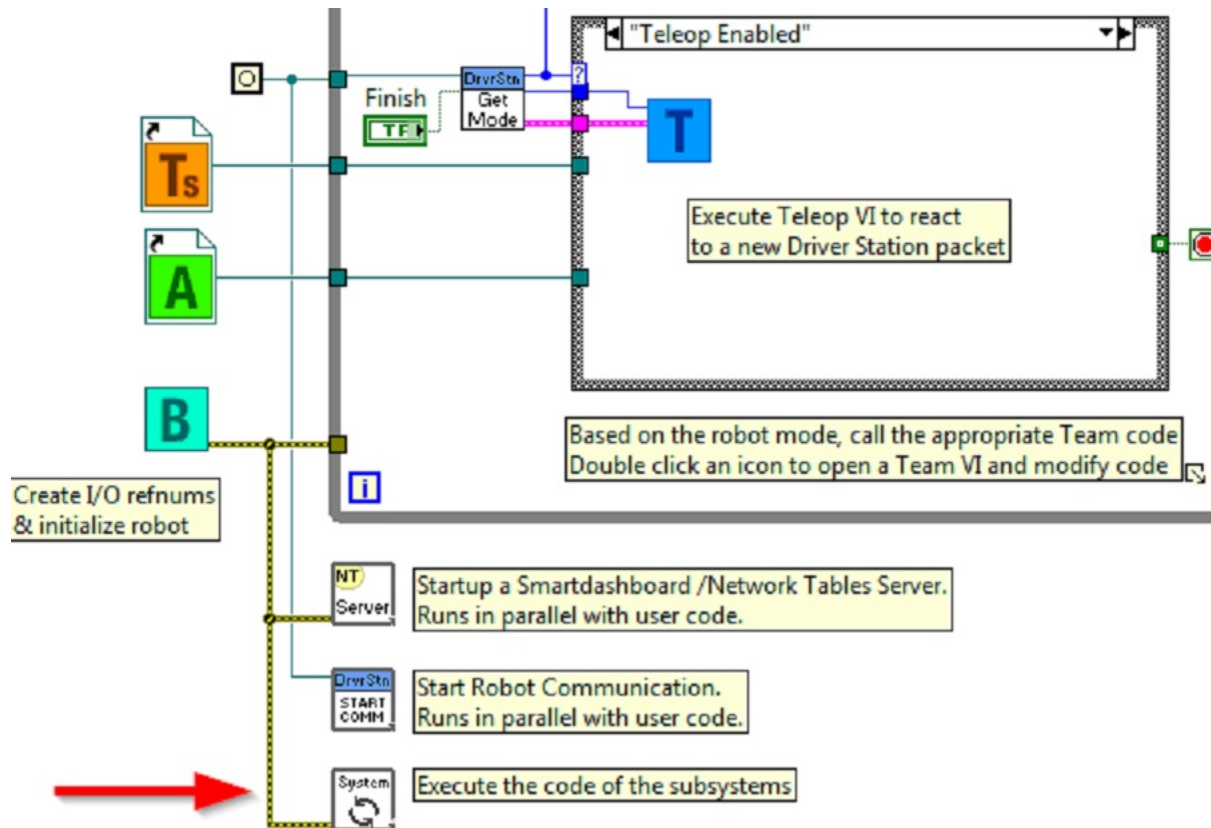
**Teleop.vi** VI that is called for each TeleOp packet.

**Test.vi** VI that runs when driver station is in test mode.

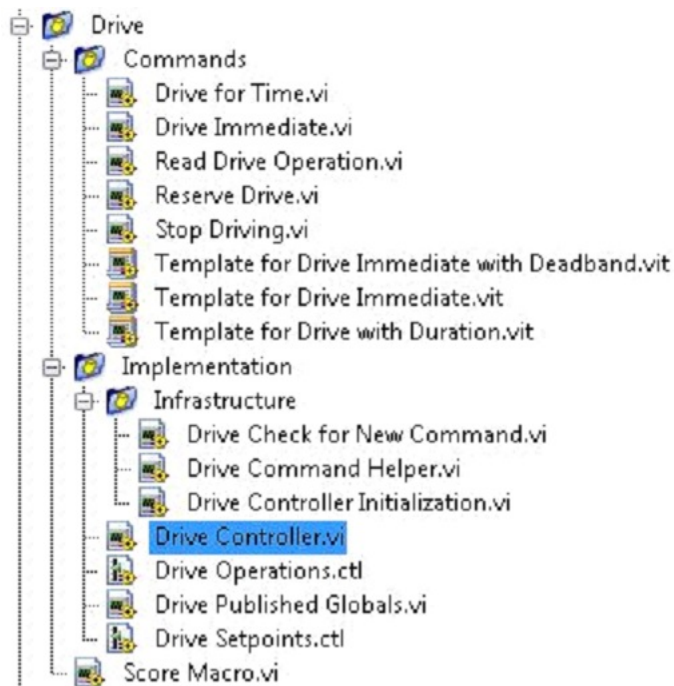
**SubSystems.vi** VI that contains and starts all subsystems.

**Dependencies** Shows the files used by the robot code.

**Build Specifications** Used to build and run the code as a startup application once code works correctly.



## Drive Subsystem Project Explorer



**Commands:** This folder contains the command VIs that request the controller carry out an

operation. It also contains templates for creating additional drive commands.

---

**Note:** After creating a new command, you may need to edit `Drive Setpoints.ctl` to add or update fields that controller uses to define the new operation. You also need to go into the `Drive Controller.vi` and modify the case structure to add a case for every value.

---

## Implementation

These are the VIs and Controls used to build the subsystem.

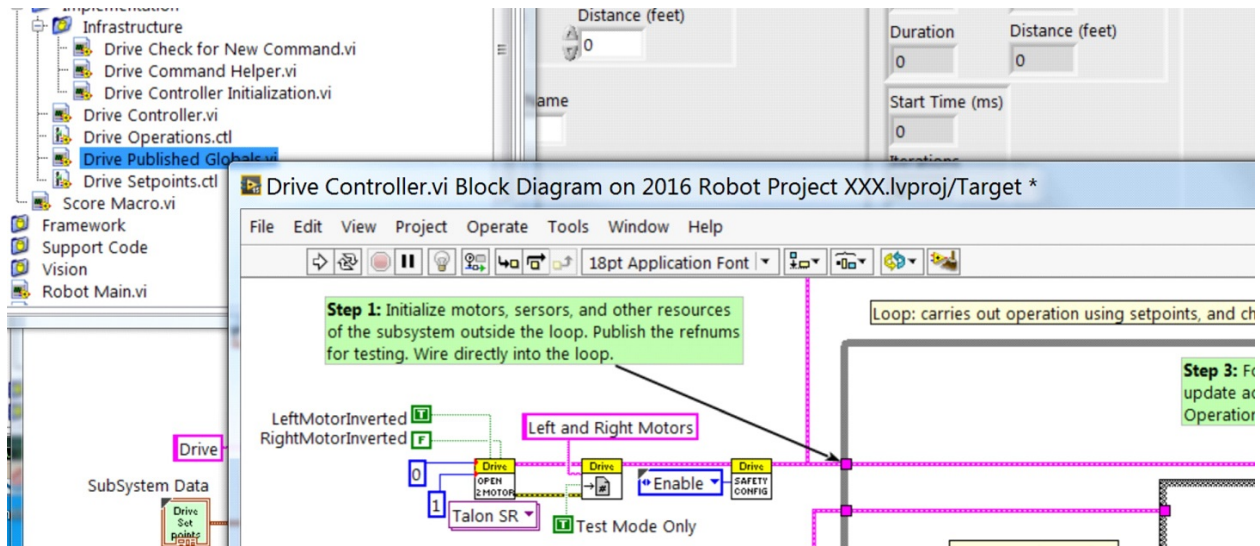
### Infrastructure VIs

- **Drive Check for New Command:** It is called each iteration of the controller loop. It checks for new commands, updates timing data, and upon completion notifies a waiting command.
- **Drive Command Helper.vi:** Commands call this VI to notify the controller that a new command has been issued.
- **Drive Controller Initialization.vi:** It allocates the notifier and combines the timing, default command, and other information into a single data wire.
- **Drive Controller.vi:** This VI contains the control/state machine loop. The panel may also contain displays useful for debugging.
- **Drive Operation.ctl:** This typedef defines the operational modes of the controller. Many commands can share an operation.
- **Drive Setpoint.ctl:** It contains the data fields used by all operating modes of the Drive subsystem.
- **Drive Published Globals.vi:** A useful place for publishing global information about the drive subsystem.

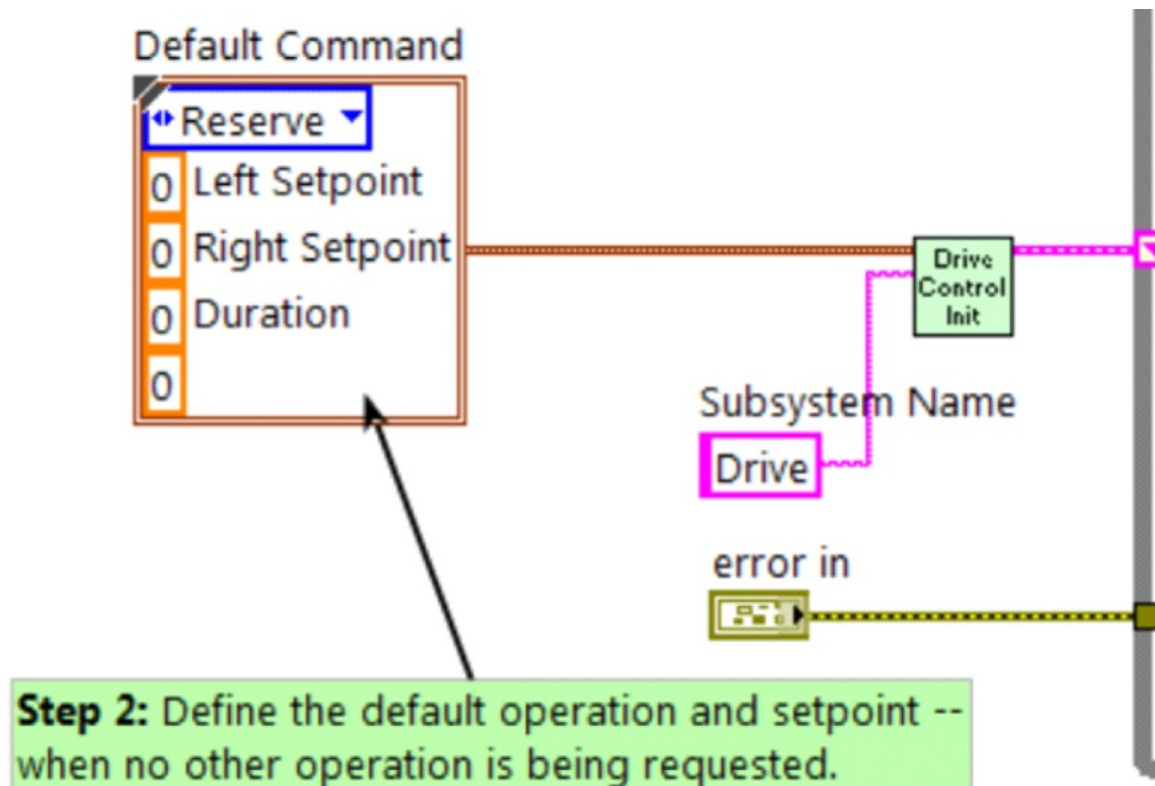
## Part 2: Initializing the Drive Subsystem

There are green comments on the controller's block diagram that point out key areas that you will want to know how to edit.

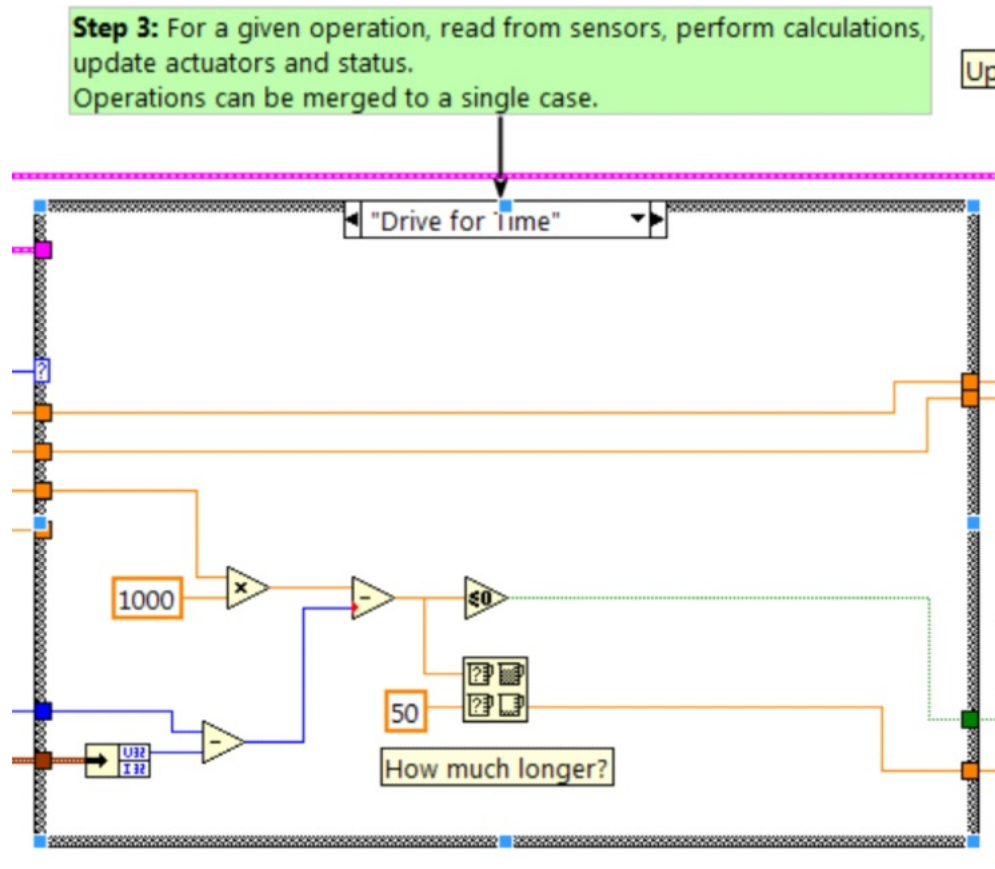
The area to the left of the control loop will execute once when the subsystem starts up. This is where you will typically allocate and initialize all I/O and state data. You may publish the I/O refs, or you may register them for Test Mode Only to keep them private so that other code cannot update motors without using a command.



**Note:** Initializing the resources for each subsystem in their respective Controller.vi rather than in Begin.vi improves I/O encapsulation, reducing potential resource conflicts and simplifies debugging.



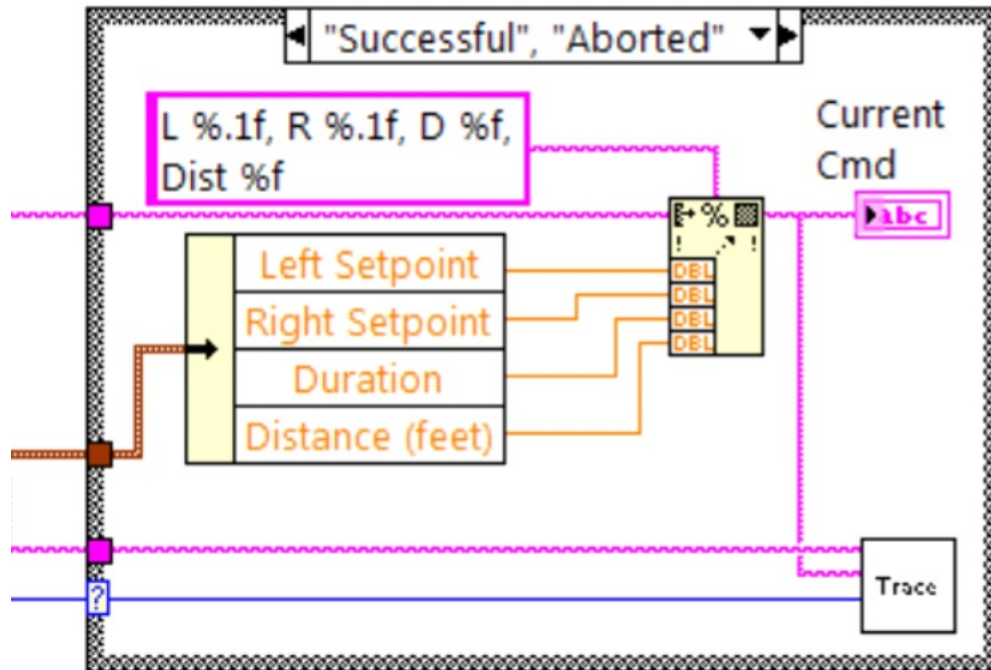
Part of the initialization is to select the default operation and set point values when no other operation is being processed.



Inside the control loop is a case statement where operations are actually implemented. Set point values, iteration delay, iteration count, and sensors can all have influence on how the subsystem operates. This case structure has a value for each operation state of the subsystem.



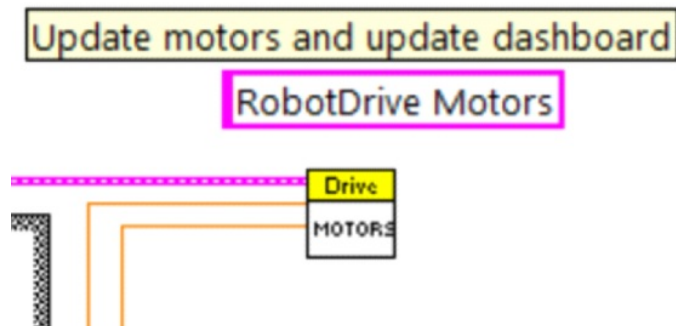
### Step 4: Format a string to describe this cmd and how the previous cmd finished



Each iteration of the controller loop will optionally update the Trace VI. The framework already incorporates the subsystem name, operation, and description, and you may find it helpful to format additional set point values into the trace information. Open the Trace VI and click Enable while the robot code is running to current setpoints and commands sent to each subsystem.

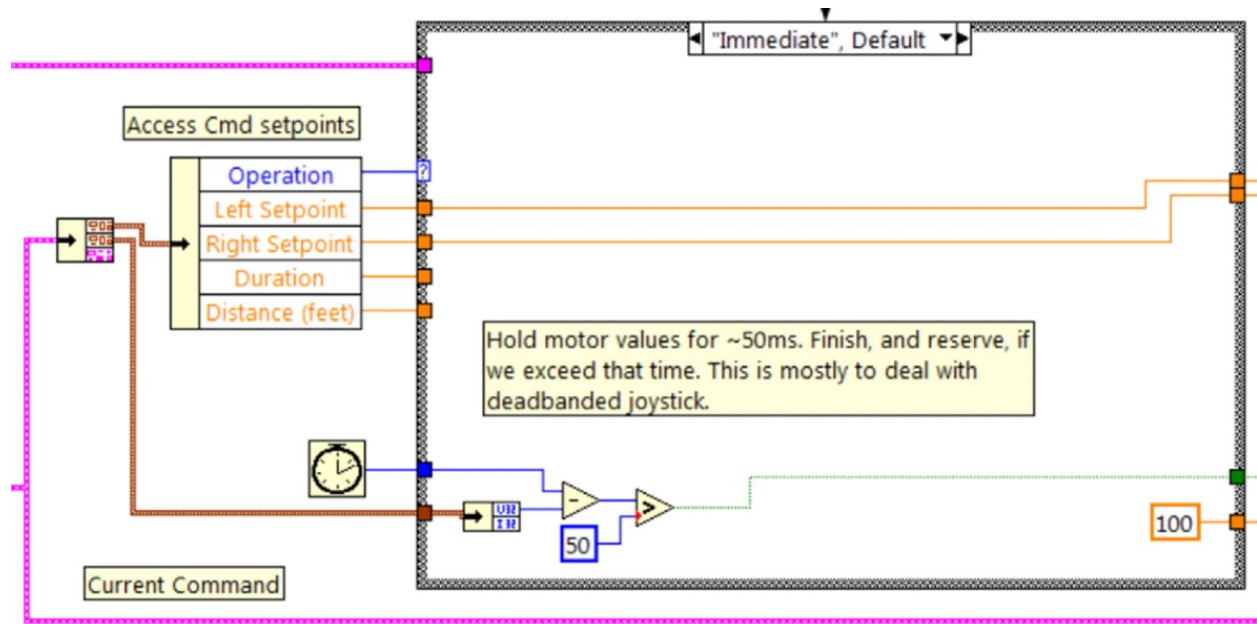
The primary goal of the controller is to update actuators for the subsystem. This can occur within the case structure, but many times, it is beneficial to do it downstream of the structure to ensure that values are always updated with the correct value and in only one location in the code.

### Step 5: Update your I/O





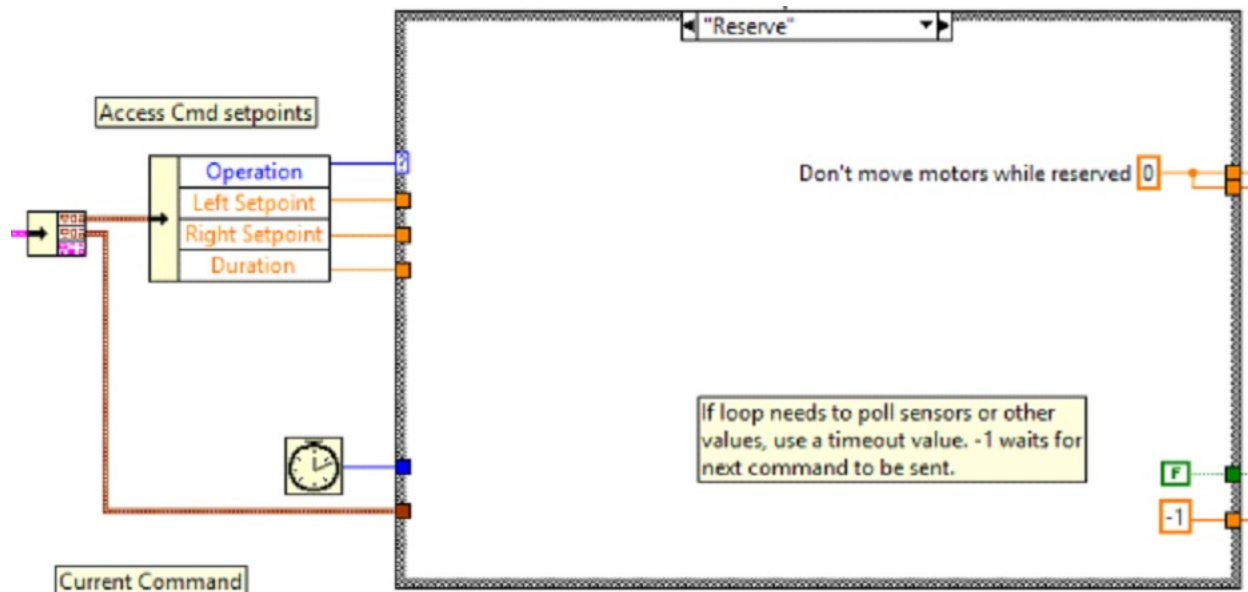




## Stop Driving.vi

Zero the drive motors, making the robot stationary.

The Reserve command turns off the motors and waits for a new command. When used with a named command sequence, reserve identifies that the drive subsystem is part of a sequence, even if not currently moving the robot. This helps to arbitrate subsystem resource between simultaneously running commands.

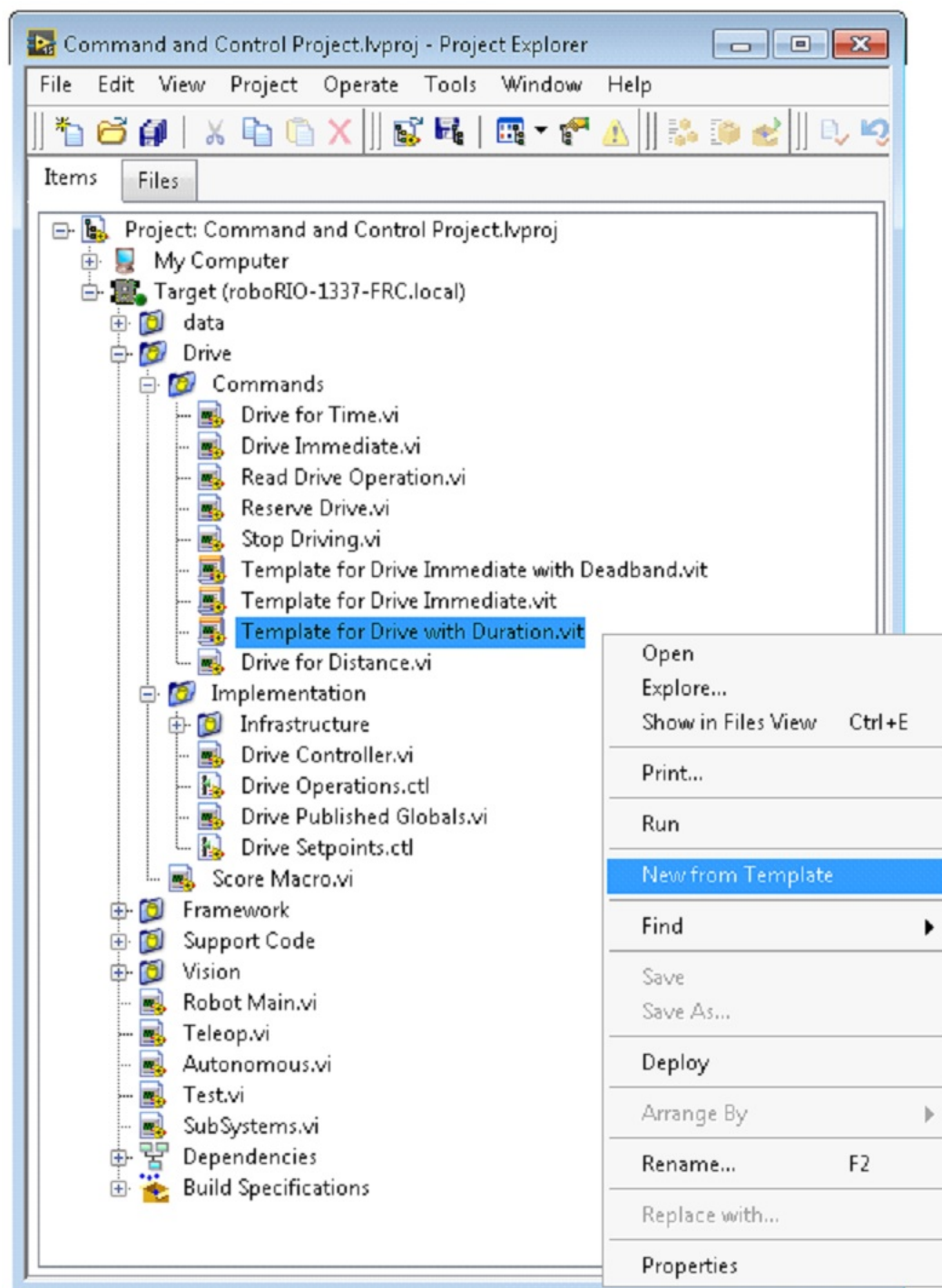


## Part 4: Creating New Commands

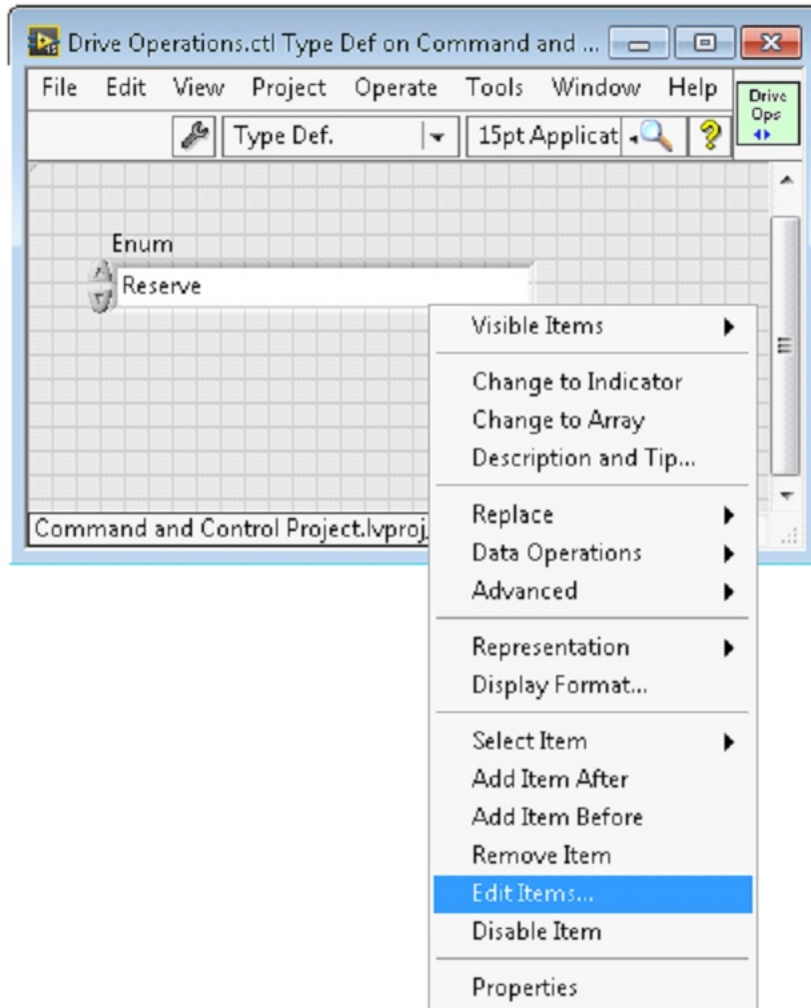
The Command and Control framework allows users to easily create new commands for a subsystem. To Create a new command open the subsystem folder/Commands In the project explorer window, choose one of the VI Templates to use as the starting point of your new command, right click, and select New From Template.

- **Immediate:** This VI notifies the subsystem about the new setpoint.
- **Immediate with deadband:** This VI compares the input value to the deadband and optionally notifies the subsystem about the new setpoint. This is very useful when joystick continuous values are being used.
- **With duration:** This VI notifies the subsystem to perform this command for the given duration, and then return to the default state. Synchronization determines whether this VI Starts the operation and returns immediately, or waits for the operation to complete. The first option is commonly used for TeleOp, and the second for Autonomous sequencing.

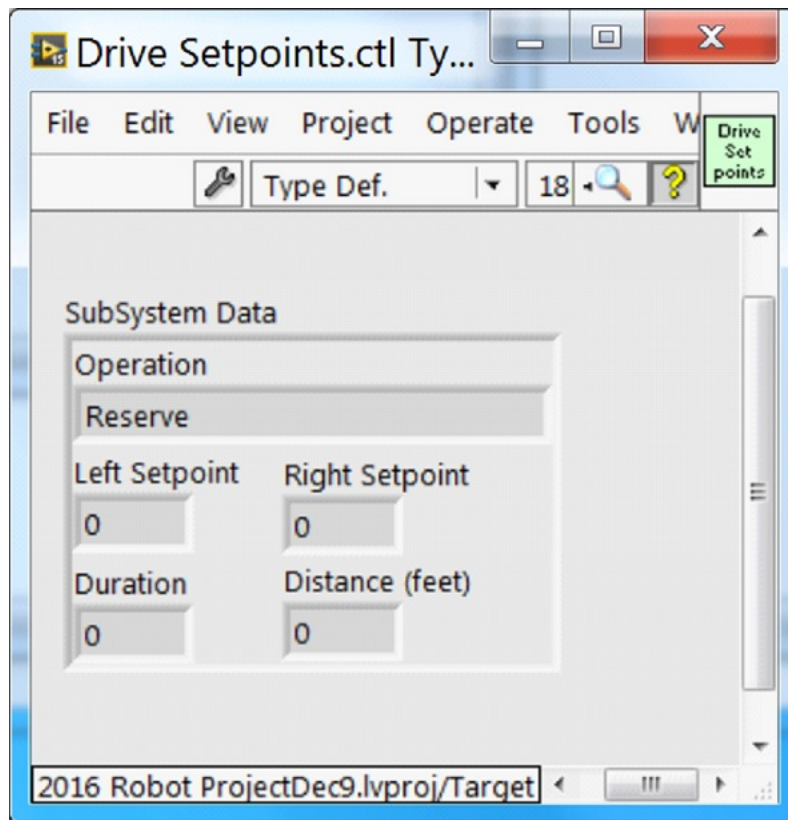
In this example we will add the new command “Drive for Distance”.



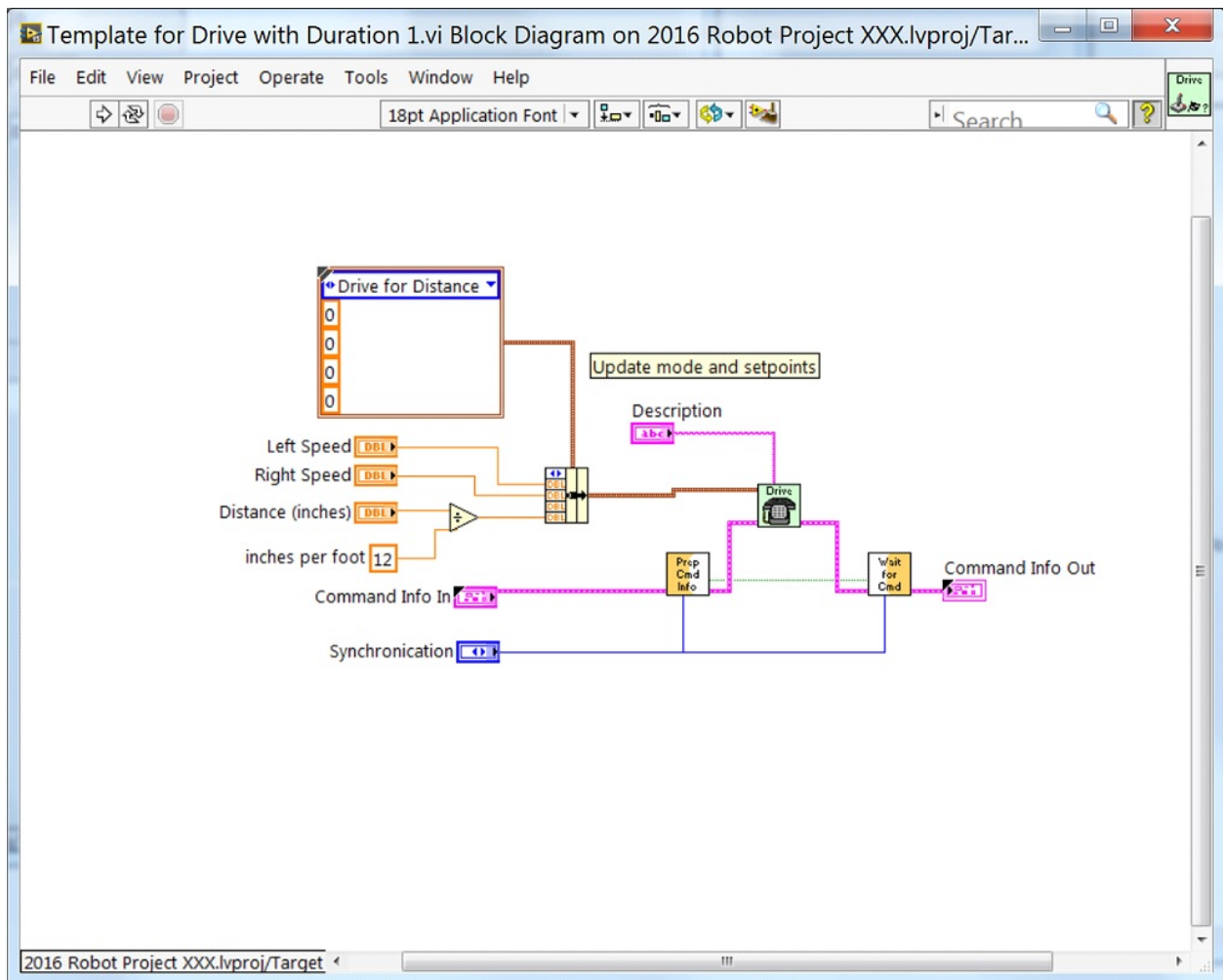
First, save the new VI with a descriptive name such as “Drive for Distance”. Next, determine whether the new command needs a new value added the Drive Operations enum typedef. The initial project code already has an enum value of Drive for Distance, but the following image shows how you would add one if needed.



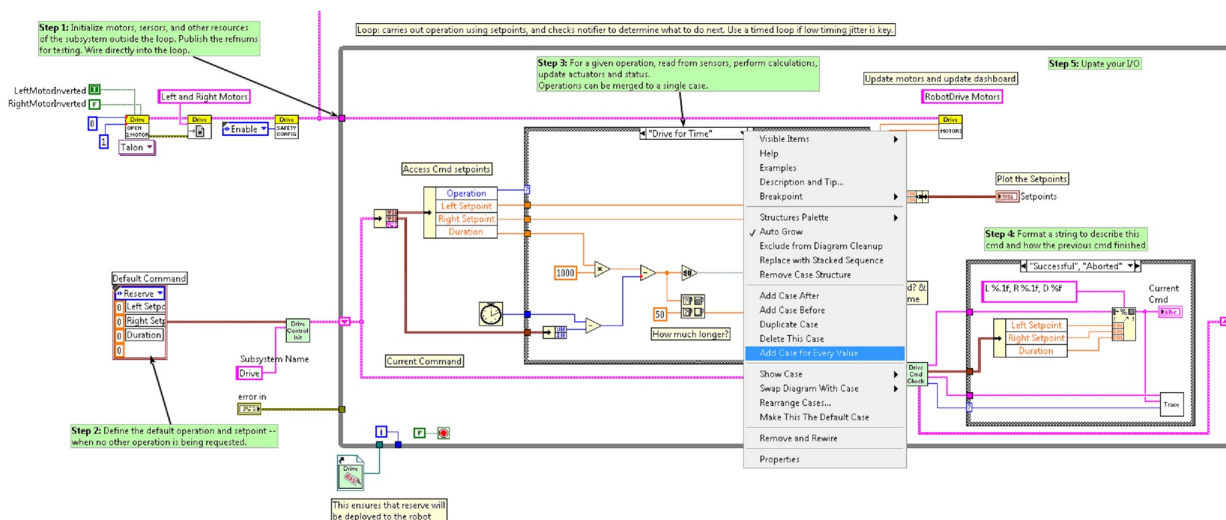
If a command needs additional information to execute, add it to the setpoints control. By default, the Drive subsystem has fields for the Left Setpoint, Right Setpoint, and Duration along with the operation to be executed. The Drive for Distance command could reuse Duration as distance, but let's go ahead and add a numeric control to the Drive Setpoints.ctl called Distance (feet).



Once that we have all of the fields needed to specify our command, we can modify the newly created Drive for Distance.vi. As shown below, select Drive for Distance from the enum's drop down menu and add a VI parameters to specify distance, speeds, etc. If the units do not match, the command VI is a great place to map between units.



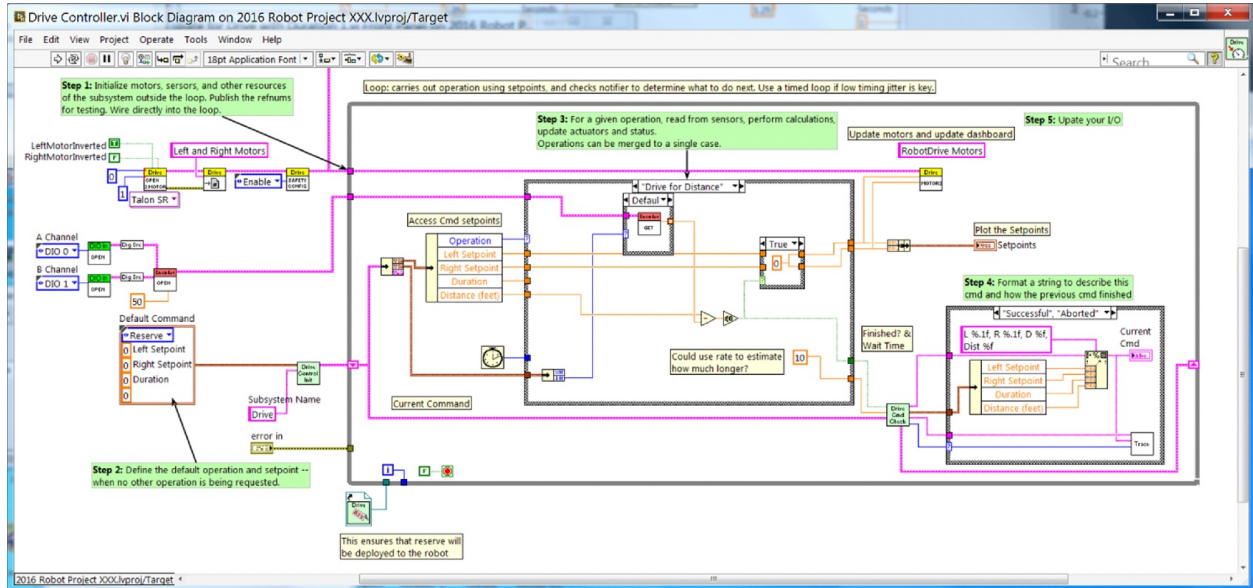
Next, add code to the Drive Controller to define what happens when the Drive for Distance command executes. Right click on the Case Structure and Duplicate or Add Case for Every Value. This will create a new “Drive for Distance” case.



In order to access new setpoint fields, grow the “Access Cmd setpoints” unbundle node. Open

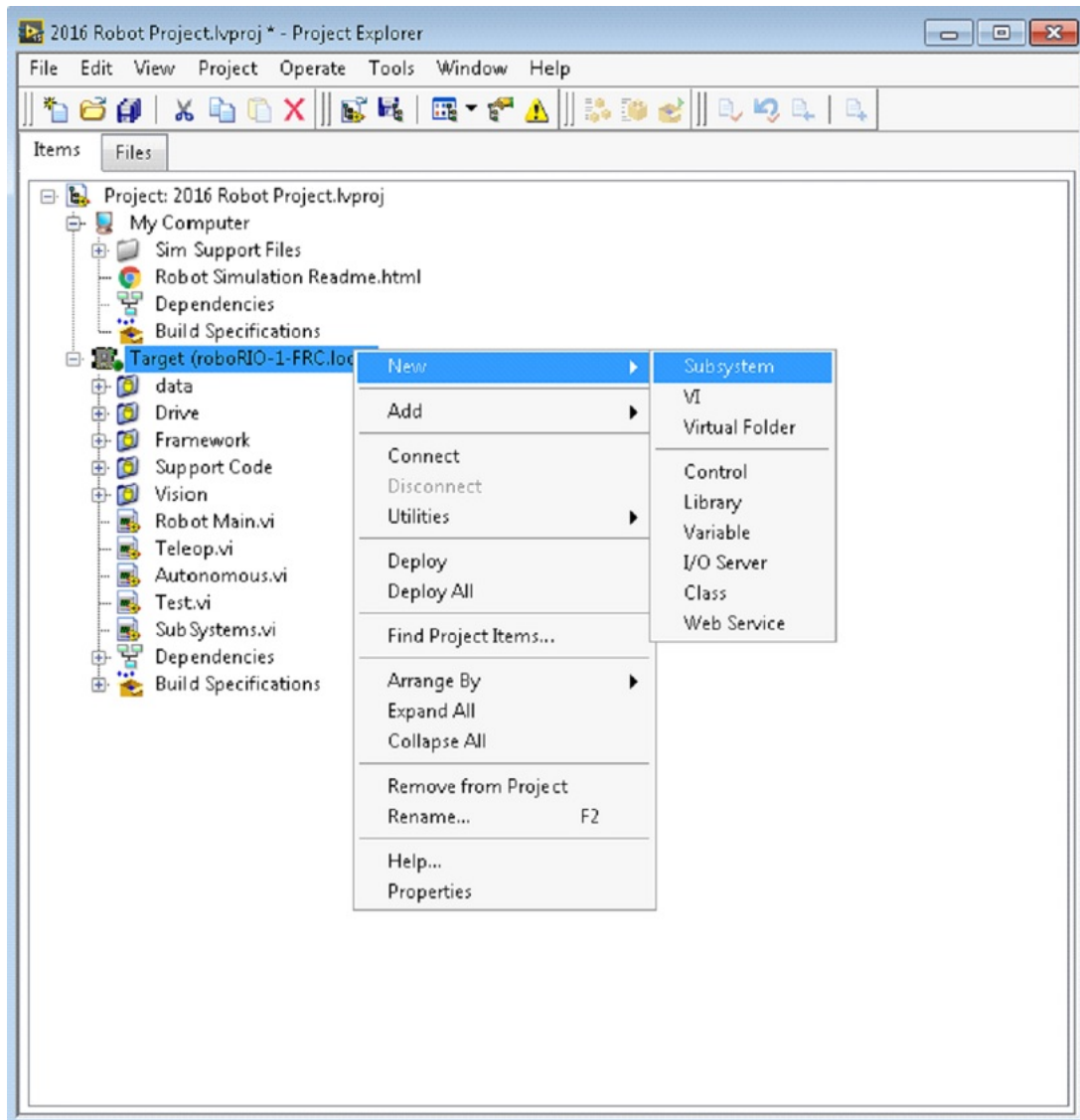


your encoder(s) on the outside, to the left of the loop. In the new diagram of the case structure, we added a call to reset the encoder on the first loop iteration and read it otherwise. There is also some simple code that compares encoder values and updates the motor power. If new controls are added to the setpoints cluster, you should also consider adding them to the Trace. The necessary changes are shown in the image below.



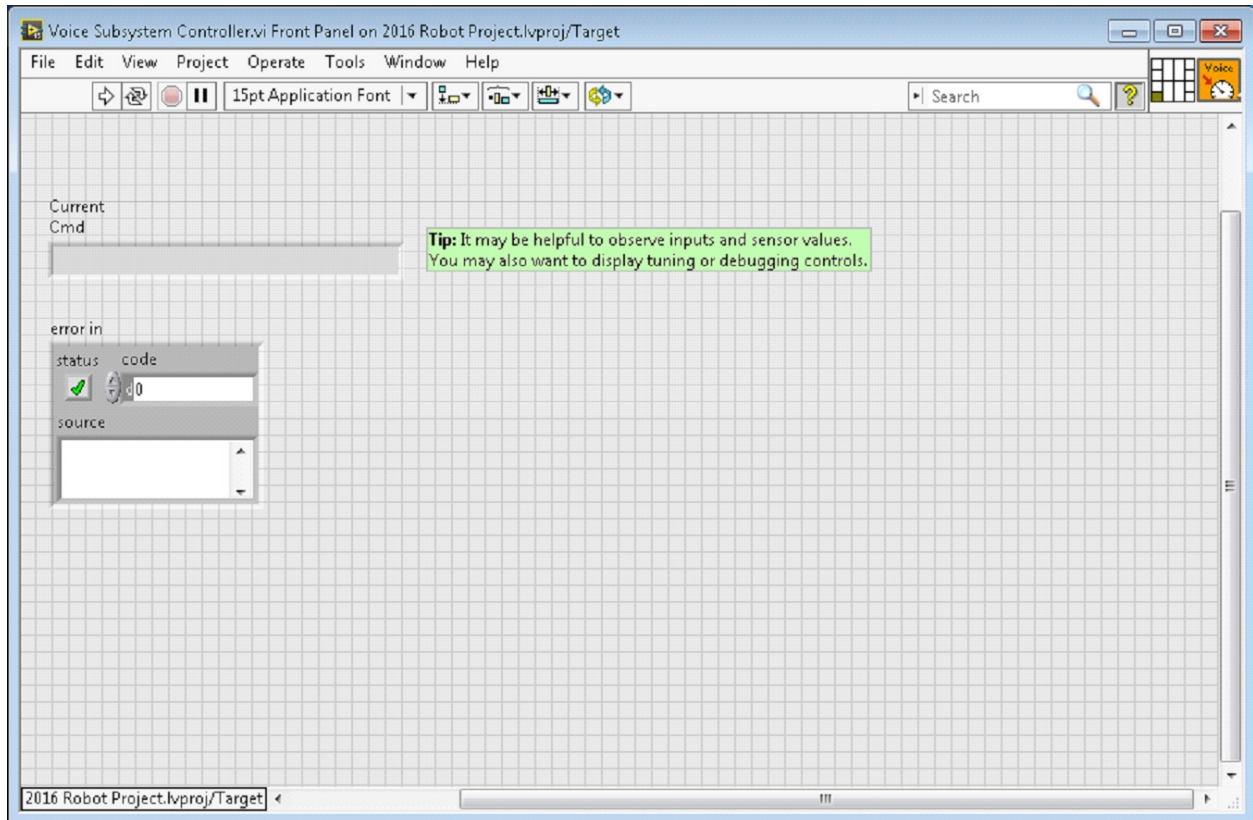
### Part 5: Creating a Subsystem

In order to create a new subsystem, right click on the roboRIO target and select New» Subsystem. In the pop up dialog box, enter the name of the subsystem, list the operational modes, and specify the color of the icon.

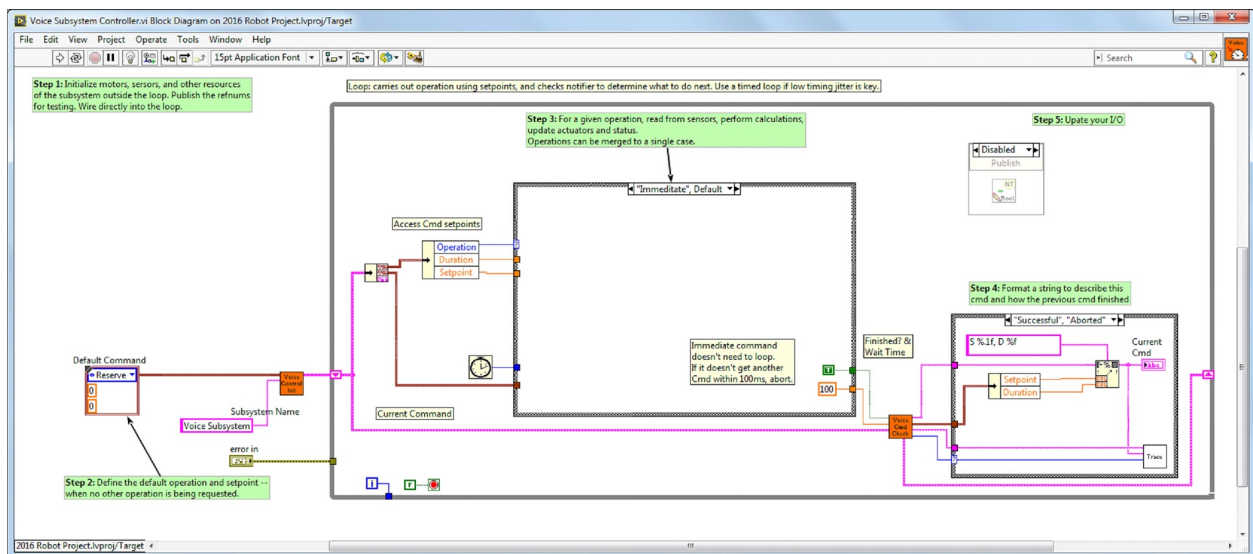


When you click OK, the subsystem folder will be generated and added to the project disk folder and tree. It will contain a base implementation of the VIs and controls that make up a subsystem. A call to the new controller will be inserted into the Subsystems VI. The controller VI will open, ready for you to add I/O and implement state machine or control code. Generated VI icons will use the color and name provided in the dialog. The generated code will use typedefs for set point fields and operations.





Below is the block diagram of the newly created subsystem. This code will be generated automatically when you create the subsystem.



## 4.2 LabVIEW Resources

### 4.2.1 LabVIEW Resources



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**Note:** To learn more about programming in LabVIEW and specifically programming FRC robots in LabVIEW, check out the following resources.

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#### LabVIEW Basics

National Instruments provides a [combination of videos and traditional text/picture tutorials on the basics of LabVIEW](#). These tutorials can help you get acquainted with the LabVIEW environment and the basics of the graphical, dataflow programming model used in LabVIEW.

#### NI FRC Tutorials

National Instruments also hosts many [FRC specific tutorials and presentations ranging from basic to advanced](#). For an in-depth single resource check out the FRC Basic and Advanced Training Classes linked near the bottom of the page.

#### Installed Tutorials and Examples

There are also tutorials and examples for all sorts of tasks and components provided as part of your LabVIEW installation. To access the tutorials, from the LabVIEW Splash screen (the screen that appears when the program is first launched) click on the Tutorials tab on the left side. Note that the tutorials are all in one document, so once it is open you are free to browse to other tutorials without returning to the splash screen.

To access the examples either click the Support tab, then Find FRC Examples or anytime you're working on a program open the Help menu, select Find Examples and open the FRC Robotics folder.

### 4.2.2 Waiting for Target to Respond - Recovering from bad loops



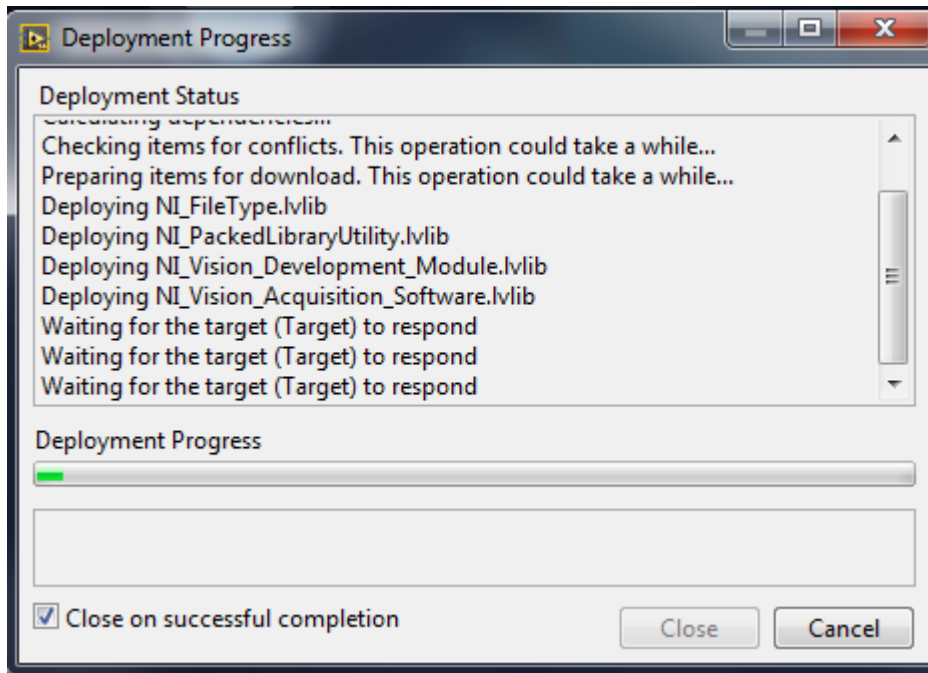
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**Note:** If you download LabVIEW code which contains an unconstrained loop (a loop with no delay) it is possible to get the roboRIO into a state where LabVIEW is unable to connect to

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download new code. This document explains the process required to load new, fixed, code to recover from this state.waiting-for-target-to-respond/

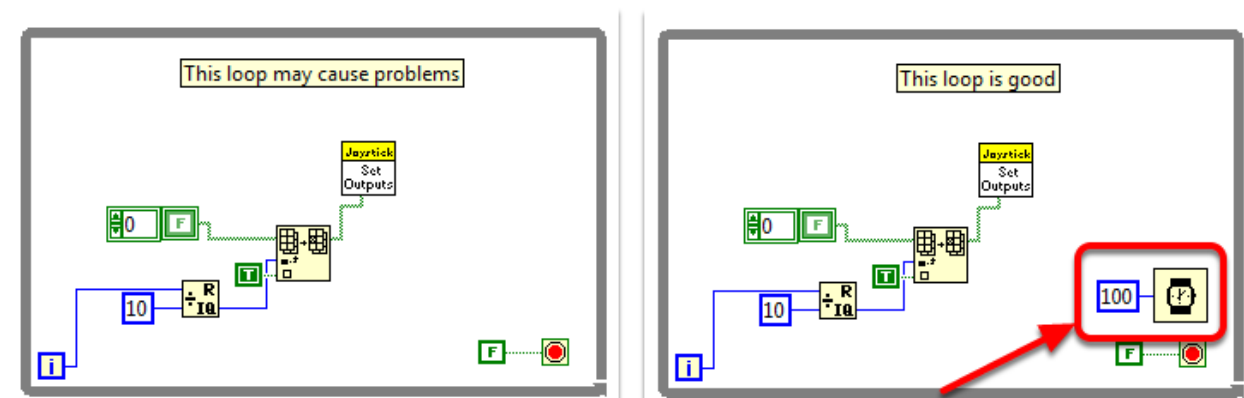
### The Symptom



The primary symptom of this issue is attempts to download new robot code hang at the “Waiting for the target (Target) to respond” step as shown above. Note that there are other possible causes of this symptom (such as switching from a C++/Java program to LabVIEW program) but the steps described here should resolve most or all of them.

Click Cancel to close the download dialog.

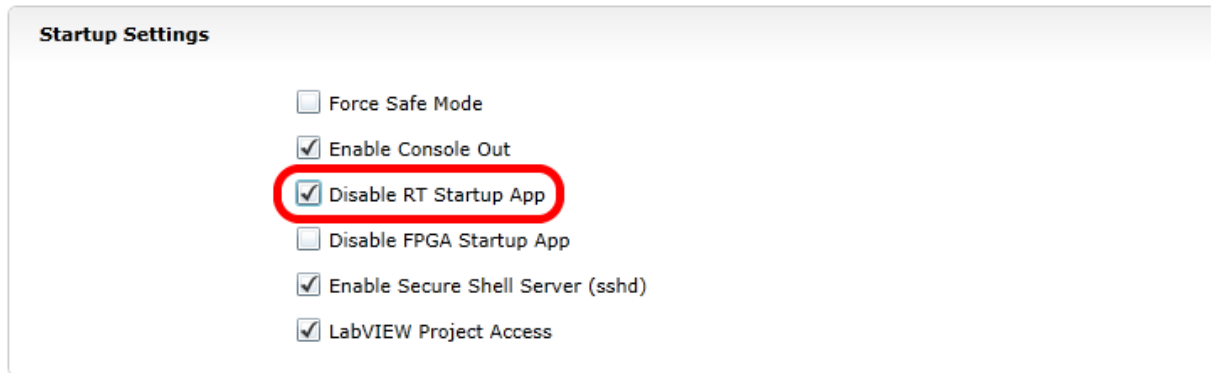
### The Problem



One common source of this issue is unconstrained loops in your LabVIEW code. An unconstrained loop is a loop which does not contain any delay element (such as the one on the left).

If you are unsure where to begin looking, Disabled.VI, Periodic Tasks.VI and Vision Processing.VI are the common locations for this type of loop. To fix the issue with the code, add a delay element such as the Wait (ms) VI from the Timing palette, found in the right loop.

## Set No App



The image shows a 'Startup Settings' dialog box with the following options:

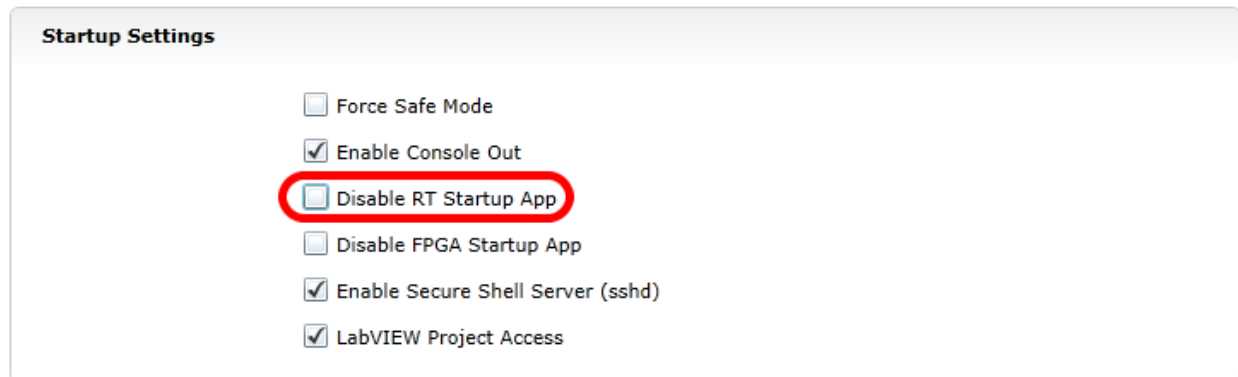
- ☐ Force Safe Mode
- ☒ Enable Console Out
- ☒ Disable RT Startup App (circled in red)
- ☐ Disable FPGA Startup App
- ☒ Enable Secure Shell Server (sshd)
- ☒ LabVIEW Project Access

Using the roboRIO webserver (see the article roboRIO Webdashboard for more details). **Check** the box to “Disable RT Startup App”.

## Reboot

Reboot the roboRIO, either using the Reset button on the device or by click Restart in the top right corner of the webpage.

## Clear No App



The image shows a 'Startup Settings' dialog box with the following options:

- ☐ Force Safe Mode
- ☒ Enable Console Out
- ☐ Disable RT Startup App (circled in red)
- ☐ Disable FPGA Startup App
- ☒ Enable Secure Shell Server (sshd)
- ☒ LabVIEW Project Access

Using the roboRIO webserver (see the article roboRIO Webdashboard for more details). **Uncheck** the box to “Disable RT Startup App”.

## Load LabVIEW Code

Load LabVIEW code (either using the Run button or Run as Startup). Make sure to set LabVIEW code to Run as Startup before rebooting the roboRIO or you will need to follow the

instructions above again.

### 4.2.3 Talon SRX CAN

The Talon SRX motor controller is a CAN-enabled “smart motor controller” from Cross The Road Electronics/VEX Robotics. The Talon SRX can be controlled over the CAN bus or PWM interface. When using the CAN bus control, this device can take inputs from limit switches and potentiometers, encoders, or similar sensors in order to perform advanced control such as limiting or PID(F) closed loop control on the device.

Extensive documentation about programming the Talon SRX in all three FRC languages can be found in the [Talon SRX Software Reference Manual on CTRE’s Talon SRX product page](#).

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**Note:** CAN Talon SRX has been removed from WPILib. See [this blog](#) for more info and find the CTRE Toolsuite installer [here](#)

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### 4.2.4 How To Toggle Between Two Camera Modes



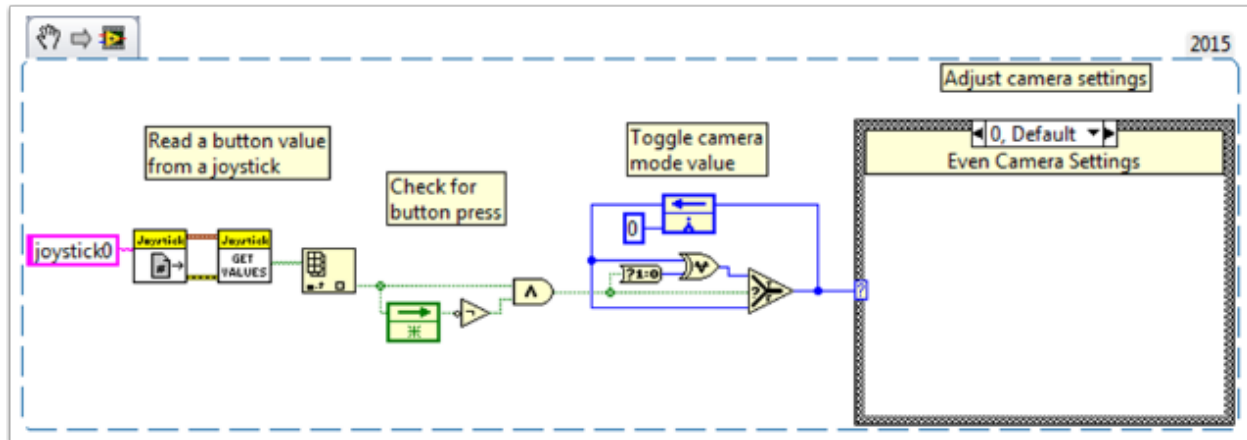
This code shows how to use a button to toggle between two distinct camera modes. The code consists of four stages.

In the first stage, the value of a button on the joystick is read.

Next, the current reading is compared to the previous reading using a **Feedback Node** and some Boolean arithmetic. Together, these ensure that the camera mode is only toggled when the button is initially pressed rather than toggling back and forth multiple times while the button is held down.

After that, the camera mode is toggled by masking the result of the second stage over the current camera mode value. This is called bit masking and by doing it with the **XOR** function the code will toggle the camera mode when the second stage returns true and do nothing otherwise.

Finally, you can insert the code for each camera mode in the case structure at the end. Each time the code is run, this section will run the code for the current camera mode.



#### 4.2.5 LabVIEW Examples and Tutorials



##### Popular Tutorials

##### Autonomous Timed Movement Tutorial

- Move your robot autonomously based on different time intervals
- [See more on Autonomous Movement](#)

##### Basic Motor Control Tutorial

- Setup your roboRIO motor hardware and software
- Learn to setup the FRC Control System and FRC Robot Project
- [See more on Motor Control](#)

##### Image Processing Tutorial

- Learn basic Image Processing techniques and how to use NI Vision Assistant
- [See more on Cameras and Image Processing](#)

##### PID Control Tutorial

- What is PID Control and how can I implement it?

##### Command and Control Tutorial

- What is Command and Control?
- How do I implement it?

##### Driver Station Tutorial

- Get to know the FRC Driver Station

##### Test Mode Tutorial

- Learn to setup and use Test Mode

Looking for more examples and discussions? Search through more documents or post your own discussion, example code, or tutorial by [clicking here!](#) Don't forget to mark your posts with a tag!

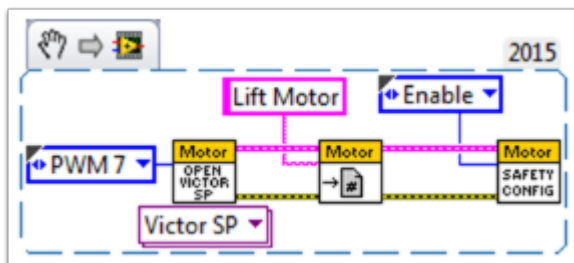
### 4.2.6 Add an Independent Motor to a Project



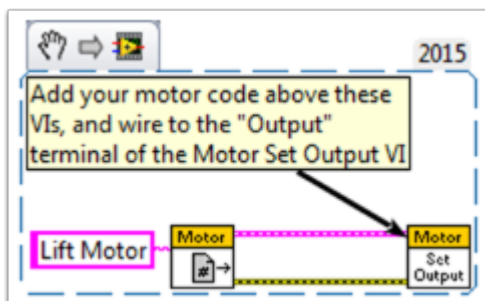
Once your drive that controls the wheels is all set, you might need to add an additional motor to control something completely independent of the wheels, such as an arm. Since this motor will not be part of your tank, arcade, or mecanum drive, you'll definitely want independent control of it.

These VI Snippets show how to set up a single motor in a project that may already contain a multi-motor drive. If you see the HAND>ARROW>LABVIEW symbol, just drag the image into your block diagram, and voila: code! Ok, here's how you do it.

FIRST, create a motor reference in the **Begin.vi**, using the **Motor Control Open VI** and **Motor Control Refnum Registry Set VI**. These can be found by right-clicking in the block diagram and going to **WPI Robotics Library>>RobotDrive>>Motor Control**. Choose your PWM line and name your motor. I named mine "Lift Motor" and connected it to PWM 7. (I also included and enabled the Motor Control Safety Config VI, which automatically turns off the motor if it loses connection.)

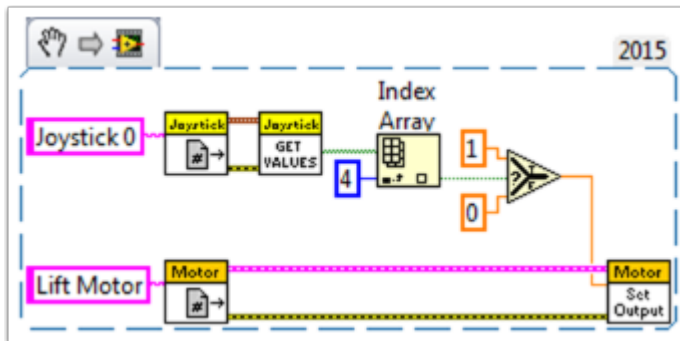


Now, reference your motor (the name has to be exact) in the **Teleop.vi** using the **Motor Control Refnum Registry Get VI** and tell it what to do with the **Motor Control Set Output VI**. These are in the same place as the above VIs.

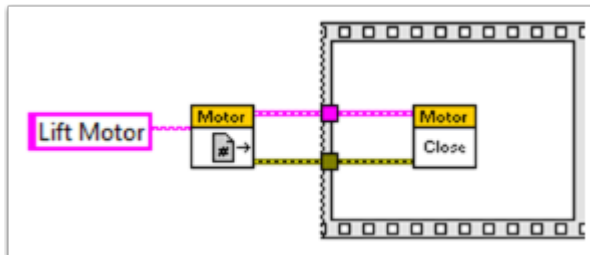


For example, the next snippet tells the Lift Motor to move forward if button 4 is pressed on Joystick 0 and to remain motionless otherwise. For me, button 4 is the left bumper on my

Xbox style controller (“Joystick 0”). For much more in-depth joystick button options, check out [How to Use Joystick Buttons to Control Motors or Solenoids](#).



Finally, we need to close the references in the **Finish.vi** (just like we do with the drive and joystick), using the **Motor Control Refnum Registry Get VI** and **Motor Control Close VI**. While this picture shows the Close VI in a flat sequence structure by itself, we really want all of the Close VIs in the same frame. You can just put these two VIs below the other Get VIs and Close VIs (for the joystick and drive).



I hope this helps you program the best robot ever! Good luck!

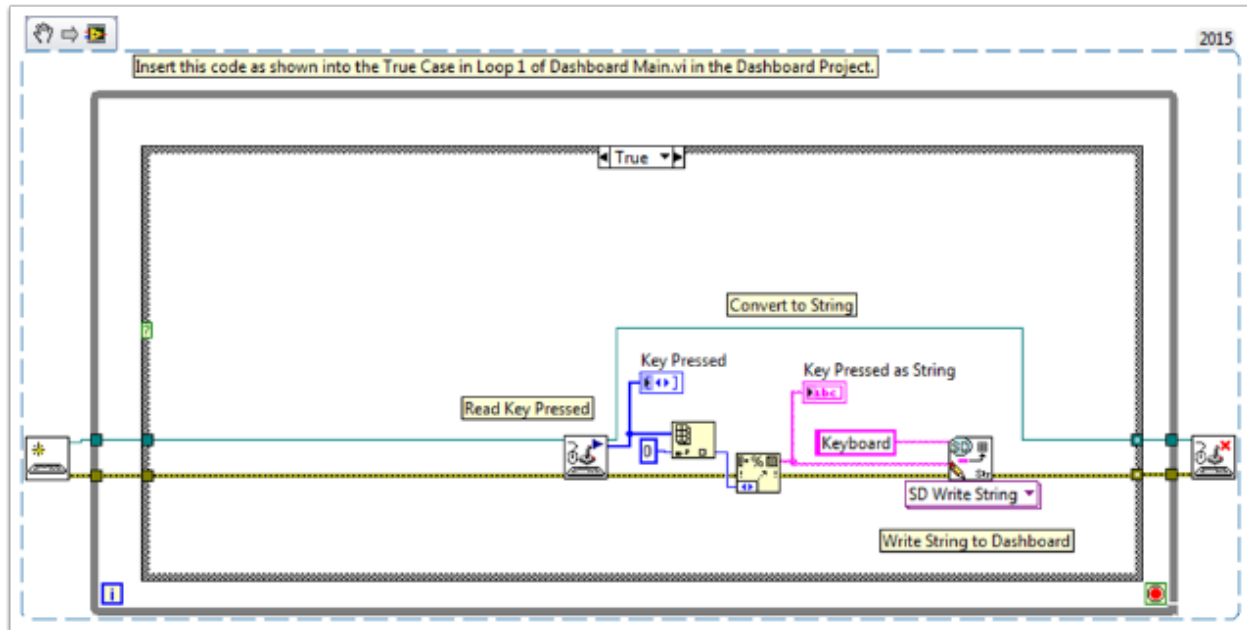
#### 4.2.7 Keyboard Navigation with the roboRIO



This example provides some suggestions for controlling the robot using keyboard navigation in place of a joystick or other controller. In this case, we use the A, W, S, and D keys to control two drive motors in a tank drive configuration.

The first VI Snippet is the code that will need to be included in the Dashboard Main VI. You can insert this code into the True case of Loop 1. The code opens a connection to the keyboard before the loop begins, and on each iteration it reads the pressed key. This information is converted to a string, which is then passed to the Teleop VI in the robot project. When Loop 1 stops running, the connection to the keyboard is closed.





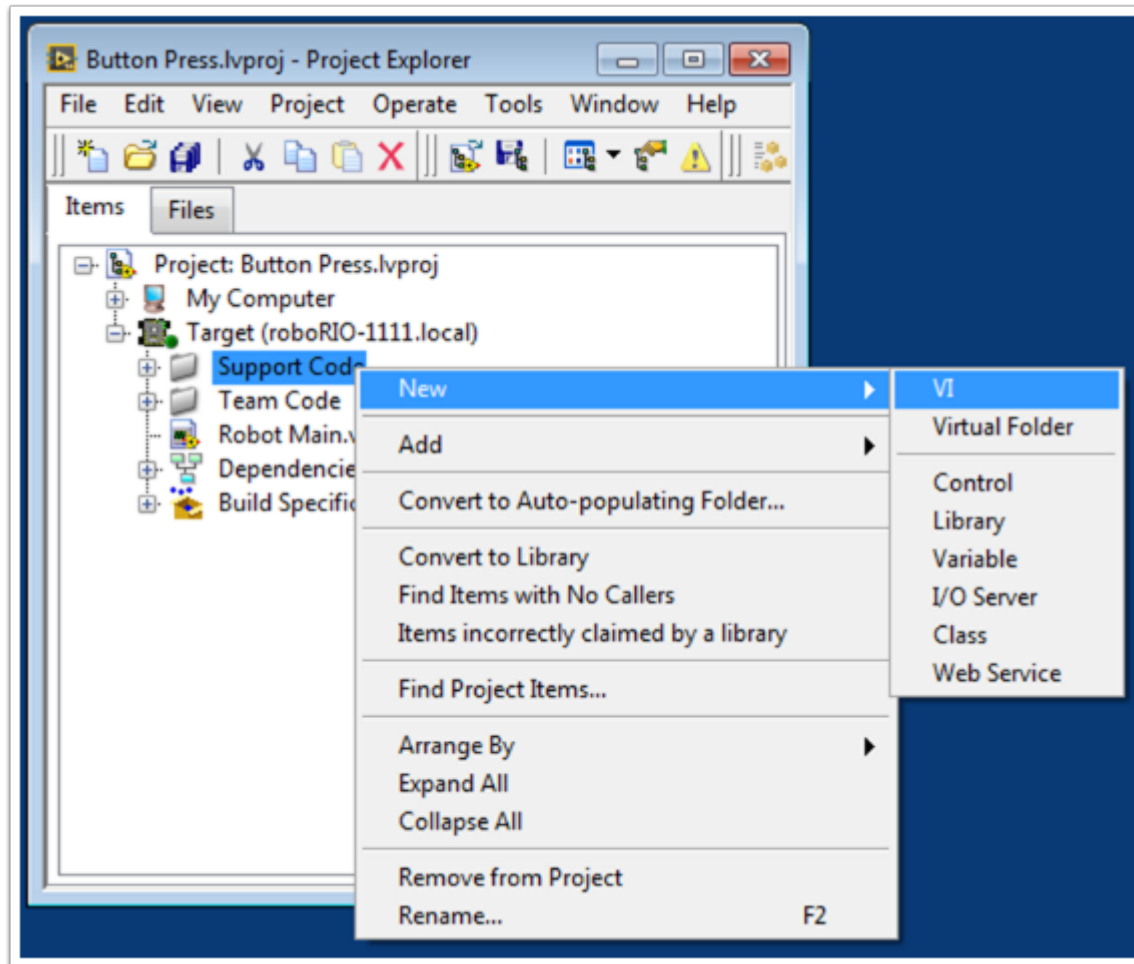
The second VI Snippet is code that should be included in the Teleop VI. This reads the string value from the Dashboard that indicates which key was pressed. A Case Structure then determines which values should be written to the left and right motors, depending on the key. In this case, W is forward, A is left, D is right, and S is reverse. Each case in this example runs the motors at half speed. You can keep this the same in your code, change the values, or add additional code to allow the driver to adjust the speed, so you can drive fast or slow as necessary. Once the motor values are selected, they are written to the drive motors, and motor values are published to the dashboard.

#### 4.2.8 Making a One-Shot Button Press

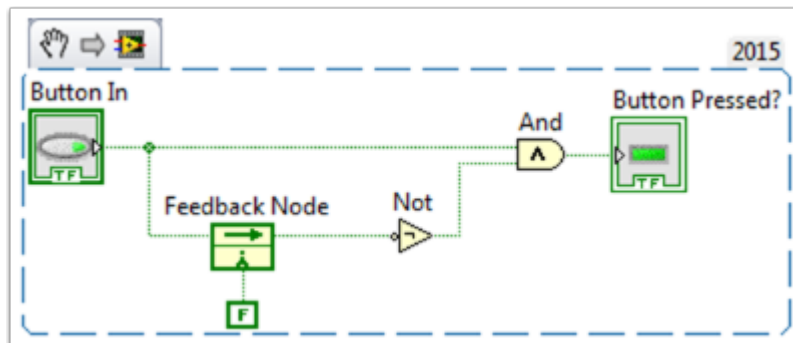


When using the Joystick Get Values function, pushing a joystick button will cause the button to read TRUE until the button is released. This means that you will most likely read multiple TRUE values for each press. What if you want to read only one TRUE value each time the button is pressed? This is often called a “One-Shot Button”. The following tutorial will show you how to create a subVI that you can drop into your Teleop.vi to do this.

First, create a new VI in the Support Code folder of your project.



Now on the block diagram of the new VI, drop in the following code snippet.

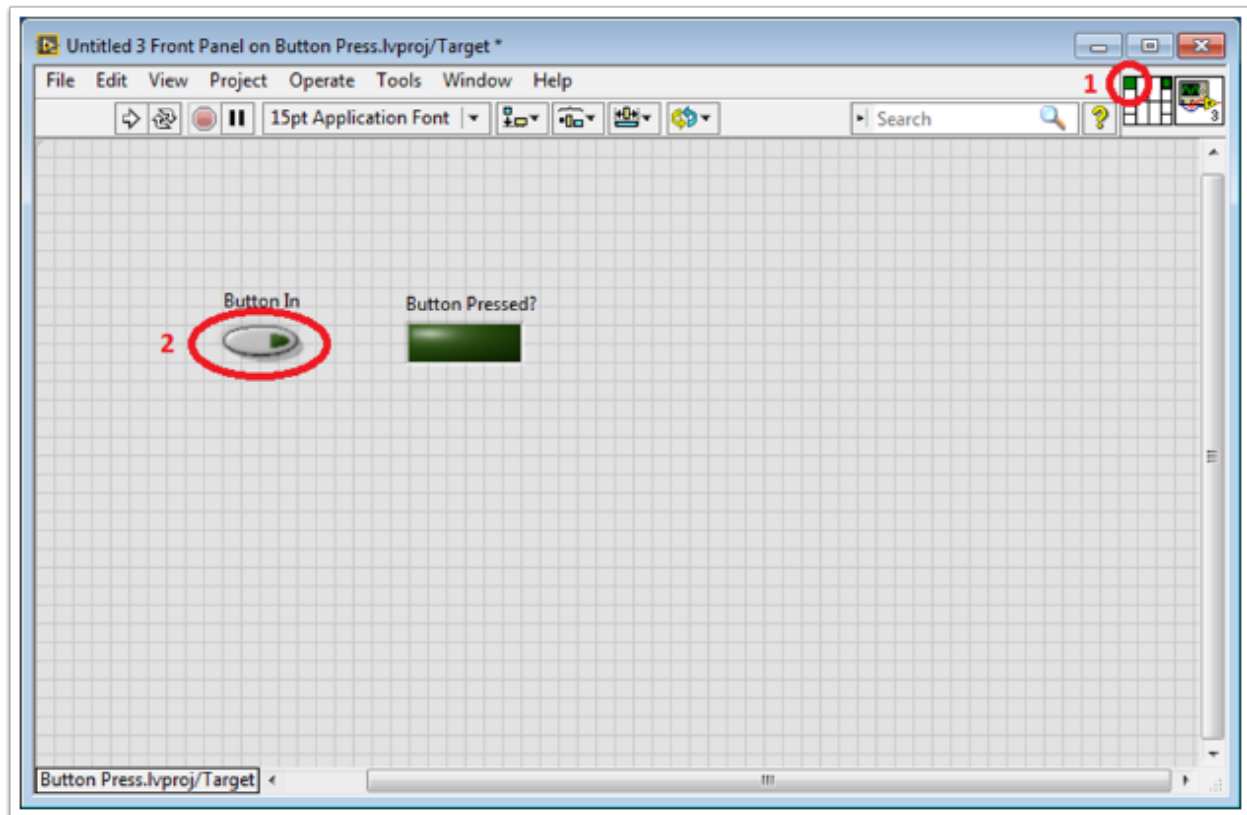


This code uses a function called the Feedback Node. We have wired the current value of the button into the left side of the feedback node. The wire coming out of the arrow of the feedback node represents the previous value of the button. If the arrow on your feedback node is going the opposite direction as shown here, right click to find the option to reverse the direction.

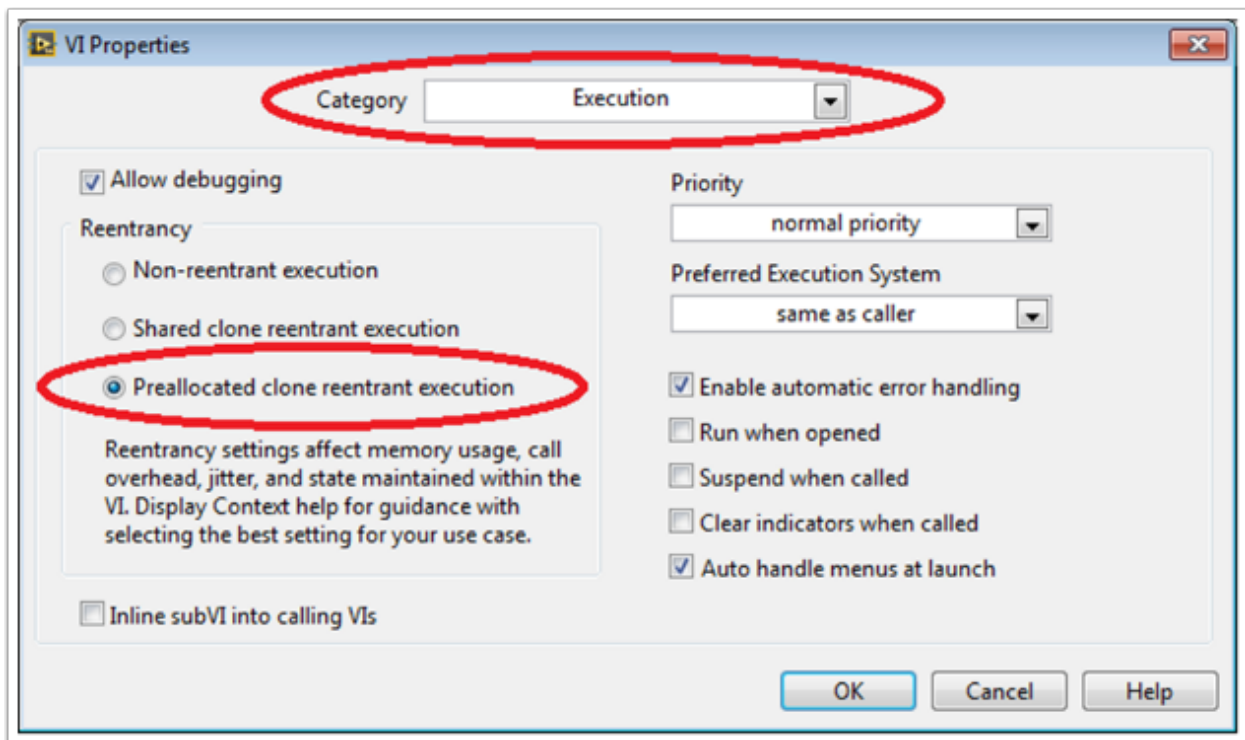
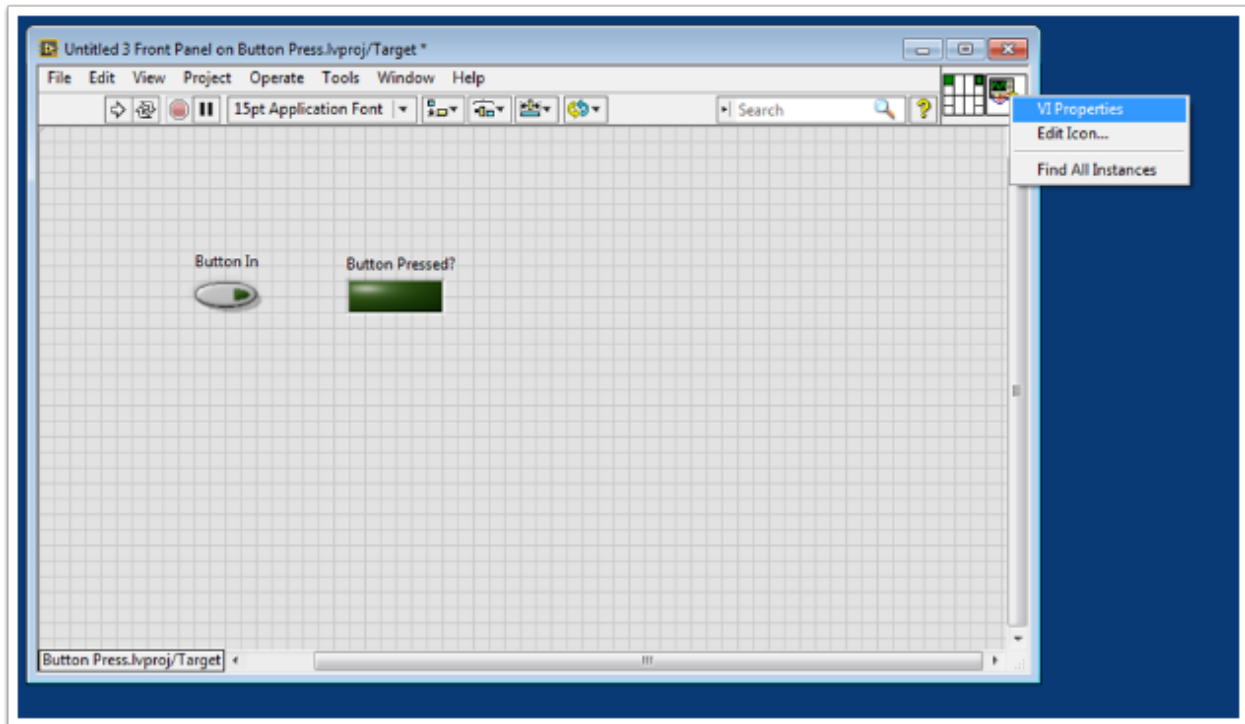
When a button is pressed, the value of the button goes from FALSE to TRUE. We want the output of this VI to be TRUE only when the current value of the button is TRUE, and the previous value of the button is FALSE.

Next we need to connect the boolean control and indicator to the inputs and outputs of the

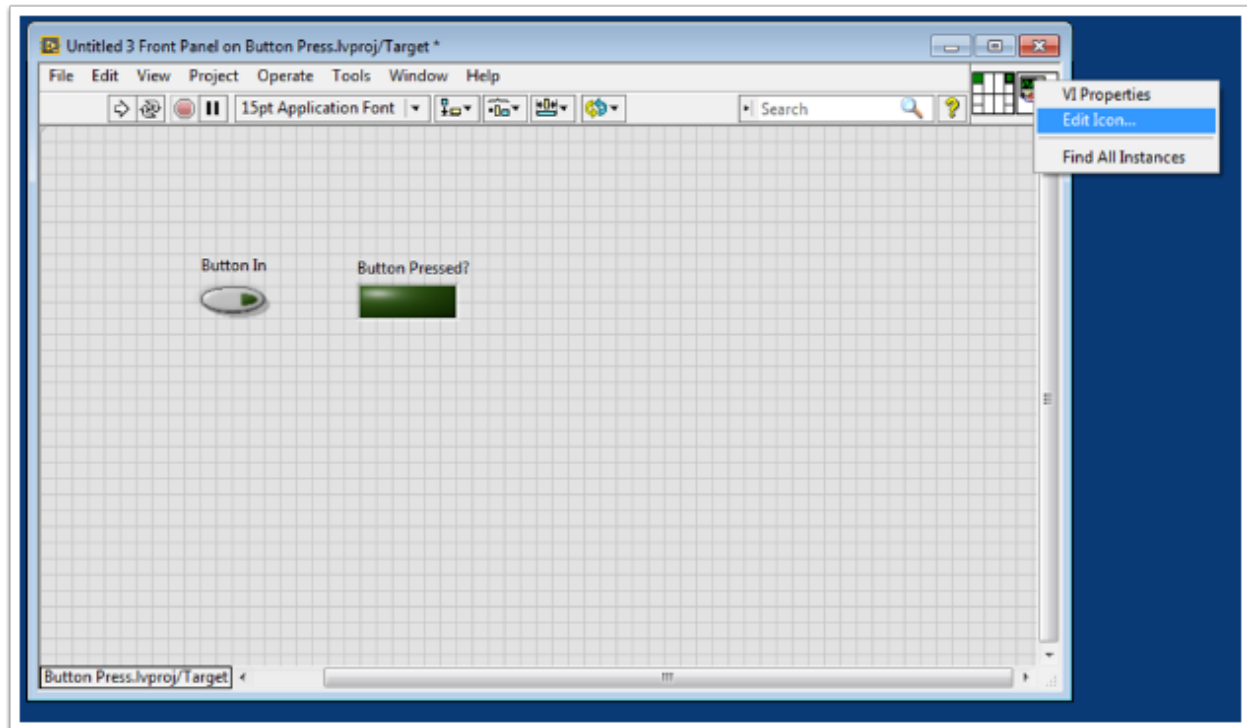
VI. To do this, first click the block on the connector pane, then click the button to connect the two (see the diagram below). Repeat this for the indicator.



Next, we need to change the properties of this VI so that we can use multiples of this VI in our TeleOp.vi. Right click the VI Icon and go to VI Properties. Then select the category "Execution" and select "Preallocated clone reentrant execution".

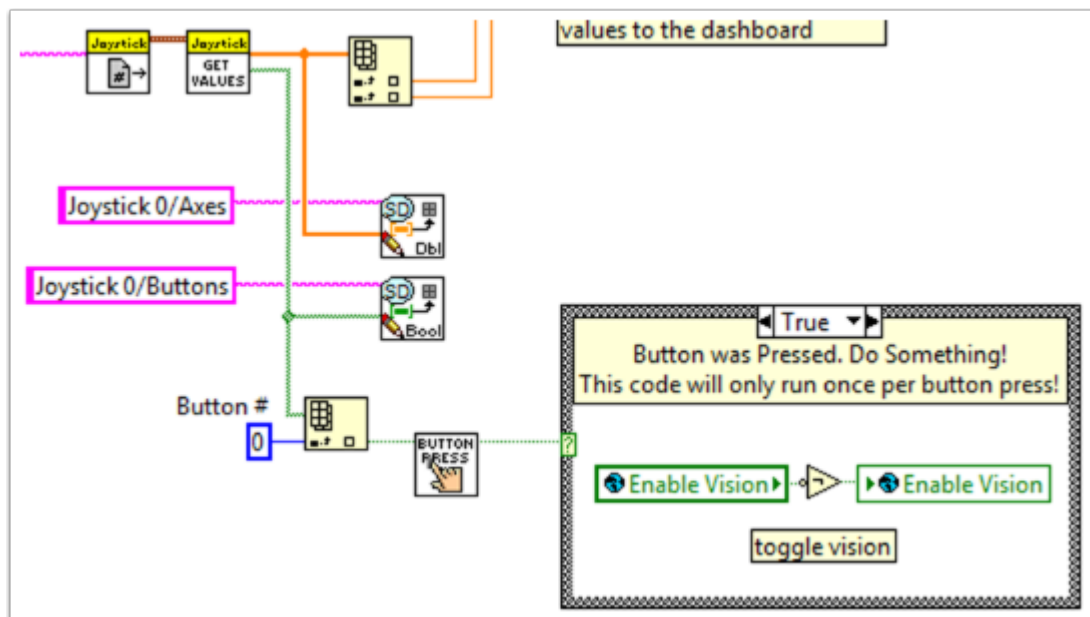


Lastly, we should change the VI Icon to be more descriptive of the VI's function. Right click the Icon and go to Edit Icon. Create a new Icon.



Finally, save the VI with a descriptive name. You can now drag and drop this VI from the Support Files folder into your TeleOp.vi. Here is a copy of the completed VI: Button\_Press.vi

Here's an example of how you could use this VI.



### 4.2.9 Adding Safety Features to Your Robot Code

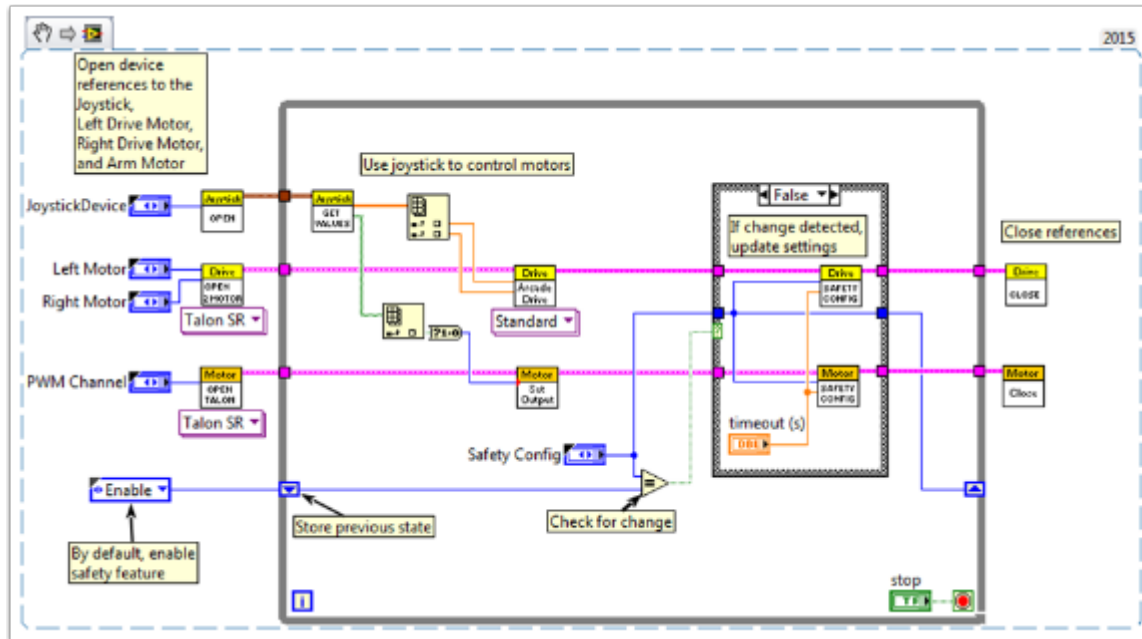


A common problem with complex projects is making sure that all of your code is executing when you expect it to. Problems can arise when tasks with high priority, long execution times, or frequent calls hog processing power on the roboRIO. This leads to what is known as “starvation” for the tasks that are not able to execute due to the processor being busy. In most cases this will simply slow the reaction time to your input from the joysticks and other devices. However, this can also cause the drive motors of your robot to stay on long after you try to stop them. To avoid any robotic catastrophes from this, you can implement safety features that check for task input starvation and automatically shut down potentially harmful operations.

There are built-in functions for the motors that allow easy implementation of safety checks. These functions are:

- Robot Drive Safety Configuration
- Motor Drive Safety Configuration
- Relay Safety Configuration
- PWM Safety Configuration
- Solenoid Safety Configuration
- Robot Drive Delay and Update Safety

In all of the Safety Configuration functions, you can enable and disable the safety checks while your programming is running and configure what timeout you think is appropriate. The functions keep a cache of all devices that have the safety enabled and will check if any of them have exceeded their time limit. If any has, all devices in the cache will be disabled and the robot will come to an immediate stop or have its relay/PWM/solenoid outputs turned off. The code below demonstrates how to use the Drive Safety Configuration functions to set a maximum time limit that the motors will receive no input before being shut off.



To test the safety shut-off, try adding a Wait function to the loop that is longer than your timeout!

The final function that relates to implementing safety checks—Robot Drive Delay and Update Safety—allows you to put the roboRIO in Autonomous Mode without exceeding the time limit. It will maintain the current motor output without making costly calls to the Drive Output functions, and will also make sure that the safety checks are regularly updated so that the motors will not suddenly stop.

Overall, it is highly recommended that some sort of safety check is implemented in your project to make sure that your robot is not unintentionally left in a dangerous state!

#### 4.2.10 How to Use Joystick Buttons to Control Motors or Solenoids



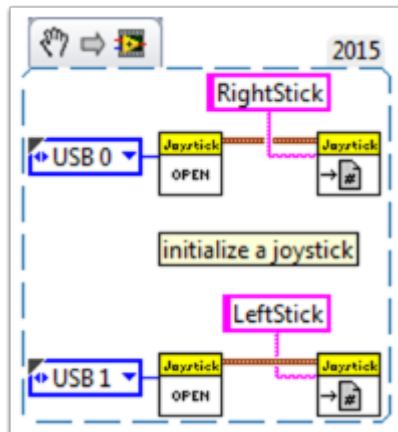
As we all get our drive systems working, we are moving on to connecting our auxiliary devices such as motors and solenoids. With this, we will generally use joystick buttons to control these devices. To get started with this, we'll go through several ways to control devices with joystick buttons.

Did you know that you can click and drag a VI Snippet from a document like this right into your LabVIEW code? Try it with the snippets in this document.

##### Setup:

No matter what the configuration, you'll need to add one, two, or more (if you're really excited) joysticks to the "Begin.vi". The first example uses 2 joysticks and the others only use one. Give each one a unique name so we can use it in other places, like the snippet below. I named

them “LeftStick” and “RightStick” because they are on the left and right sides of my desk. If your joysticks are already configured, great! You can skip this step.

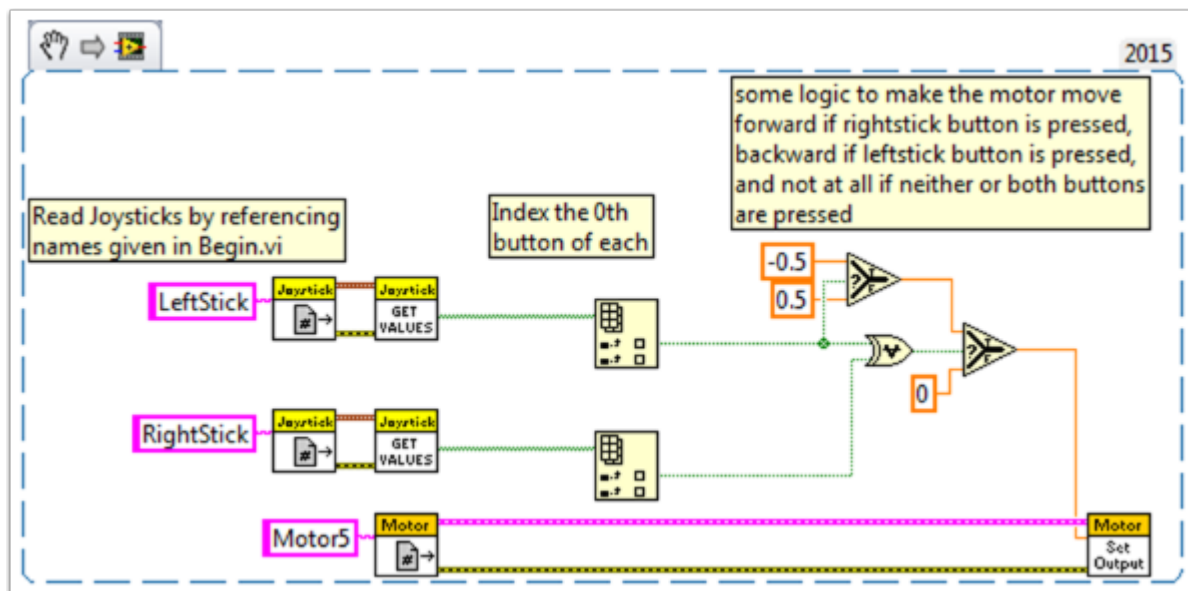


The rest of the code in this document will be placed in the “Teleop.VI” This is where we will be programming our joystick buttons to control different aspects of our motors or solenoids.

## Scenario 1

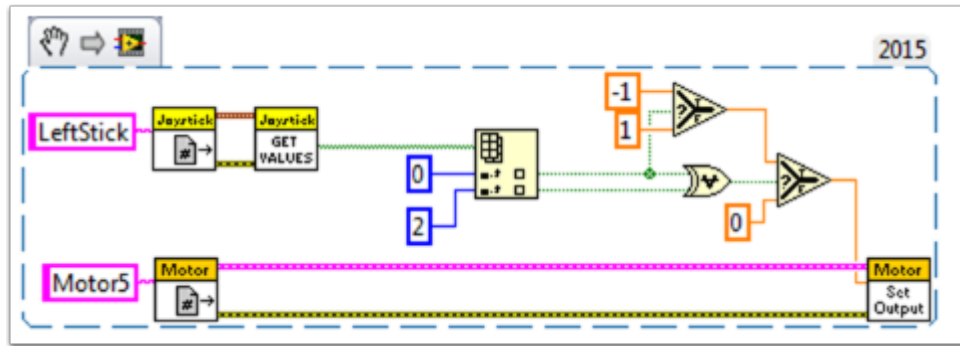
**“I want a motor to move one way when I press one button and the other way when I press a different button.”**

This code uses button 0 on two different joysticks to control the same motor. If button 0 on LeftStick is pressed, the motor moves backward, and if button 0 on RightStick is pressed, the motor moves forward. If both buttons are pressed or neither button is pressed, the motor doesn't move. Here I named my motor reference “Motor5”, but you can name your motor whatever you want in the “Begin.vi”



You may want to use multiple buttons from the same joystick for control. For an example of this, look at the following VI snippet or the VI snippet in Scenario 2.





Here I used joystick buttons 0 and 2, but feel free to use whatever buttons you need.

## Scenario 2

### “I want different joystick buttons move at various speeds.”

This example could be helpful if you need to have one motor do different things based on the buttons you press. For instance, let’s say my joystick has a trigger (button 0) and 4 buttons on top (buttons 1 through 4). In this case, the following buttons should have the following functions:

- button 1 - move backward at half speed
- button 2 - move forward at half speed
- button 3 - move backward at 1/4 speed
- button 4 - move forward at 1/4 speed
- trigger - full speed ahead! (forward at full speed)

We would then take the boolean array from the “JoystickGetValues.vi” and wire it to a “Boolean Array to Number” node (Numeric Palette-Conversion Palette). This converts the boolean array to a number that we can use. Wire this numeric to a case structure.

Each case corresponds to a binary representation of the values in the array. In this example, each case corresponds to a one-button combination. We added six cases: 0 (all buttons off), 1 (button 0 on), 2 (button 1 on), 4 (button 2 on), 8 (button 3 on), and 16 (button 4 on). Notice we skipped value 3. 3 would correspond to buttons 0 and 1 pressed at the same time. We did not define this in our requirements so we’ll let the default case handle it.

It might be helpful to review the LabVIEW 2014 Case Structure Help document here:

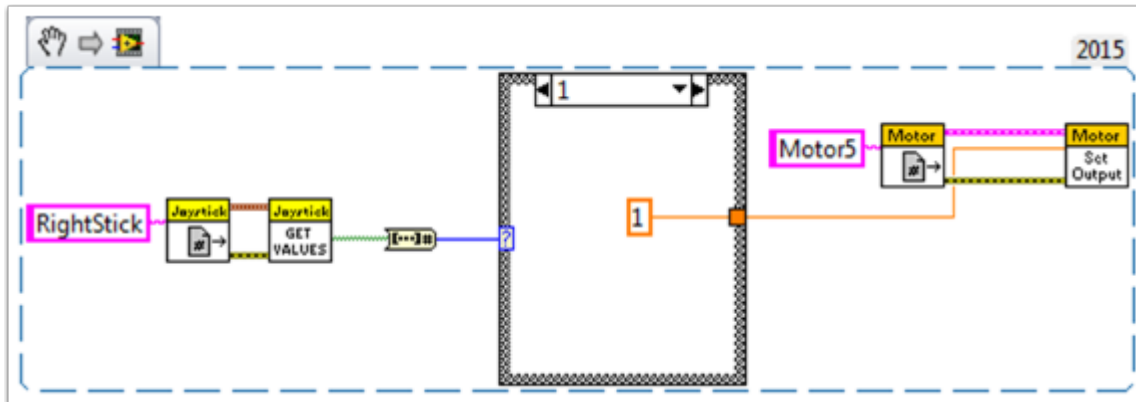
[https://zone.ni.com/reference/en-XX/help/371361L-01/glang/case\\_structure/](https://zone.ni.com/reference/en-XX/help/371361L-01/glang/case_structure/)

There are also 3 Community Tutorials on case structures here:

<https://forums.ni.com/t5/Curriculum-and-Labs-for/Unit-3-Case-Structures-Lesson-1/ta-p/3505945?profile.language=en>

<https://forums.ni.com/t5/Curriculum-and-Labs-for/Unit-3-Case-Structures-Lesson-2/ta-p/3505933?profile.language=en>

<https://forums.ni.com/t5/Curriculum-and-Labs-for/Unit-3-Case-Structures-Lesson-3/ta-p/3505979?profile.language=en>

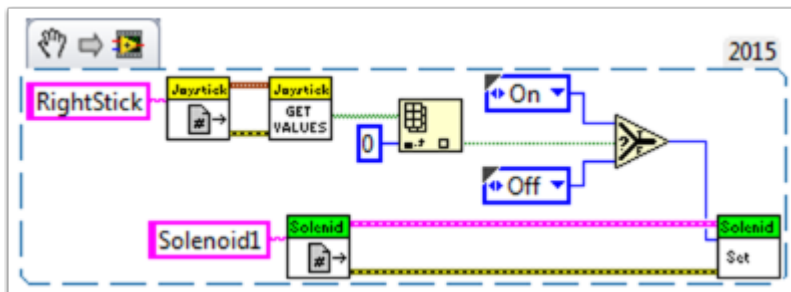


Since our requirements were simple, we only need a single constant in each case. For case 1 (full ahead) we use a 1, for case 2 (half back) we use a -0.5, etc. We can use any constant value between 1 and -1. I left case 0 as the default so if multiple buttons are pressed (any undefined state was reached) the motor will stop. You of course are free to customize these states however you want.

### Scenario 3

#### “I want to control a solenoid with my joystick buttons.”

By now, we are familiar with how the joystick outputs the buttons in an array of booleans. We need to index this array to get the button we are interested in, and wire this boolean to a select node. Since the “Solenoid Set.vi” requires a Enum as an input, the easiest way to get the enum is to right click the “Value” input of the “Solenoid Set.vi” and select “Create Constant”. Duplicate this constant and wire one copy to the True terminal and one to the False terminal of the select node. Then wire the output of the select node to the “Value” input of the solenoid VI.



Happy Roboting!

### 4.2.11 Local and Global Variables in LabVIEW for FRC



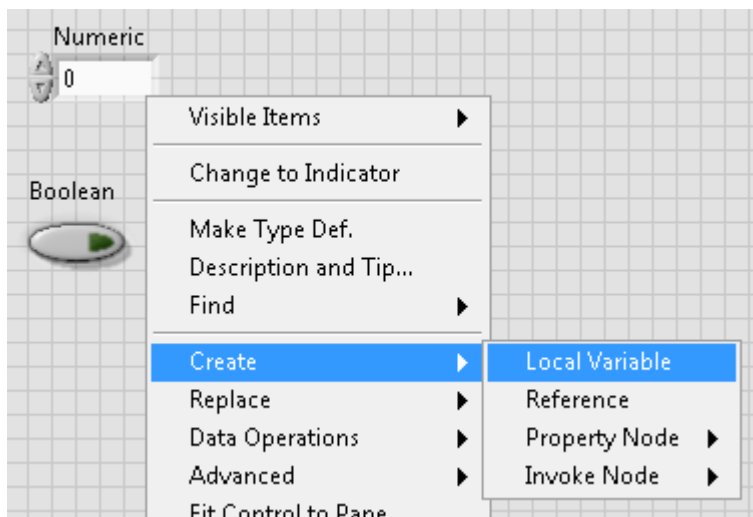
This example serves as an introduction to local and global variables, how they are used in the default LabVIEW for FRC Robot Project, and how you might want to use them in your project.

Local variables and global variables may be used to transfer data between locations within the same VI (local variables) or within different VI's (global variables), breaking the conventional [Data Flow Paradigm](#) for which LabVIEW is famous. Thus, they may be useful when, for whatever reason, you cannot wire the value directly to the node to another.

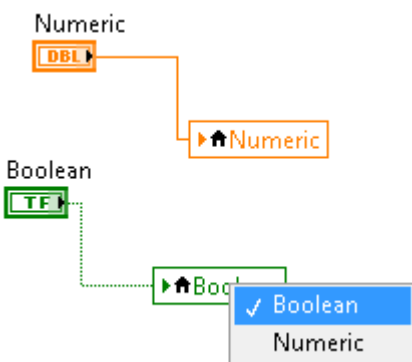
Note: One possible reason may be that you need to pass data between consecutive loop iterations; Miro\_T covered this [in this post](#). It should also be noted that the [feedback node](#) in LabVIEW may be used as an equivalent to the shift register, although that may be a topic for another day!

### Introduction to Local and Global Variables

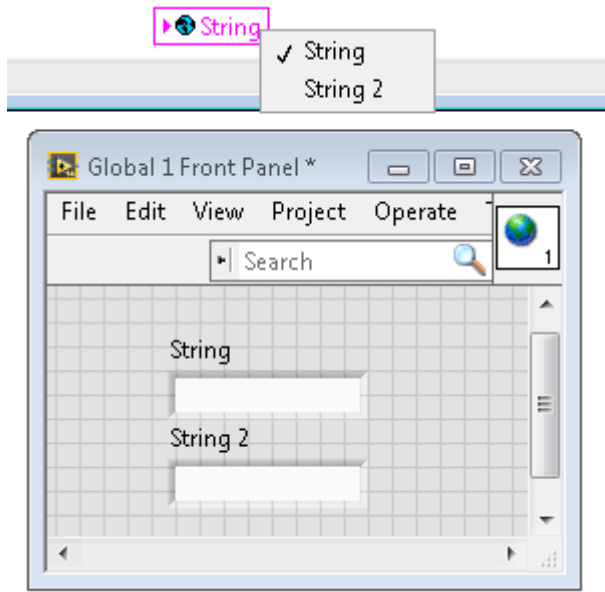
Local variables may be used within the same VI. Create a local variable by right-clicking a control or indicator on your Front Panel:



You may create a local variable from the Structures palette on the block diagram as well. When you have multiple local variables in one VI, you can left-click to choose which variable it is:



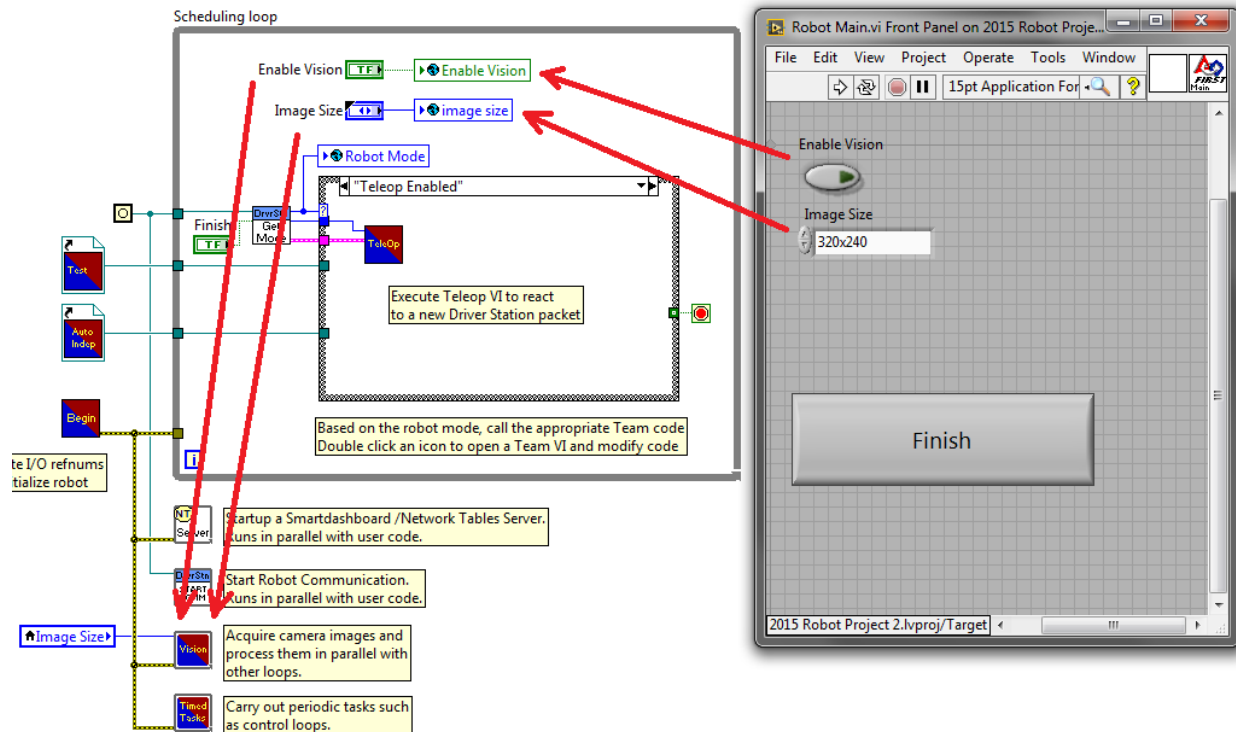
Global variables are created slightly differently. Add one to the block diagram from the Structures palette, and notice that when you double-click it, it opens a separate front panel. This front panel does not have a block diagram, but you add as many entities to the front panel as you wish and save it as a \*.vi file:



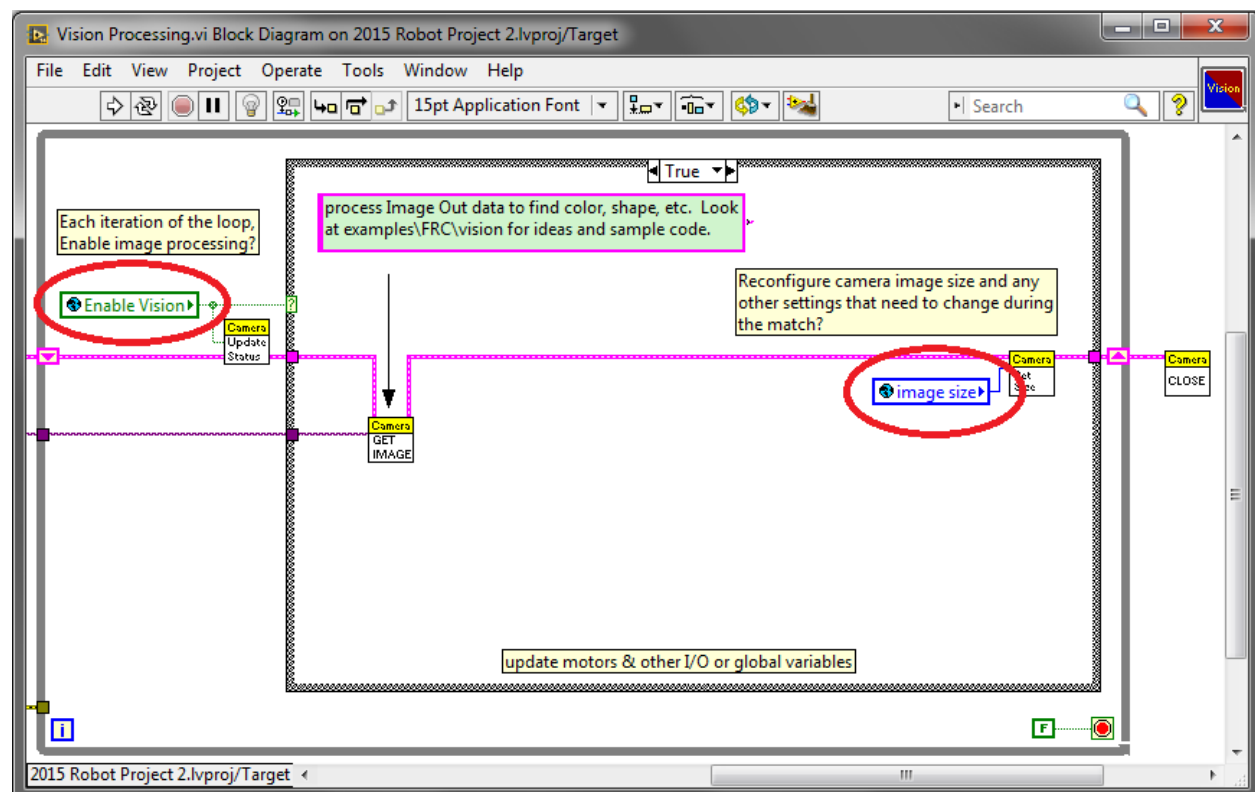
**Note:** Be very careful to avoid race conditions when using local and global variables! Essentially, make sure that you are not accidentally writing to the same variable in multiple locations without a way to know to which location it was last written. For a more thorough explanation, see [this help document](#)

### How They are Used in the Default LabVIEW for FRC Robot Project

Global variables for “Enable Vision” and “Image Size” are written to during each iteration of the Robot Main VI...



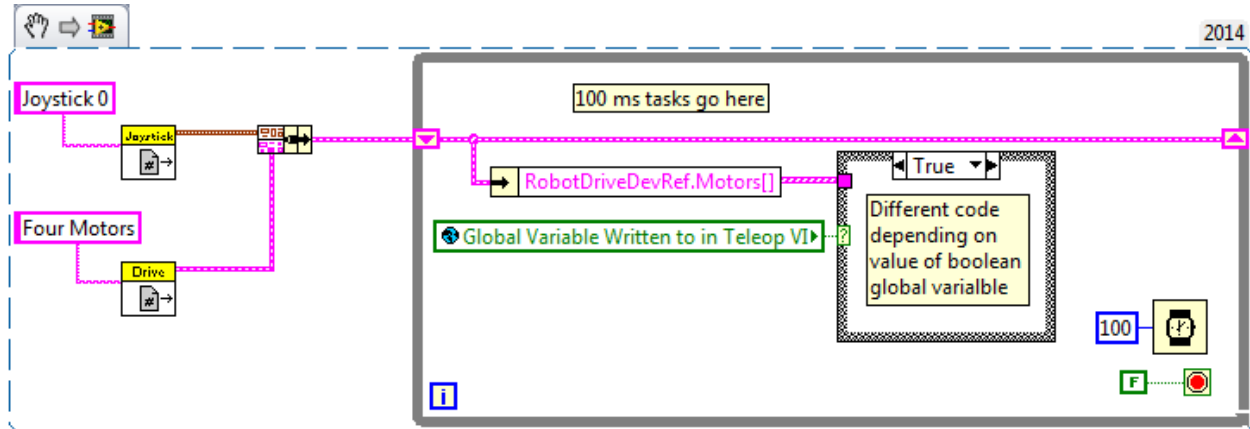
... And then read in each iteration of the Vision Processing VI:



This allows the user, when deploying to Robot Main VI from the LabVIEW Development Environment, to enable/disable vision and change the image size from Robot Main's Front Panel.

## How Can You Use Them in Your Project?

Check out the block diagram for the Periodic Tasks VI. Perhaps there is some value, such as a boolean, that may be written to a global variable in the Teleop VI, and then read from in the Periodic Tasks VI. You can then decide what code or values to use in the Periodic Tasks VI, depending on the boolean global variable:



### 4.2.12 Using the Compressor in LabVIEW



This snippet shows how to set up your roboRIO project to use the Pneumatic Control Module (PCM). The PCM automatically starts and stops the compressor when specific pressures are measured in the tank. In your roboRIO program, you will need to add the following VIs.

For more information, check out the following links:

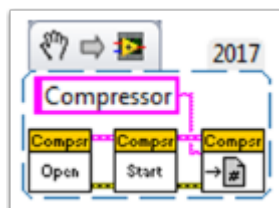
[FRC Pneumatics Manual](#)

[PCM User's Guide](#)

[Pneumatics Step by Step for the roboRIO](#)

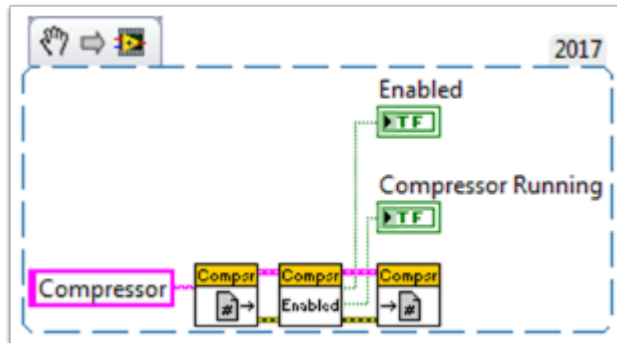
## Begin VI

Place this snippet in the Begin.vi.



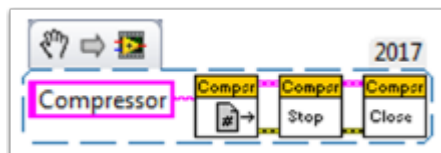
### Teleop VI

Place this snippet in the Teleop.vi. This portion is only required if you are using the outputs for other processes.



### Finish VI

Place this snippet in Close Refs, save data, etc. frame of the Finish.vi.



## 5.1 Actuator Overview

This section discusses the control of motors and pneumatics through speed controllers, solenoids and pneumatics, and their interface with C++ and Java WPILib.

### 5.1.1 Speed controllers

A speed controller is responsible on your robot for making motors move. For brushed DC motors such as CIMs or 775s, the speed controller regulates the voltage that the motor receives, much like a light bulb. For brushless speed controllers such as the Spark MAX, the controller regulates the power delivered to each “phase” of the motor.

**Warning:** Connecting a BRUSHLESS motor controller straight to power, such as to a conventional brushed motor controller, will destroy the motor!

### FRC Legal Motor Controllers

Speed controllers come in lots of shapes, sizes and feature sets. This is the full list of FRC Legal speed controllers as of January 2020:

- DMC 60/DMC 60c Motor Controller (P/N: 410-334-1, 410-334-2)
- Jaguar Motor Controller (P/N: MDL-BDC, MDL-BDC24, and 217-3367) connected to PWM only
- Nidec Dynamo BLDC Motor with Controller to control integral actuator only (P/N 840205-000, am-3740)
- SD540 Motor Controller (P/N: SD540x1, SD540x2, SD540x4, SD540Bx1, SD540Bx2, SD540Bx4, SD540C)
- Spark Motor Controller (P/N: REV-11-1200)
- Spark MAX Motor Controller (P/N: REV-11-2158)



- Talon FX Motor Controller (P/N: 217-6515, 19-708850, am-6515, am-6515\_Short) for controlling integral Falcon 500 only
- Talon Motor Controller (P/N: CTRE\_Talon, CTRE\_Talon\_SR, and am-2195)
- Talon SRX Motor Controller (P/N: 217-8080, am-2854, 14-838288)
- Victor 884 Motor Controller (P/N: VICTOR-884-12/12)
- Victor 888 Motor Controller (P/N: 217-2769)
- Victor SP Motor Controller (P/N: 217-9090, am-2855, 14-868380)
- Victor SPX Motor Controller (P/N: 217-9191, 17-868388, am-3748)
- Venom Motor with Controller (P/N BDC-10001) for controlling integral motor only

### 5.1.2 Pneumatics

Pneumatics are a quick and easy way to make something that's in one state or another using compressed air. For information on operating pneumatics, see [Operating pneumatic cylinders](#).

#### FRC Legal Relay Modules

- Spike H-Bridge Relay (P/N: 217-0220 and SPIKE-RELAY-H)
- Automation Direct Relay (P/N: AD-SSR6M12-DC200D, AD-SSR6M25-DC200D, AD-SSR6M40-DC200D)

#### FRC Legal Pneumatics controllers

- Pneumatics Control Module (P/N: am-2858, 217-4243)

## 5.2 Operating pneumatic cylinders

### 5.2.1 Using the FRC Control System to control Pneumatics

---

**Note:** The Pneumatics Control Module (PCM) is a CAN-based device that provides complete control over the compressor and up to 8 solenoids per module. The PCM is integrated into WPILib through a series of classes that make it simple to use. The closed loop control of the Compressor and Pressure switch is handled by the PCM hardware and the Solenoids are handled by the upgraded Solenoid class that now controls the solenoid channels on the PCM. An additional PCM module can be used where the modules corresponding solenoids are differentiated by the module number in the constructors of the Solenoid and Compressor classes.

---



The Pneumatics Control Module from CTR Electronics is responsible for regulating the robot's pressure using a pressure switch and a compressor and switching solenoids on and off. The PCM communicates with the roboRIO over CAN. For more information, see *FRC Control System Hardware Overview*

### 5.2.2 PCM Module Numbers

PCM Modules are identified by their Node ID. The default Node ID for PCMs is 0. If using a single PCM on the bus it is recommended to leave it at the default Node ID.

### 5.2.3 Generating and Storing Pressure

In FRC, pressure is created using a pneumatic compressor and stored in pneumatic tanks. The compressor doesn't necessarily have to be on the robot, but must be powered by the robot's PCM(s). The "Closed Loop" mode on the Compressor is enabled by default, and it is *not* recommended that teams change this setting. When closed loop control is enabled the PCM will automatically turn the compressor on when the pressure switch is closed (below the pressure threshold) and turn it off when the pressure switch is open (~120PSI). When closed loop control is disabled the compressor will not be turned on. Using a Compressor, users can query the status of the compressor. The state (currently on or off), pressure switch state, and compressor current can all be queried from the Compressor object.

**Note:** The Pneumatics Control Module from Cross the Road Electronics allows for integrated closed loop control of a compressor. Creating any instance of a Solenoid or Double Solenoid

object will enable the Compressor control on the corresponding PCM. The Compressor object is only needed if you want the ability to turn off the compressor or query compressor status.

---

Java

```
Compressor c = new Compressor(0);

c.setClosedLoopControl(true);
c.setClosedLoopControl(false);

boolean enabled = c.enabled();
boolean pressureSwitch = c.getPressureSwitchValue();
double current = c.getCompressorCurrent();
```

C++

```
frc::Compressor c {0};

c.SetClosedLoopControl(true);
c.SetClosedLoopControl(false);

bool enabled = c.Enabled();
bool pressureSwitch = c.GetPressureSwitchValue();
double current = c.GetCompressorCurrent();
```

### 5.2.4 Solenoid control

FRC teams use solenoids to preform a variety of tasks, from shifting gearboxes to operating robot mechanisms. A solenoid is a valve used to electronically switch a pressurized air line “on” or “off”. For more information on solenoids, see [this wikipedia article](#). Solenoids are controlled by a robot’s Pneumatics Control Module, or PCM, which is in turn connected to the robot’s roboRIO via CAN. The easiest way to see a solenoid’s state is via the small red LED (which indicates if the valve is “on” or not), and solenoids can be manually actuated when un-powered with the small button adjacent to the LED.

Single acting solenoids apply or vent pressure from a single output port. They are typically used either when an external force will provide the return action of the cylinder (spring, gravity, separate mechanism) or in pairs to act as a double solenoid. A double solenoid switches air flow between two output ports (many also have a center position where neither output is vented or connected to the input). Double solenoid valves are commonly used when you wish to control both the extend and retract actions of a cylinder using air pressure. Double solenoid valves have two electrical inputs which connect back to two separate channels on the solenoid breakout.

PCM Modules are identified by their CAN Device ID. The default CAN ID for PCMs is 0. If using a single PCM on the bus it is recommended to leave it at the default CAN ID. This ID can be changed with the Phoenix Tuner application, in addition to other debug information. Phoenix Tuner can be downloaded [from GitHub](#). For more information about setting PCM CAN IDs see Updating and Configuring Pneumatics Control Module and Power Distribution Panel.

### 5.2.5 Single Solenoids in WPILib

Single solenoids in WPILib are controlled using the Solenoid class. To construct a Solenoid object, simply pass the desired port number (assumes CAN ID 0) or CAN ID and port number to the constructor. To set the value of the solenoid call `set(true)` to enable or `set(false)` to disable the solenoid output.

Java

```
Solenoid exampleSolenoid = new Solenoid(1);

exampleSolenoid.set(true);
exampleSolenoid.set(false);
```

C++

```
frc::Solenoid exampleSolenoid {1};

exampleSolenoid.Set(true);
exampleSolenoid.Set(false);
```

### 5.2.6 Double Solenoids in WPILib

Double solenoids are controlled by the DoubleSolenoid class in WPILib. These are constructed similarly to the single solenoid but there are now two port numbers to pass to the constructor, a forward channel (first) and a reverse channel (second). The state of the valve can then be set to `kOff` (neither output activated), `kForward` (forward channel enabled) or `kReverse` (reverse channel enabled). Additionally, the PCM CAN ID can be passed to the DoubleSolenoid if teams have a non-standard PCM CAN ID

Java

```
// Using "import static an.enum.or.constants.inner.class.*;" helps reduce verbosity
// this replaces "DoubleSolenoid.Value.kForward" with just kForward
// further reading is available at https://www.geeksforgeeks.org/static-import-java/
import static edu.wpi.first.wpilibj.DoubleSolenoid.Value.*;

DoubleSolenoid exampleDouble = new DoubleSolenoid(1, 2);
DoubleSolenoid anotherDoubleSolenoid = new DoubleSolenoid(/* The PCM CAN ID */ 9, 4, 5);

exampleDouble.set(kOff);
exampleDouble.set(kForward);
exampleDouble.set(kReverse);
```

C++

```
frc::DoubleSolenoid exampleDouble {1, 2};
frc::DoubleSolenoid exampleDouble {/* The PCM CAN ID */ 9, 1, 2};

exampleDouble.Set(frc::DoubleSolenoid::Value::kOff);
exampleDouble.Set(frc::DoubleSolenoid::Value::kForward);
exampleDouble.Set(frc::DoubleSolenoid::Value::kReverse);
```

## 5.3 Using Motor Controllers in Code

Motor controllers come in two main flavors: CAN and PWM. A CAN controller can send more detailed status information back to the roboRIO, whereas a PWM controller can only be set to a value. For information on using these motors with the WPI drivetrain classes, see [Using the WPILib Classes to Drive your Robot](#).

### 5.3.1 Using PWM Speed Controllers

PWM speed controllers can be controlled in the same way as a CAN speed controller. For a more detailed background on *how* they work, see [PWM Speed Controllers in Depth](#). To use a PWM speed controller, simply use the appropriate speed controller class provided by WPI and supply it the port the speed controller(s) are plugged into on the roboRIO. All approved motor controllers have WPI classes provided for them.

Java

```
Spark spark = new Spark(
    // The RIO PWM port this is connected to
    0
);

spark.set(
    // the output of the motor, between -1 and 1
    -0.75
);

VictorSP victor = new VictorSP(
    // The RIO PWM port this is connected to
    0
);

victor.set(
    // the output of the motor, between -1 and 1
    0.6
);
```

C++

```
frc::Spark spark{
    // The RIO PWM port this is connected to
    0
};

spark.Set(
    // the output of the motor, between -1 and 1
    -0.75
);

frc::VictorSP victor{
    // The RIO PWM port this is connected to
    0
};

victor.set(
```

(continues on next page)

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```
// the output of the motor, between -1 and 1
0.6
);
```

### 5.3.2 CAN Motor Controllers

A handful of CAN speed controllers are available through vendors such as CTR Electronics and REV Robotics.

#### SPARK MAX

For information regarding the SparkMAX CAN Speed Controller, which can be used in either CAN or PWM mode, please refer to the SparkMAX [software resources](#) and [example code](#).

#### CTRE CAN Motor Controllers

Please refer to the third party CTR documentation on the Phoenix software for more detailed information. The documentation is available [here](#).

## 5.4 PWM Speed Controllers in Depth

---

**Hint:** WPILib has extensive support for motor control. There are a number of classes that represent different types of speed controllers and servos. There are currently two classes of speed controllers, PWM based motor controllers and CAN based motor controllers. WPILib also contains composite classes (like DifferentialDrive) which allow you to control multiple motors with a single object. This article will cover the details of PWM motor controllers; CAN controllers and composite classes will be covered in separate articles.

---

### 5.4.1 PWM Controllers, brief theory of operation

The acronym PWM stands for Pulse Width Modulation. For motor controllers, PWM can refer to both the input signal and the method the controller uses to control motor speed. To control the speed of the motor the controller must vary the perceived input voltage of the motor. To do this the controller switches the full input voltage on and off very quickly, varying the amount of time it is on based on the control signal. Because of the mechanical and electrical time constants of the types of motors used in FRC this rapid switching produces an effect equivalent to that of applying a fixed lower voltage (50% switching produces the same effect as applying ~6V).

The PWM signal the controllers use for an input is a little bit different. Even at the bounds of the signal range (max forward or max reverse) the signal never approaches a duty cycle of 0% or 100%. Instead the controllers use a signal with a period of either 5ms or 10ms and a midpoint pulse width of 1.5ms. Many of the controllers use the typical hobby RC controller timing of 1ms to 2ms.

### 5.4.2 Raw vs Scaled output values

In general, all of the motor controller classes in WPILib take a scaled -1.0 to 1.0 value as the output to an actuator. The PWM module in the FPGA on the roboRIO is capable of generating PWM signals with periods of 5, 10, or 20ms and can vary the pulse width in 2000 steps of ~.001ms each around the midpoint (1000 steps in each direction around the midpoint). The raw values sent to this module are in this 0-2000 range with 0 being a special case which holds the signal low (disabled). The class for each motor controller contains information about what the typical bound values (min, max and each side of the deadband) are as well as the typical midpoint. WPILib can then use these values to map the scaled value into the proper range for the motor controller. This allows for the code to switch seamlessly between different types of controllers and abstracts out the details of the specific signaling. Calibrating Speed Controllers

So if WPILib handles all this scaling, why would you ever need to calibrate your speed controller? The values WPILib uses for scaling are approximate based on measurement of a number of samples of each controller type. Due to a variety of factors, the timing of an individual speed controller may vary slightly. In order to definitively eliminate “humming” (midpoint signal interpreted as slight movement in one direction) and drive the controller all the way to each extreme, calibrating the controllers is still recommended. In general, the calibration procedure for each controller involves putting the controller into calibration mode then driving the input signal to each extreme, then back to the midpoint. For examples on how to use these speed controllers in your code, see [Using Motor Controllers in Code/Using PWM Speed Controllers](#)

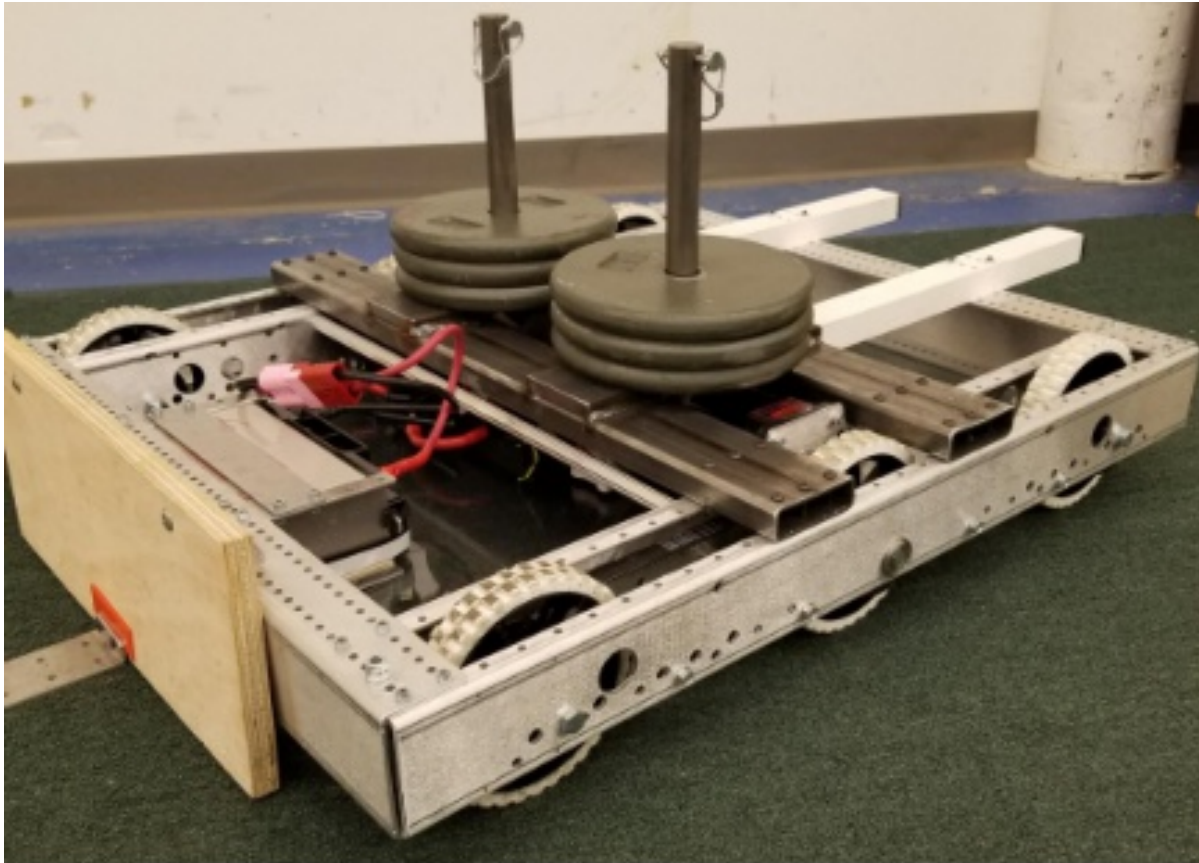
## 5.5 Using the WPILib Classes to Drive your Robot

WPILib includes many classes to help make your robot get driving faster.

### 5.5.1 Standard drivetrains



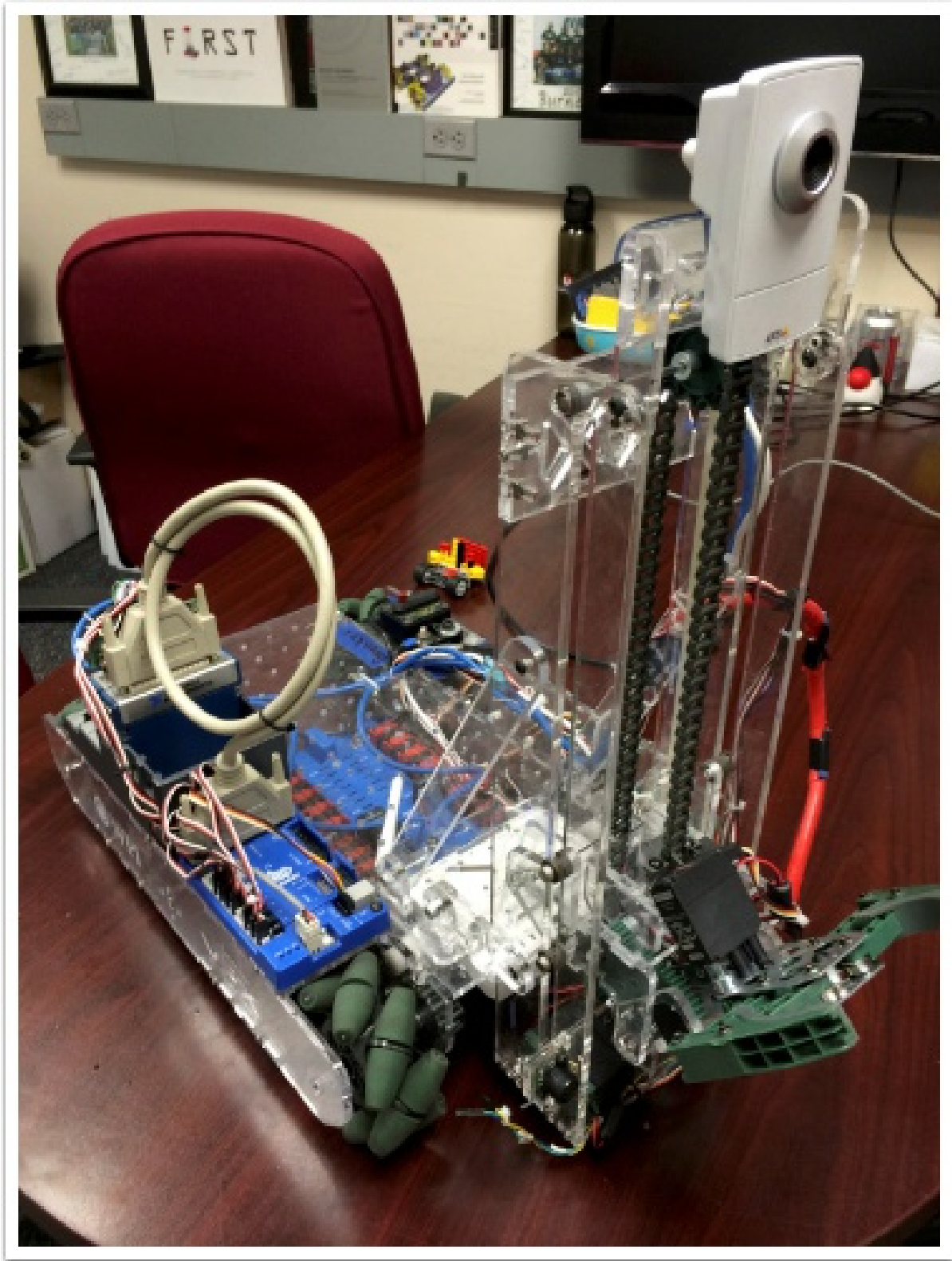
## Differential Drive Robots



These drive bases typically have two or more in-line traction or omni wheels per side (e.g., 6WD or 8WD) and may also be known as “skid-steer”, “tank drive”, or “West Coast Drive”. The Kit of Parts drivetrain is an example of a differential drive. These drivetrains are capable of driving forward/backward and can turn by driving the two sides in opposite directions causing the wheels to skid sideways. These drivetrains are not capable of sideways translational movement.



## **Mecanum Drive**



Mecanum drive is a method of driving using specially designed wheels that allow the robot

to drive in any direction without changing the orientation of the robot. A robot with a conventional drivetrain (all wheels pointing in the same direction) must turn in the direction it needs to drive. A mecanum robot can move in any direction without first turning and is called a holonomic drive. The wheels (shown on this robot) have rollers that cause the forces from driving to be applied at a 45 degree angle rather than straight forward as in the case of a conventional drive.

When viewed from the top, the rollers on a mecanum drivetrain should form an 'X' pattern. This results in the force vectors (when driving the wheel forward) on the front two wheels pointing forward and inward and the rear two wheels pointing forward and outward. By spinning the wheels in different directions, various components of the force vectors cancel out, resulting in the desired robot movement. A quick chart of different movements has been provided below, drawing out the force vectors for each of these motions may help in understanding how these drivetrains work. By varying the speeds of the wheels in addition to the direction, movements can be combined resulting in translation in any direction and rotation, simultaneously.

### 5.5.2 Drive Class Conventions

---

**Note:** This article describes conventions and defaults used by the WPILib Drive classes (DifferentialDrive, MecanumDrive, and KilloughDrive). For further details on using these classes, see the subsequent articles.

---

#### Motor Inversion

By default, the class inverts the motor outputs for the right side of the drivetrain. Generally this will mean that no inversion needs to be done on the individual SpeedController objects. To disable this behavior, use the `setRightSideInverted()` method.

#### Squaring Inputs & Input Deadband

When driving robots, it is often desirable to manipulate the joystick inputs such that the robot has finer control at low speeds while still using the full output range. One way to accomplish this is by squaring the joystick input, then reapplying the sign. By default the Differential Drive class will square the inputs. If this is not desired (e.g. if passing values in from a PIDController), use one of the drive methods with the `squaredInputs` parameter and set it to false.

By default, the Differential Drive class applies an input deadband of .02. This means that input values with a magnitude below .02 (after any squaring as described above) will be set to 0. In most cases these small inputs result from imperfect joystick centering and are not sufficient to cause drivetrain movement, the deadband helps reduce unnecessary motor heating that may result from applying these small values to the drivetrain. To change the deadband, use the `setDeadband()` method.

#### Motor Safety

Motor Safety is a mechanism in WPILib that takes the concept of a watchdog and breaks it out into one watchdog (Motor Safety timer) for each individual actuator. Note that this pro-

tection mechanism is in addition to the System Watchdog which is controlled by the Network Communications code and the FPGA and will disable all actuator outputs if it does not receive a valid data packet for 125ms.

The purpose of the Motor Safety mechanism is the same as the purpose of a watchdog timer, to disable mechanisms which may cause harm to themselves, people or property if the code locks up and does not properly update the actuator output. Motor Safety breaks this concept out on a per actuator basis so that you can appropriately determine where it is necessary and where it is not. Examples of mechanisms that should have motor safety enabled are systems like drive trains and arms. If these systems get latched on a particular value they could cause damage to their environment or themselves. An example of a mechanism that may not need motor safety is a spinning flywheel for a shooter. If this mechanism gets latched on a particular value it will simply continue spinning until the robot is disabled. By default Motor Safety is enabled for RobotDrive objects and disabled for all other speed controllers and servos.

The Motor Safety feature operates by maintaining a timer that tracks how long it has been since the feed() method has been called for that actuator. Code in the Driver Station class initiates a comparison of these timers to the timeout values for any actuator with safety enabled every 5 received packets (100ms nominal). The set() methods of each speed controller class and the set() and setAngle() methods of the servo class call feed() to indicate that the output of the actuator has been updated.

The Motor Safety interface of speed controllers can be interacted with by the user using the following methods:

Java

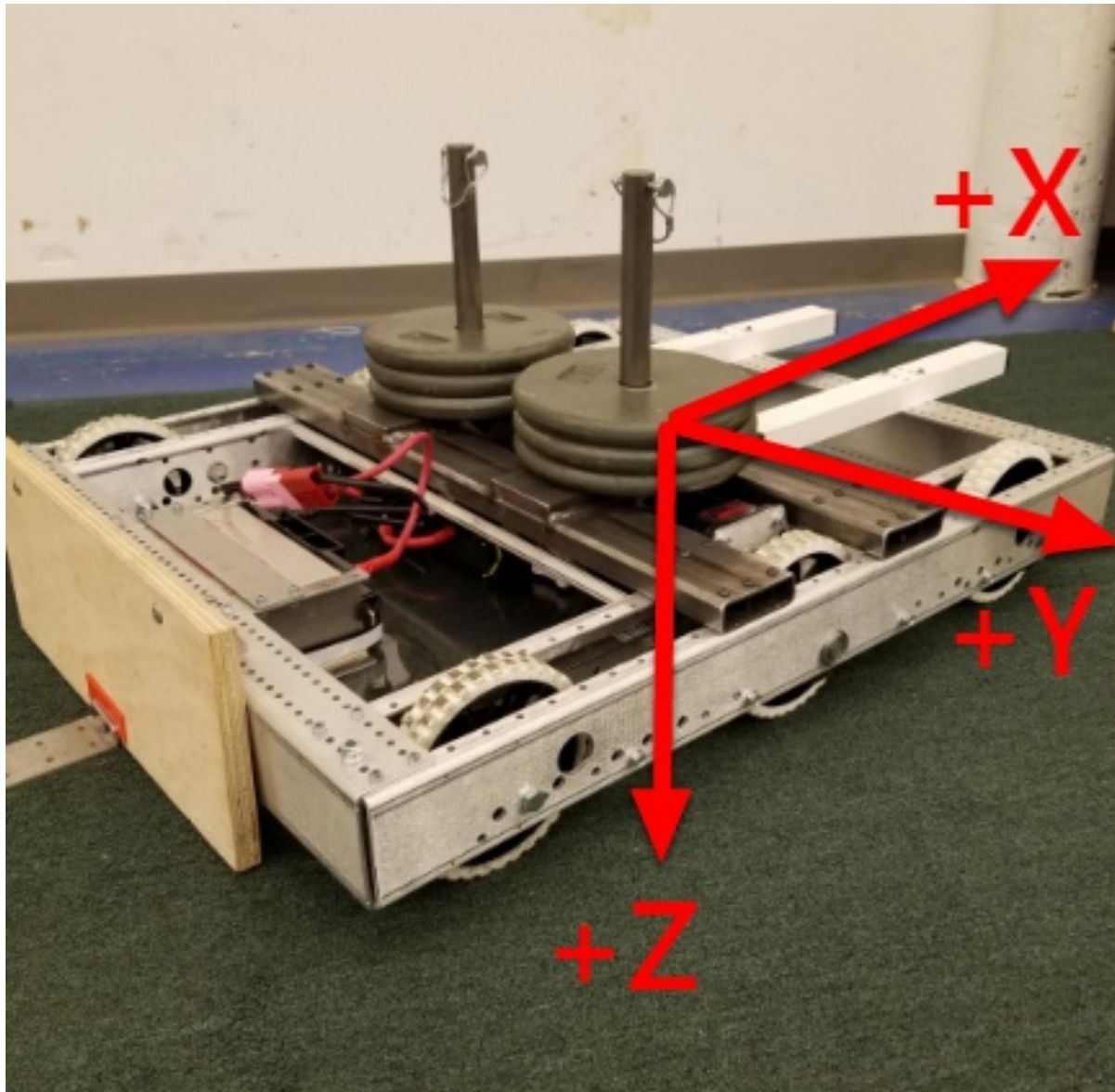
```
exampleJaguar.setSafetyEnabled(true);
exampleJaguar.setSafetyEnabled(false);
exampleJaguar.setExpiration(.1);
exampleJaguar.feed();
```

C++

```
exampleJaguar->SetSafetyEnabled(true);
exampleJaguar->SetSafetyEnabled(false);
exampleJaguar->SetExpiration(.1);
exampleJaguar->Feed();
```

By default all RobotDrive objects enable Motor Safety. Depending on the mechanism and the structure of your program, you may wish to configure the timeout length of the motor safety (in seconds). The timeout length is configured on a per actuator basis and is not a global setting. The default (and minimum useful) value is 100ms.

## Axis Conventions



This library uses the NED axes convention (North-East-Down as external reference in the world frame). The positive X axis points ahead, the positive Y axis points right, and the positive Z axis points down. Rotations follow the right-hand rule, so clockwise rotation around the Z axis is positive.

**Warning:** This convention is different than the convention for joysticks which typically have -Y as Up (commonly mapped to throttle) and +X as Right. Pay close attention to the examples below if you want help with typical Joystick->Drive mapping.

### 5.5.3 Using the DifferentialDrive class to control Differential Drive (WCD) robots

**Note:** WPILib provides separate Robot Drive classes for the most common drive train configurations (differential, mecanum, and Killough). The DifferentialDrive class handles the differential drivetrain configuration. These drive bases typically have two or more in-line traction or omni wheels per side (e.g., 6WD or 8WD) and may also be known as “skid-steer”, “tank drive”, or “West Coast Drive”. The Kit of Parts drivetrain is an example of a differential drive. There are methods to control the drive with 3 different styles (“Tank”, “Arcade”, or “Curvature”), explained in the article below.

DifferentialDrive is a method provided for the control of “skid-steer” or “West Coast” drivetrains, such as the Kit of Parts chassis. Instantiating a DifferentialDrive is as simple as so:

Java

```
public class Robot {
    Spark m_left = new Spark(1);
    Spark m_right = new Spark(2);
    DifferentialDrive m_drive = new DifferentialDrive(m_left, m_right);

    public void robotInit() {
        m_left.setInverted(true); // if you want to invert motor outputs, you must do so
        ↪ here
    }
}
```

C++ (Header)

```
class Robot {
    private:
        frc::Spark m_left{1};
        frc::Spark m_right{2};
        frc::DifferentialDrive m_drive{m_left, m_right};
}
```

C++ (Source)

```
void Robot::RobotInit() {
    m_left.SetInverted(true); // if you want to invert motor outputs, you must do so
    ↪ here
}
```

### Multi-Motor DifferentialDrive with SpeedControllerGroups

Many FRC drivetrains have more than 1 motor on each side. In order to use these with DifferentialDrive, the motors on each side have to be collected into a single SpeedController, using the SpeedControllerGroup class. The examples below show a 4 motor (2 per side) drivetrain. To extend to more motors, simply create the additional controllers and pass them all into the SpeedController group constructor (it takes an arbitrary number of inputs).

Java

```
public class Robot {
    Spark m_frontLeft = new Spark(1);
```

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```

Spark m_rearLeft = new Spark(2);
SpeedControllerGroup m_left = new SpeedControllerGroup(m_frontLeft, m_rearLeft);

Spark m_frontRight = new Spark(3);
Spark m_rearRight = new Spark(4);
SpeedControllerGroup m_right = new SpeedControllerGroup(m_frontRight, m_
↪rearRight);
DifferentialDrive m_drive = new DifferentialDrive(m_left, m_right);

public void robotInit() {
    m_left.setInverted(true); // if you want to invert the entire side you can do ↪
↪so here
}

```

C++ (Header)

```

class Robot {
public:
    frc::Spark m_frontLeft{1};
    frc::Spark m_rearLeft{2};
    frc::SpeedControllerGroup m_left{m_frontLeft, m_rearLeft};

    frc::Spark m_frontRight{3};
    frc::Spark m_rearRight{4};
    frc::SpeedControllerGroup m_right{m_frontRight, m_rearRight};

    frc::DifferentialDrive m_drive{m_left, m_right};
}

```

C++ (Source)

```

void Robot::RobotInit() {
    m_left.SetInverted(true); // if you want to invert the entire side you can do so ↪
↪here
}

```

## Drive Modes

**Note:** The DifferentialDrive class contains three different default modes of driving your robot's motors.

- Tank Drive, which controls the left and right side independently
- Arcade Drive, which controls a forward and turn speed
- Curvature Drive, a subset of Arcade Drive, which makes your robot handle like a car with constant-curvature turns.

As stated above, the DifferentialDrive class contains three default methods for controlling skid-steer or WCD robots. Note that you can create your own methods of controlling the robot's driving and have them call tankDrive() with the derived inputs for left and right motors.

The Tank Drive mode is used to control each side of the drivetrain independently (usually with an individual joystick axis controlling each). This example shows how to use the Y-axis of two

separate joysticks to run the drivetrain in Tank mode. Construction of the objects has been omitted, for above for drivetrain construction and here for Joystick construction.

The Arcade Drive mode is used to control the drivetrain using speed/throttle and rotation rate. This is typically used either with two axes from a single joystick, or split across joysticks (often on a single gamepad) with the throttle coming from one stick and the rotation from another. This example shows how to use a single joystick with the Arcade mode. Construction of the objects has been omitted, for above for drivetrain construction and here for Joystick construction.

Like Arcade Drive, the Curvature Drive mode is used to control the drivetrain using speed/throttle and rotation rate. The difference is that the rotation control is attempting to control radius of curvature instead of rate of heading change. This mode also has a quick-turn parameter that is used to engage a sub-mode that allows for turning in place. This example shows how to use a single joystick with the Curvature mode. Construction of the objects has been omitted, for above for drivetrain construction and here for Joystick construction.

Java

```
public void teleopPeriodic() {
    myDrive.tankDrive(leftStick.getY(), rightStick.getY());
    myDrive.arcadeDrive(driveStick.getY(), driveStick.getX());
    myDrive.curvatureDrive(driveStick.getY(), driveStick.getX(), driveStick.
    ↪GetButton(1));
}
```

C++

```
void TeleopPeriodic() override {
    myDrive.TankDrive(leftStick.GetY(), rightStick.GetY());
    myDrive.ArcadeDrive(driveStick.GetY(), driveStick.GetX());
    myDrive.CurvatureDrive(driveStick.GetY(), driveStick.GetX(), driveStick.
    ↪GetButton(1));
}
```

## 5.6 Repeatable Low Power Movement - Controlling Servos with WPILib

Servo motors are a type of motor which integrates positional feedback into the motor in order to allow a single motor to perform repeatable, controllable movement, taking position as the input signal. WPILib provides the capability to control servos which match the common hobby input specification (PWM signal, 1.0ms-2.0ms pulse width)

### 5.6.1 Constructing a Servo object

Java

```
Servo exampleServo = new Servo(1);
```

C++

```
frc::Servo exampleServo {1};
```



A servo object is constructed by passing a channel.

## 5.6.2 Setting Servo Values

Java

```
exampleServo.set(.5);  
exampleServo.setAngle(75);
```

C++

```
exampleServo.Set(.5);  
exampleServo.SetAngle(75);
```

There are two methods of setting servo values in WPILib:

- Scaled Value - Sets the servo position using a scaled 0 to 1.0 value. 0 corresponds to one extreme of the servo and 1.0 corresponds to the other
- Angle - Set the servo position by specifying the angle, in degrees. This method will work for servos with the same range as the Hitec HS-322HD servo (0 to 170 degrees). Any values passed to this method outside the specified range will be coerced to the boundary.

## 5.7 Addressable LEDs

LED strips have been commonly used by teams for several years for a variety of reasons. They allow teams to debug robot functionality from the audience, provide a visual marker for their robot, and can simply add some visual appeal. WPILib has an API for controlling WS2812 LEDs with their data pin connected via PWM.

### 5.7.1 Instantiating the AddressableLED Object

You first create an AddressableLED object that takes the PWM port as an argument. It *must* be a PWM header on the roboRIO. Then you set the number of LEDs located on your LED strip, with can be done with the `setLength()` function.

---

**Important:** It is important to note that setting the length of the LED header is an expensive task and it's **not** recommended to run this periodically.

---

After the length of the strip has been set, you'll have to create an AddressableLEDBuffer object that takes the number of LEDs as an input. You'll then call `myAddressableLed.setData(myAddressableLEDBuffer)` to set the led output data. Finally, you can call `myAddressableLed.start()` to write the output continuously. Below is a full example of the initialization process.

---

**Note:** C++ does not have an AddressableLEDBuffer, and instead uses an Array.

---

Java



```

21 public void robotInit() {
22     // PWM port 9
23     // Must be a PWM header, not MXP or DIO
24     m_led = new AddressableLED(9);
25
26     // Reuse buffer
27     // Default to a length of 60, start empty output
28     // Length is expensive to set, so only set it once, then just update data
29     m_ledBuffer = new AddressableLEDBuffer(60);
30     m_led.setLength(m_ledBuffer.getLength());
31
32     // Set the data
33     m_led.setData(m_ledBuffer);
34     m_led.start();
35 }

```

C++

```

14 class Robot : public frc::TimedRobot {
15     static constexpr int kLength = 60;
16
17     // PWM port 9
18     // Must be a PWM header, not MXP or DIO
19     frc::AddressableLED m_led{9};
20     std::array<frc::AddressableLED::LEDData, kLength>
21         m_ledBuffer; // Reuse the buffer
22     // Store what the last hue of the first pixel is
23     int firstPixelHue = 0;

```

```

41 void RobotInit() override {
42     // Default to a length of 60, start empty output
43     // Length is expensive to set, so only set it once, then just update data
44     m_led.SetLength(kLength);
45     m_led.SetData(m_ledBuffer);
46     m_led.Start();
47 }

```

## 5.7.2 Setting the Entire Strip to One Color

Color can be set to an individual led on the strip using two methods. “setRGB” which takes RGB values as an input and setHSV() which takes HSV values as an input.

### Using RGB Values

RGB stands for Red, Green, and Blue. This is a fairly common color model as it’s quite easy to understand. LEDs can be set with the setRGB method that takes 4 arguments: index of the LED, amount of red, amount of green, amount of blue. The amount of Red, Green, and Blue are integer values between 0-255.

Java

```

for (var i = 0; i < m_ledBuffer.getLength(); i++) {
    // Sets the specified LED to the RGB values for red

```

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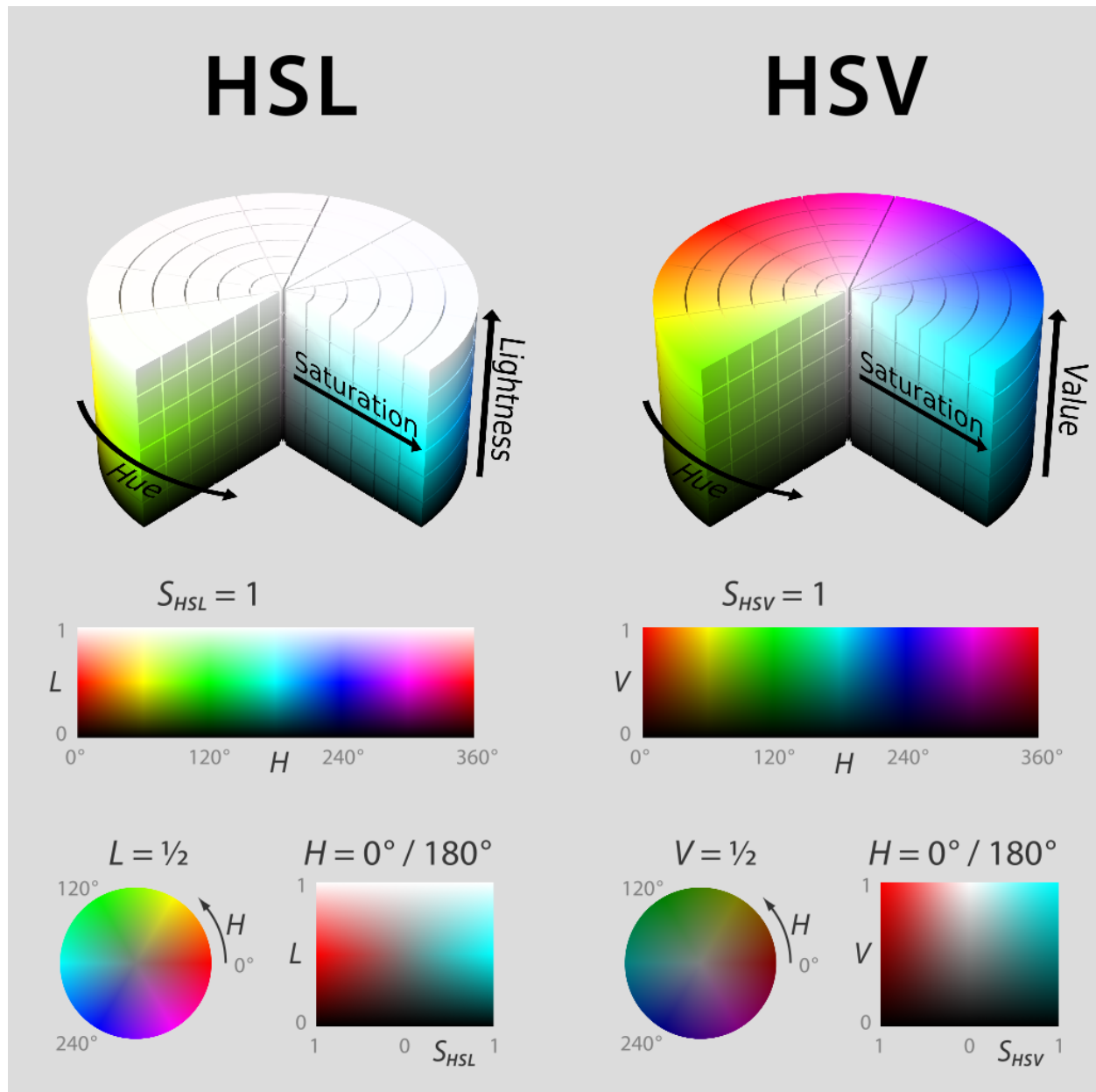
```
m_ledBuffer.setRGB(i, 255, 0, 0);  
}  
m_led.setData(m_ledBuffer);
```

C++

```
for (int i = 0; i < kLength; i++) {  
    m_ledBuffer[i].SetRGB(255, 0, 0);  
}  
m_led.SetData(m_ledBuffer);
```

## Using HSV Values

HSV stands for Hue, Saturation, and Value. Hue describes the color or tint, saturation being the amount of gray, and value being the brightness. In WPILib, Hue is an integer from 0 - 180. Saturation and Value are integers from 0 - 255. If you look at a color picker like [Google's](#), Hue will be 0 - 360 and Saturation and Value are from 0% to 100%. This is the same way that OpenCV handles HSV colors. Make sure the HSV values entered to WPILib are correct, or the color produced might not be the same as was expected.



LEDs can be set with the `setHSV` method that takes 4 arguments: index of the LED, hue, saturation, and value. An example is shown below for setting the color of an LED strip to red (hue of 0).

Java

```
for (var i = 0; i < m_ledBuffer.getLength(); i++) {
    // Sets the specified LED to the HSV values for red
    m_ledBuffer.setHSV(i, 0, 100, 100);
}

m_led.setData(m_ledBuffer);
```

C++

```

for (int i = 0; i < kLength; i++) {
    m_ledBuffer[i].SetHSV(0, 100, 100);
}

m_led.SetData(m_ledBuffer);

```

### 5.7.3 Creating a Rainbow Effect

The below method does a couple of important things. Inside of the *for* loop, it equally distributes the hue over the entire length of the strand and stores the individual LED hue to a variable called *hue*. Then the *for* loop sets the HSV value of that specified pixel using the *hue* value.

Moving outside of the *for* loop, the *m\_rainbowFirstPixelHue* then iterates the pixel that contains the “initial” hue creating the rainbow effect. *m\_rainbowFirstPixelHue* then checks to make sure that the hue is inside the hue boundaries of 180. This is because HSV hue is a value from 0-180.

**Note:** It’s good robot practice to keep the *robotPeriodic()* method as clean as possible, so we’ll create a method for handling setting our LED data. We’ll call this method *rainbow()* and call it from *robotPeriodic()*.

Java

```

45 private void rainbow() {
46     // For every pixel
47     for (var i = 0; i < m_ledBuffer.getLength(); i++) {
48         // Calculate the hue - hue is easier for rainbows because the color
49         // shape is a circle so only one value needs to precess
50         final var hue = (m_rainbowFirstPixelHue + (i * 180 / m_ledBuffer.getLength()))
↪ % 180;
51         // Set the value
52         m_ledBuffer.setHSV(i, hue, 255, 128);
53     }
54     // Increase by to make the rainbow "move"
55     m_rainbowFirstPixelHue += 3;
56     // Check bounds
57     m_rainbowFirstPixelHue %= 180;
58 }

```

C++

```

26 void Rainbow() {
27     // For every pixel
28     for (int i = 0; i < kLength; i++) {
29         // Calculate the hue - hue is easier for rainbows because the color
30         // shape is a circle so only one value needs to precess
31         const auto pixelHue = (firstPixelHue + (i * 180 / kLength)) % 180;
32         // Set the value
33         m_ledBuffer[i].SetHSV(pixelHue, 255, 128);
34     }
35     // Increase by to make the rainbow "move"
36     firstPixelHue += 3;

```

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```
37  // Check bounds
38  firstPixelHue %= 180;
39  }
```

Now that we have our rainbow method created, we have to actually call the method and set the data of the LED.

Java

```
37  @Override
38  public void robotPeriodic() {
39      // Fill the buffer with a rainbow
40      rainbow();
41      // Set the LEDs
42      m_led.setData(m_ledBuffer);
43  }
```

C++

```
49  void RobotPeriodic() override {
50      // Fill the buffer with a rainbow
51      Rainbow();
52      // Set the LEDs
53      m_led.SetData(m_ledBuffer);
54  }
55  };
```

## 6.1 Sensor Overview - Software

---

**Note:** This section covers using sensors in software. For a guide to sensor hardware, see [Sensor Overview - Hardware](#).

---

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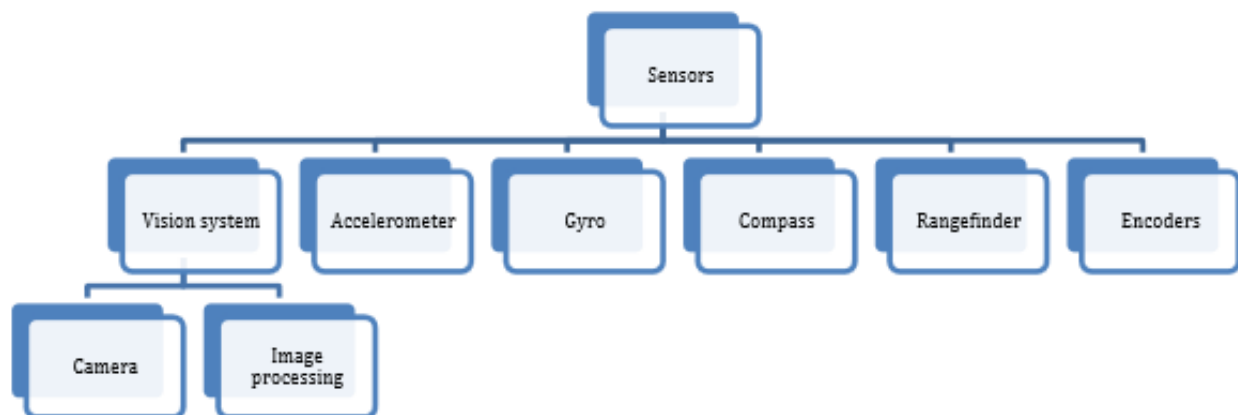
**Note:** While cameras may definitely be considered “sensors”, vision processing is a sufficiently-complicated subject that it is covered in [its own section](#), rather than here.

---

In order to be effective, it is often vital for robots to be able to gather information about their surroundings. Devices that provide feedback to the robot on the state of its environment are called “sensors.” WPILib innately supports a large variety of sensors through classes included in the library. This section will provide a guide to both using common sensor types through WPILib, as well as writing code for sensors without official support.

### 6.1.1 What sensors does WPILIB support?

The roboRIO includes a [FPGA](#) which allows accurate real-time measuring of a variety of sensor input. WPILib, in turn, provides a number of classes for accessing this functionality.



WPILib provides native support for:

- *Accelerometers*
- *Gyroscopes*
- *Ultrasonic rangefinders*
- *Potentiometers*
- *Counters*
- *Quadrature encoders*
- *Limit switches*

Additionally, WPILib includes lower-level classes for interfacing directly with the FPGA's digital and analog inputs and outputs.

## 6.2 Accelerometers - Software

---

**Note:** This section covers accelerometers in software. For a hardware guide to accelerometers, see *Accelerometers - Hardware*.

---

An accelerometer is a device that measures acceleration.

Accelerometers generally come in two types: single-axis and 3-axis. A single-axis accelerometer measures acceleration along one spatial dimension; a 3-axis accelerometer measures acceleration along all three spatial dimensions at once.

WPILib supports single-axis accelerometers through the *AnalogAccelerometer* class.

Three-axis accelerometers often require more complicated communications protocols (such as SPI or I2C) in order to send multi-dimensional data. WPILib has native support for the following 3-axis accelerometers:

- *ADXL345\_I2C*
- *ADXL345\_SPI*
- *ADXL362*
- *BuiltInAccelerometer*

### 6.2.1 AnalogAccelerometer

The *AnalogAccelerometer* class (Java, C++) allows users to read values from a single-axis accelerometer that is connected to one of the roboRIO's analog inputs.

Java

```
// Creates an analog accelerometer on analog input 0
AnalogAccelerometer accelerometer = new AnalogAccelerometer(0);

// Sets the sensitivity of the accelerometer to 1 volt per G
accelerometer.setSensitivity(1);
```

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```
// Sets the zero voltage of the accelerometer to 3 volts
accelerometer.setZero(3);
```

```
// Gets the current acceleration
double accel = accelerometer.getAcceleration();
```

C++

```
// Creates an analog accelerometer on analog input 0
frc::AnalogAccelerometer accelerometer{0};

// Sets the sensitivity of the accelerometer to 1 volt per G
accelerometer.SetSensitivity(1);

// Sets the zero voltage of the accelerometer to 3 volts
accelerometer.SetZero(3);

// Gets the current acceleration
double accel = accelerometer.GetAcceleration();
```

If users have a 3-axis analog accelerometer, they can use three instances of this class, one for each axis.

## 6.2.2 The Accelerometer interface

All 3-axis accelerometers in WPILib implement the Accelerometer interface (Java, C++). This interface defines functionality and settings common to all supported 3-axis accelerometers.

The Accelerometer interface contains getters for the acceleration along each cardinal direction (x, y, and z), as well as a setter for the range of accelerations the accelerometer will measure.

**Warning:** Not all accelerometers are capable of measuring all ranges.

Java

```
// Sets the accelerometer to measure between -8 and 8 G's
accelerometer.setRange(Accelerometer.Range.k8G);
```

C++

```
// Sets the accelerometer to measure between -8 and 8 G's
accelerometer.SetRange(Accelerometer::Range::kRange_8G);
```

### ADXL345\_I2C

The ADXL345\_I2C class (Java, C++) provides support for the ADXL345 accelerometer over the I2C communications bus.

Java



```
// Creates an ADXL345 accelerometer object on the MXP I2C port
// with a measurement range from -8 to 8 G's
Accelerometer accelerometer = new ADXL345_I2C(I2C.Port.kMXP, Accelerometer.Range.k8G);
```

C++

```
// Creates an ADXL345 accelerometer object on the MXP I2C port
// with a measurement range from -8 to 8 G's
frc::ADXL345_I2C accelerometer{I2C::Port::kMXP, Accelerometer::Range::kRange_8G};
```

### ADXL345\_SPI

The ADXL345\_SPI class (Java, C++) provides support for the ADXL345 accelerometer over the SPI communications bus.

Java

```
// Creates an ADXL345 accelerometer object on the MXP SPI port
// with a measurement range from -8 to 8 G's
Accelerometer accelerometer = new ADXL345_SPI(SPI.Port.kMXP, Accelerometer.Range.k8G);
```

C++

```
// Creates an ADXL345 accelerometer object on the MXP SPI port
// with a measurement range from -8 to 8 G's
frc::ADXL345_SPI accelerometer{SPI::Port::kMXP, Accelerometer::Range::kRange_8G};
```

### ADXL362

The ADXL362 class (Java, C++) provides support for the ADXL362 accelerometer over the SPI communications bus.

Java

```
// Creates an ADXL362 accelerometer object on the MXP SPI port
// with a measurement range from -8 to 8 G's
Accelerometer accelerometer = new ADXL362(SPI.Port.kMXP, Accelerometer.Range.k8G);
```

C++

```
// Creates an ADXL362 accelerometer object on the MXP SPI port
// with a measurement range from -8 to 8 G's
frc::ADXL362 accelerometer{SPI::Port::kMXP, Accelerometer::Range::kRange_8G};
```

### BuiltInAccelerometer

The BuiltInAccelerometer class (Java, C++) provides access to the roboRIO's own built-in accelerometer:

Java

```
// Creates an object for the built-in accelerometer
// Range defaults to +/- 8 G's
Accelerometer accelerometer = new BuiltInAccelerometer();
```

C++

```
// Creates an object for the built-in accelerometer
// Range defaults to +/- 8 G's
frc::BuiltInAccelerometer accelerometer{};
```

### 6.2.3 Third-party accelerometers

While WPILib provides native support for a number of accelerometers that are available in the kit of parts or through FIRST Choice, there are a few popular AHRS (Attitude and Heading Reference System) devices commonly used in FRC that include accelerometers. These are generally controlled through vendor libraries, though if they have a simple analog output they can be used with the [AnalogAccelerometer](#) class.

### 6.2.4 Using accelerometers in code

**Note:** Accelerometers, as their name suggests, measure acceleration. Precise accelerometers can be used to determine position through double-integration (since acceleration is the second derivative of position), much in the way that gyroscopes are used to determine heading. However, the accelerometers available for use in FRC are not nearly high-enough quality to be used this way.

It is recommended to use accelerometers in FRC for any application which needs a rough measurement of the current acceleration. This can include detecting collisions with other robots or field elements, so that vulnerable mechanisms can be automatically retracted. They may also be used to determine when the robot is passing over rough terrain for an autonomous routine (such as traversing the defenses in FIRST Stronghold).

For detecting collisions, it is often more robust to measure the jerk than the acceleration. The jerk is the derivative (or rate of change) of acceleration, and indicates how rapidly the forces on the robot are changing - the sudden impulse from a collision causes a sharp spike in the jerk. Jerk can be determined by simply taking the difference of subsequent acceleration measurements, and dividing by the time between them:

Java

```
double prevXAccel = 0;
double prevYAccel = 0;

Accelerometer accelerometer = new BuiltInAccelerometer();

@Override
public void robotPeriodic() {
    // Gets the current accelerations in the X and Y directions
    double xAccel = accelerometer.getX();
    double yAccel = accelerometer.getY();
```

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```

    // Calculates the jerk in the X and Y directions
    // Divides by .02 because default loop timing is 20ms
    double xJerk = (xAccel - prevXAccel)/.02;
    double yJerk = (yAccel - prevYAccel)/.02;

    prevXAccel = xAccel;
    prevYAccel = yAccel;
}

```

C++

```

double prevXAccel = 0;
double prevYAccel = 0;

frc::BuiltInAccelerometer accelerometer{};

void Robot::RobotPeriodic() {
    // Gets the current accelerations in the X and Y directions
    double xAccel = accelerometer.GetX();
    double yAccel = accelerometer.GetY();

    // Calculates the jerk in the X and Y directions
    // Divides by .02 because default loop timing is 20ms
    double xJerk = (xAccel - prevXAccel)/.02;
    double yJerk = (yAccel - prevYAccel)/.02;

    prevXAccel = xAccel;
    prevYAccel = yAccel;
}

```

Most accelerometers legal for FRC use are quite noisy, and it is often a good idea to combine them with the `LinearFilter` class (Java, C++) to reduce the noise:

Java

```

Accelerometer accelerometer = new BuiltInAccelerometer();

// Create a LinearDigitalFilter that will calculate a moving average of the measured
// X acceleration over the past 10 iterations of the main loop
LinearDigitalFilter xAccelFilter = LinearDigitalFilter.movingAverage(10);

@Override
public void robotPeriodic() {
    // Get the filtered X acceleration
    double filteredXAccel = xAccelFilter.calculate(accelerometer.getX());
}

```

C++

```

frc::BuiltInAccelerometer accelerometer;

// Create a LinearDigitalFilter that will calculate a moving average of the measured
// X acceleration over the past 10 iterations of the main loop
auto xAccelFilter = frc::LinearDigitalFilter::MovingAverage(10);

void Robot::RobotPeriodic() {

```

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```
// Get the filtered X acceleration
double filteredXAccel = xAccelFilter.Calculate(accelerometer.GetX());
}
```

## 6.3 Gyroscopes - Software

**Note:** This section covers gyros in software. For a hardware guide to gyros, see [Gyroscopes - Hardware](#).

A gyroscope, or “gyro,” is an angular rate sensor typically used in robotics to measure and/or stabilize robot headings. WPILib natively provides specific support for the ADXRS450 gyro available in the kit of parts, as well as more general support for a wider variety of analog gyros through the [AnalogGyro](#) class.

### 6.3.1 The Gyro interface

All natively-supported gyro objects in WPILib implement the Gyro interface ([Java](#), [C++](#)). This interface provides methods for getting the current angular rate and heading, zeroing the current heading, and calibrating the gyro.

**Note:** It is crucial that the robot remain stationary while calibrating a gyro.

#### ADXRS450\_Gyro

The ADXRS450\_Gyro class ([Java](#), [C++](#)) provides support for the Analog Devices ADXRS450 gyro available in the kit of parts, which connects over the SPI bus.

**Note:** ADXRS450 Gyro accumulation is handled through special circuitry in the FPGA; accordingly only a single instance of ADXRS450\_Gyro may be used.

Java

```
// Creates an ADXRS450 Gyro object on the MXP SPI port
Gyro gyro = new ADXRS450_Gyro(SPI.Port.kMXP);
```

C++

```
// Creates an ADXRS450_Gyro object on the MXP SPI port
ADXRS450_Gyro gyro{SPI::Port::kMXP};
```

#### AnalogGyro

The AnalogGyro class ([Java](#), [C++](#)) provides support for any single-axis gyro with an analog output.

---

**Note:** Gyro accumulation is handled through special circuitry in the FPGA; accordingly, AnalogGyro's may only be used on analog ports 0 and 1.

---

Java

```
// Creates an AnalogGyro object on port 0
Gyro gyro = new AnalogGyro(0);
```

C++

```
// Creates an AnalogGyro object on port 0
AnalogGyro gyro{0};
```

### 6.3.2 Third-party gyros

While WPILib provides native support for the ADXRS450 gyro available in the kit of parts and for any analog gyro, there are a few popular AHRS (Attitude and Heading Reference System) devices commonly used in FRC that include accelerometers and require more complicated communications. These are generally controlled through vendor libraries.

### 6.3.3 Using gyros in code

---

**Note:** As gyros measure rate rather than position, position is inferred by integrating (adding up) the rate signal to get the total change in angle. Thus, gyro angle measurements are always relative to some arbitrary zero angle (determined by the angle of the gyro when either the robot was turned on or a zeroing method was called), and are also subject to accumulated errors (called “drift”) that increase in magnitude the longer the gyro is used. The amount of drift varies with the type of gyro.

---

Gyros are extremely useful in FRC for both measuring and controlling robot heading. Since FRC matches are generally short, total gyro drift over the course of an FRC match tends to be manageably small (on the order of a couple of degrees for a good-quality gyro). Moreover, not all useful gyro applications require the absolute heading measurement to remain accurate over the course of the entire match.

#### Displaying the robot heading on the dashboard

*Shuffleboard* includes a widget for displaying heading data from a Gyro in the form of a compass. This can be helpful for viewing the robot heading when sight lines to the robot are obscured:

Java

```
Gyro gyro = new ADXRS450_Gyro(SPI.Port.kMXP);

public void robotInit() {
    // Places a compass indicator for the gyro heading on the dashboard
    // Explicit down-cast required because Gyro does not extend Sendable
```

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```

    Shuffleboard.getTab("Example tab").add((Sendable) gyro);
}

```

C++

```

frc::ADXRS450_Gyro gyro{frc::SPI::Port::kMXP};

void Robot::RobotInit() {
    // Places a compass indicator for the gyro heading on the dashboard
    frc::Shuffleboard.GetTab("Example tab").Add(gyro);
}

```

### Stabilizing heading while driving

A very common use for a gyro is to stabilize robot heading while driving, so that the robot drives straight. This is especially important for holonomic drives such as mecanum and swerve, but is extremely useful for tank drives as well.

This is typically achieved by closing a PID controller on either the turn rate or the heading, and piping the output of the loop to one's turning control (for a tank drive, this would be a speed differential between the two sides of the drive).

**Warning:** Like with all control loops, users should be careful to ensure that the sensor direction and the turning direction are consistent. If they are not, the loop will be unstable and the robot will turn wildly.

### Example: Tank drive stabilization using turn rate

The following example shows how to stabilize heading using a simple P loop closed on the turn rate. Since a robot that is not turning should have a turn rate of zero, the setpoint for the loop is implicitly zero, making this method very simple.

Java

```

Gyro gyro = new ADXRS450_Gyro(SPI.Port.kMXP);

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive
Spark left1 = new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

```

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```

@Override
public void autonomousPeriodic() {
    // Setpoint is implicitly 0, since we don't want the heading to change
    double error = -gyro.getRate();

    // Drives forward continuously at half speed, using the gyro to stabilize the
    ↪ heading
    drive.tankDrive(.5 + kP * error, .5 - kP * error);
}

```

C++

```

frc::ADXRS450_Gyro gyro{frc::SPI::Port::kMXP};

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive
frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::AutonomousPeriodic() {
    // Setpoint is implicitly 0, since we don't want the heading to change
    double error = -gyro.GetRate();

    // Drives forward continuously at half speed, using the gyro to stabilize the
    ↪ heading
    drive.TankDrive(.5 + kP * error, .5 - kP * error);
}

```

More-advanced implementations can use a more-complicated control loop. When closing the loop on the turn rate for heading stabilization, PI loops are particularly effective.

### Example: Tank drive stabilization using heading

The following example shows how to stabilize heading using a simple P loop closed on the heading. Unlike in the turn rate example, we will need to set the setpoint to the current heading before starting motion, making this method slightly more-complicated.

Java

```

Gyro gyro = new ADXRS450_Gyro(SPI.Port.kMXP);

// The gain for a simple P loop
double kP = 1;

// The heading of the robot when starting the motion
double heading;

```

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```

// Initialize motor controllers and drive
Spark left1 = new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

@Override
public void autonomousInit() {
    // Set setpoint to current heading at start of auto
    heading = gyro.getAngle();
}

@Override
public void autonomousPeriodic() {
    double error = heading - gyro.getAngle();

    // Drives forward continuously at half speed, using the gyro to stabilize the
    // heading
    drive.tankDrive(.5 + kP * error, .5 - kP * error);
}

```

C++

```

frc::ADXRS450_Gyro gyro{frc::SPI::Port::kMXP};

// The gain for a simple P loop
double kP = 1;

// The heading of the robot when starting the motion
double heading;

// Initialize motor controllers and drive
frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::AutonomousInit() {
    // Set setpoint to current heading at start of auto
    heading = gyro.GetAngle();
}

void Robot::AutonomousPeriodic() {
    double error = heading - gyro.GetAngle();
}

```

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```

    // Drives forward continuously at half speed, using the gyro to stabilize the
    ↪ heading
    drive.TankDrive(.5 + kP * error, .5 - kP * error);
}

```

More-advanced implementations can use a more-complicated control loop. When closing the loop on the heading for heading stabilization, PD loops are particularly effective.

### Turning to a set heading

Another common and highly-useful application for a gyro is turning a robot to face a specified direction. This can be a component of an autonomous driving routine, or can be used during teleoperated control to help align a robot with field elements.

Much like with heading stabilization, this is often accomplished with a PID loop - unlike with stabilization, however, the loop can only be closed on the heading. The following example code will turn the robot to face 90 degrees with a simple P loop:

Java

```

Gyro gyro = new ADXRS450_Gyro(SPI.Port.kMXP);

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive
Spark left1 = new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

@Override
public void autonomousPeriodic() {
    // Find the heading error; setpoint is 90
    double error = 90 - gyro.getAngle();

    // Turns the robot to face the desired direction
    drive.tankDrive(kP * error, kP * error);
}

```

C++

```

frc::ADXRS450_Gyro gyro{frc::SPI::Port::kMXP};

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive

```

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```

frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::AutonomousPeriodic() {
    // Find the heading error; setpoint is 90
    double error = 90 - gyro.GetAngle();

    // Turns the robot to face the desired direction
    drive.TankDrive(kP * error, kP * error);
}

```

As before, more-advanced implementations can use more-complicated control loops.

**Note:** Turn-to-angle loops can be tricky to tune correctly due to static friction in the drive-train, especially if a simple P loop is used. There are a number of ways to account for this; one of the most common/effective is to add a “minimum output” to the output of the control loop. Another effective strategy is to cascade to well-tuned velocity controllers on each side of the drive.

## 6.4 Ultrasonics - Software

**Note:** This section covers ultrasonics in software. For a hardware guide to ultrasonics, see [Ultrasonics - Hardware](#).

An ultrasonic sensor is commonly used to measure distance to an object using high-frequency sound. Generally, ultrasonics measure the distance to the closest object within their “field of view.”

There are two primary types of ultrasonics supported natively by WPILib:

- *Ping-response ultrasonics*
- *Analog ultrasonics*

### 6.4.1 Ping-response ultrasonics

The Ultrasonic class ([Java](#), [C++](#)) provides support for ping-response ultrasonics. As ping-response ultrasonics (per the: name) require separate pins for both sending the ping and measuring the response, users must specify DIO pin numbers for both output and input when constructing an Ultrasonic instance:

Java

```
// Creates a ping-response Ultrasonic object on DIO 1 and 2.
Ultrasonic ultrasonic = new Ultrasonic(1, 2);
```

C++

```
// Creates a ping-response Ultrasonic object on DIO 1 and 2.
frc::Ultrasonic ultrasonic{1, 2};
```

It is highly recommended to use ping-response ultrasonics in “automatic mode,” as this will allow WPILib to ensure that multiple sensors do not interfere with each other:

Java

```
// Starts the ultrasonic sensor running in automatic mode
ultrasonic.setAutomaticMode(true);
```

C++

```
// Starts the ultrasonic sensor running in automatic mode
ultrasonic.SetAutomaticMode(true);
```

### 6.4.2 Analog ultrasonics

Some ultrasonic sensors simply return an analog voltage corresponding to the measured distance. These sensors can may simply be used with the [AnalogPotentiometer](#) class.

### 6.4.3 Third-party ultrasonics

Other ultrasonic sensors offered by third-parties may use more complicated communications protocols (such as I2C or SPI). WPILib does not provide native support for any such ultrasonics; they will typically be controlled with vendor libraries.

### 6.4.4 Using ultrasonics in code

Ultrasonic sensors are very useful for determining spacing during autonomous routines. For example, the following code will drive the robot forward until the ultrasonic measures a distance of 12 inches to the nearest object, and then stop:

Java

```
// Creates a ping-response Ultrasonic object on DIO 1 and 2.
Ultrasonic ultrasonic = new Ultrasonic(1, 2);

// Initialize motor controllers and drive
Spark left1 = new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);
```

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```

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

@Override
public void robotInit() {
    // Start the ultrasonic in automatic mode
    ultrasonic.setAutomaticMode(true);
}

@Override
public void autonomousPeriodic() {
    if(ultrasonic.GetRangeInches() > 12) {
        drive.tankDrive(.5, .5);
    }
    else {
        drive.tankDrive(0, 0);
    }
}
}

```

## C++

```

// Creates a ping-response Ultrasonic object on DIO 1 and 2.
frc::Ultrasonic ultrasonic{1, 2};

// Initialize motor controllers and drive
frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::RobotInit() {
    // Start the ultrasonic in automatic mode
    ultrasonic.SetAutomaticMode(true);
}

void Robot::AutonomousPeriodic() {
    if(ultrasonic.GetRangeInches() > 12) {
        drive.TankDrive(.5, .5);
    }
    else {
        drive.TankDrive(0, 0);
    }
}
}

```

Additionally, ping-response ultrasonics can be sent to *Shuffleboard*, where they will be displayed with their own widgets:

## Java

```

// Creates a ping-response Ultrasonic object on DIO 1 and 2.
Ultrasonic ultrasonic = new Ultrasonic(1, 2);

```

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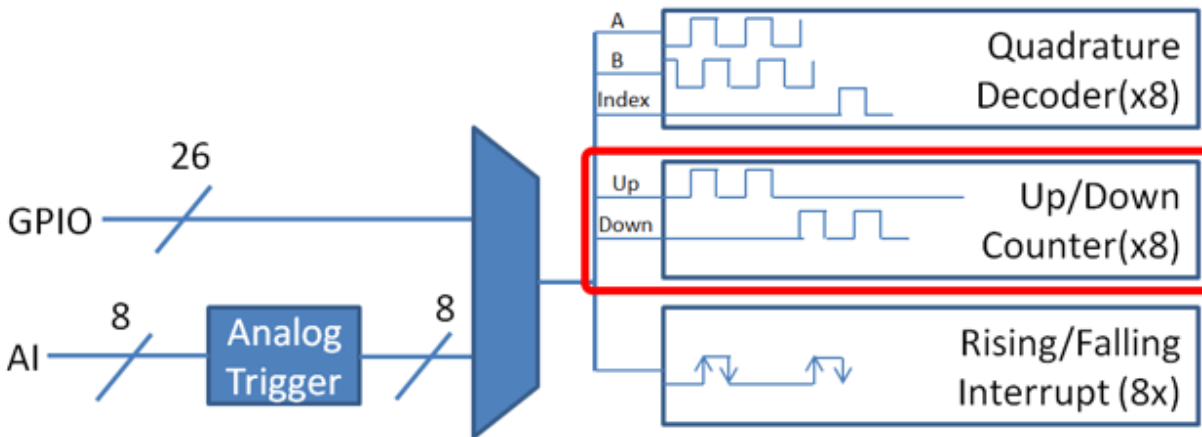
```
public void robotInit() {
    // Places a the ultrasonic on the dashboard
    Shuffleboard.getTab("Example tab").add(ultrasonic);
}
```

C++

```
// Creates a ping-response Ultrasonic object on DIO 1 and 2.
frc::Ultrasonic ultrasonic{1, 2};

void Robot::RobotInit() {
    // Places the ultrasonic on the dashboard
    frc::Shuffleboard.GetTab("Example tab").Add(ultrasonic);
}
```

## 6.5 Counters



The Counter class ([Java](#), [C++](#)) is a versatile class that allows the counting of pulse edges on a digital input. Counter is used as a component in several more-complicated WPILib classes (such as [Encoder](#) and [Ultrasonic](#)), but is also quite useful on its own.

**Note:** There are a total of 8 counter units in the roboRIO FPGA, meaning no more than 8 Counter objects may be instantiated at any one time, including those contained as resources in other WPILib objects. For detailed information on when a Counter may be used by another object, refer to the official API documentation.

### 6.5.1 Configuring a counter

The Counter class can be configured in a number of ways to provide differing functionalities.

#### Counter Modes

The Counter object may be configured to operate in one of four different modes:

1. *Two-pulse mode*: Counts up and down based on the edges of two different channels.
2. *Semi-period mode*: Measures the duration of a pulse on a single channel.
3. *Pulse-length mode*: Counts up and down based on the edges of one channel, with the direction determined by the duration of the pulse on that channel.
4. *External direction mode*: Counts up and down based on the edges of one channel, with a separate channel specifying the direction.

---

**Note:** In all modes except semi-period mode, the counter can be configured to increment either once per edge (2X decoding), or once per pulse (1X decoding). By default, counters are set to two-pulse mode, if only one channel is specified, the counter will only count up.

---

## Two-pulse mode

In two-pulse mode, the Counter will count up for every edge/pulse on the specified “up channel,” and down for every edge/pulse on the specified “down channel.” A counter can be initialized in two-pulse with the following code:

Java

```
// Create a new Counter object in two-pulse mode
Counter counter = new Counter(Counter.Mode.k2Pulse);

@Override
public void robotInit() {
    // Set up the input channels for the counter
    counter.setUpSource(1);
    counter.setDownSource(2);

    // Set the decoding type to 2X
    counter.setUpSourceEdge(true, true);
    counter.setDownSourceEdge(true, true);
}
```

C++

```
// Create a new Counter object in two-pulse mode
frc::Counter counter{frc::Counter::Mode::k2Pulse};

void Robot::RobotInit() {
    // Set up the input channels for the counter
    counter.SetUpSource(1);
    counter.SetDownSource(2);

    // Set the decoding type to 2X
    counter.SetUpSourceEdge(true, true);
    counter.SetDownSourceEdge(true, true);
}
```

## Semi-period mode

In semi-period mode, the Counter will count the duration of the pulses on a channel, either from a rising edge to the next falling edge, or from a falling edge to the next rising edge. A

counter can be initialized in semi-period mode with the following code:

Java

```
// Create a new Counter object in two-pulse mode
Counter counter = new Counter(Counter.Mode.kSemiperiod);

@Override
public void robotInit() {
    // Set up the input channel for the counter
    counter.setUpSource(1);

    // Set the encoder to count pulse duration from rising edge to falling edge
    counter.setSemiPeriodMode(true);
}
```

C++

```
// Create a new Counter object in two-pulse mode
frc::Counter counter{frc::Counter::Mode::kSemiperiod};

void Robot() {
    // Set up the input channel for the counter
    counter.SetUpSource(1);

    // Set the encoder to count pulse duration from rising edge to falling edge
    counter.SetSemiPeriodMode(true);
}
```

To get the pulse width, call the `getPeriod()` method:

Java

```
// Return the measured pulse width in seconds
counter.GetPeriod();
```

C++

```
// Return the measured pulse width in seconds
counter.getPeriod();
```

## Pulse-length mode

In pulse-length mode, the counter will count either up or down depending on the length of the pulse. A pulse below the specified threshold time will be interpreted as a forward count and a pulse above the threshold is a reverse count. This is useful for some gear tooth sensors which encode direction in this manner. A counter can be initialized in this mode as follows:

Java

```
// Create a new Counter object in two-pulse mode
Counter counter = new Counter(Counter.Mode.kPulseLength);

@Override
public void robotInit() {
    // Set up the input channel for the counter
    counter.setUpSource(1);
}
```

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```

// Set the decoding type to 2X
counter.setUpSourceEdge(true, true);

// Set the counter to count down if the pulses are longer than .05 seconds
counter.SetPulseLengthMode(.05)
}

```

C++

```

// Create a new Counter object in two-pulse mode
frc::Counter counter{frc::Counter::Mode::kPulseLength};

void Robot::RobotInit() {
    // Set up the input channel for the counter
    counter.SetUpSource(1);

    // Set the decoding type to 2X
    counter.SetUpSourceEdge(true, true);

    // Set the counter to count down if the pulses are longer than .05 seconds
    counter.setPulseLengthMode(.05)
}

```

## External direction mode

In external direction mode, the counter counts either up or down depending on the level on the second channel. If the direction source is low, the counter will increase, if the direction source is high, the counter will decrease (to reverse this, see the next section). A counter can be initialized in this mode as follows:

Java

```

// Create a new Counter object in two-pulse mode
Counter counter = new Counter(Counter.Mode.kExternalDirection);

@Override
public void robotInit() {
    // Set up the input channels for the counter
    counter.setUpSource(1);
    counter.setDownSource(2);

    // Set the decoding type to 2X
    counter.setUpSourceEdge(true, true);
}

```

C++

```

// Create a new Counter object in two-pulse mode
frc::Counter counter{frc::Counter::Mode::kExternalDirection};

void RobotInit() {
    // Set up the input channels for the counter
    counter.SetUpSource(1);
    counter.SetDownSource(2);
}

```

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```
// Set the decoding type to 2X
counter.SetupSourceEdge(true, true);
```

---

## Configuring counter parameters

---

**Note:** The Counter class does not make any assumptions about units of distance; it will return values in whatever units were used to calculate the distance-per-pulse value. Users thus have complete control over the distance units used. However, units of time are *always* in seconds.

---

---

**Note:** The number of pulses used in the distance-per-pulse calculation does *not* depend on the decoding type - each “pulse” should always be considered to be a full cycle (rising and falling).

---

Apart from the mode-specific configurations, the Counter class offers a number of additional configuration methods:

Java

```
// Configures the counter to return a distance of 4 for every 256 pulses
// Also changes the units of getRate
counter.setDistancePerPulse(4./256.);

// Configures the counter to consider itself stopped after .1 seconds
counter.setMaxPeriod(.1);

// Configures the counter to consider itself stopped when its rate is below 10
counter.setMinRate(10);

// Reverses the direction of the counter
counter.setReverseDirection(true);

// Configures an counter to average its period measurement over 5 samples
// Can be between 1 and 127 samples
counter.setSamplesToAverage(5);
```

C++

```
// Configures the counter to return a distance of 4 for every 256 pulses
// Also changes the units of getRate
counter.SetDistancePerPulse(4./256.);

// Configures the counter to consider itself stopped after .1 seconds
counter.SetMaxPeriod(.1);

// Configures the counter to consider itself stopped when its rate is below 10
counter.SetMinRate(10);

// Reverses the direction of the counter
counter.SetReverseDirection(true);
```

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```
// Configures an counter to average its period measurement over 5 samples
// Can be between 1 and 127 samples
counter.SetSamplesToAverage(5);
```

## 6.5.2 Reading information from counters

Regardless of mode, there is some information that the Counter class always exposes to users:

### Count

Users can obtain the current count with the `get()` method:

Java

```
// returns the current count
counter.get();
```

C++

```
// returns the current count
counter.Get();
```

### Distance

**Note:** Counters measure *relative* distance, not absolute; the distance value returned will depend on the position of the encoder when the robot was turned on or the encoder value was last *reset*.

If the *distance per pulse* has been configured, users can obtain the total distance traveled by the counted sensor with the `getDistance()` method:

Java

```
// returns the current distance
counter.getDistance();
```

C++

```
// returns the current distance
counter.GetDistance();
```

### Rate

**Note:** Units of time for the Counter class are *always* in seconds.

Users can obtain the current rate of change of the counter with the `getRate()` method:

Java

```
// Gets the current rate of the counter
counter.getRate();
```

C++

```
// Gets the current rate of the counter
counter.GetRate();
```

### Stopped

Users can obtain whether the counter is stationary with the `getStopped()` method:

Java

```
// Gets whether the counter is stopped
counter.getStopped();
```

C++

```
// Gets whether the counter is stopped
counter.GetStopped();
```

### Direction

Users can obtain the direction in which the counter last moved with the `getDirection()` method:

Java

```
// Gets the last direction in which the counter moved
counter.getDirection();
```

C++

```
// Gets the last direction in which the counter moved
counter.GetDirection();
```

### Period

---

**Note:** In *semi-period mode*, this method returns the duration of the pulse, not of the period.

---

Users can obtain the duration (in seconds) of the most-recent period with the `getPeriod()` method:

Java

```
// returns the current period in seconds
counter.getPeriod();
```

C++

```
// returns the current period in seconds  
counter.GetPeriod();
```

### 6.5.3 Resetting a counter

To reset a counter to a distance reading of zero, call the `reset()` method. This is useful for ensuring that the measured distance corresponds to the actual desired physical measurement.

Java

```
// Resets the encoder to read a distance of zero  
counter.reset();
```

C++

```
// Resets the encoder to read a distance of zero  
counter.Reset();
```

### 6.5.4 Using counters in code

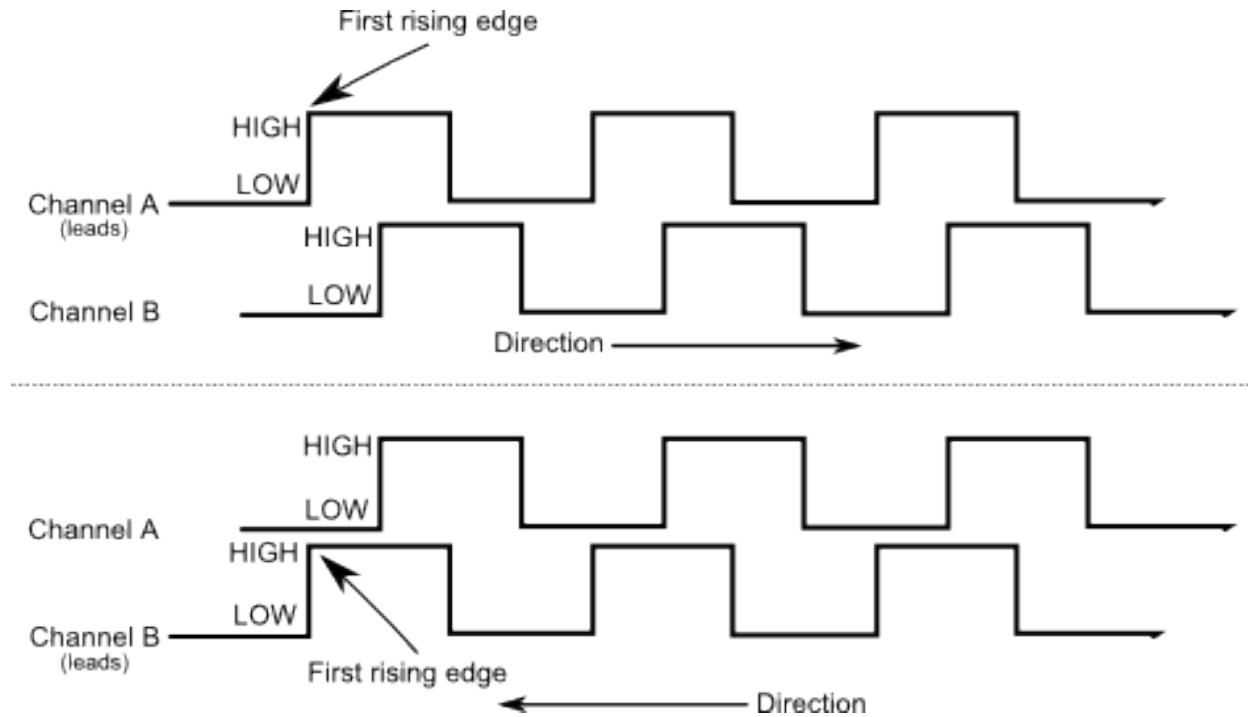
Counters are useful for a wide variety of robot applications - but since the `Counter` class is so varied, it is difficult to provide a good summary of them here. Many of these applications overlap with the `Encoder` class - a simple counter is often a cheaper alternative to a quadrature encoder. For a summary of potential uses for encoders in code, see [Encoders - Software](#).

## 6.6 Encoders - Software

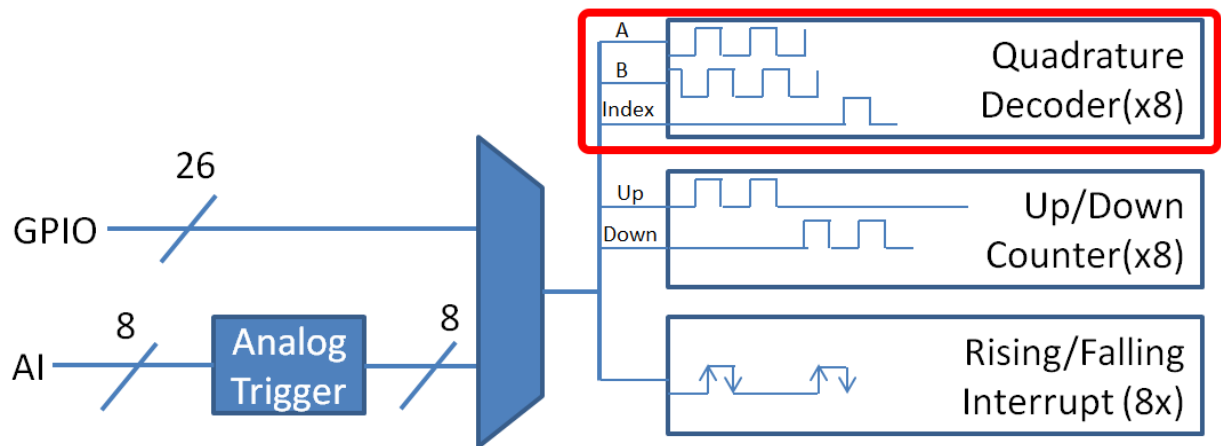
---

**Note:** This section covers encoders in software. For a hardware guide to encoders, see [Encoders - Hardware](#).

---



Encoders are devices used to measure motion (usually, the rotation of a shaft). The encoders used in FRC are known as “quadrature encoders.” These encoders produce square-wave signals on two channels that are a quarter-period out-of-phase (hence the term, “quadrature”). The pulses are used to measure the rotation, and the direction of motion can be determined from which channel “leads” the other.



The FPGA handles encoders either through a counter module or an encoder module, depending on the *decoding type* - the choice is handled automatically by WPILib. The FPGA contains 8 encoder modules.

### 6.6.1 The Encoder class

WPILib provides support for encoders through the Encoder class (Java, C++). This class provides a simple API for configuring and reading data from encoders.

## Initializing an encoder

An encoder can be instantiated as follows:

Java

```
// Initializes an encoder on DIO pins 0 and 1
// Defaults to 4X decoding and non-inverted
Encoder encoder = new Encoder(0, 1);
```

C++

```
// Initializes an encoder on DIO pins 0 and 1
// Defaults to 4X decoding and non-inverted
frc::Encoder encoder{0, 1};
```

## Decoding type

The WPILib Encoder class can decode encoder signals in three different modes:

- **1X Decoding:** Increments the distance for every complete period of the encoder signal (once per four edges).
- **2X Decoding:** Increments the distance for every half-period of the encoder signal (once per two edges).
- **4X Decoding:** Increments the distance for every edge of the encoder signal (four times per period).

4X decoding offers the greatest precision, but at the potential cost of increased “jitter” in rate measurements. To use a different decoding type, use the following constructor:

Java

```
// Initializes an encoder on DIO pins 0 and 1
// 2X encoding and non-inverted
Encoder encoder = new Encoder(0, 1, false, Encoder.EncodingType.k2X);
```

C++

```
// Initializes an encoder on DIO pins 0 and 1
// 2X encoding and non-inverted
frc::Encoder encoder{0, 1, false, frc::Encoder::EncodingType::k2X};
```

## Configuring encoder parameters

**Note:** The Encoder class does not make any assumptions about units of distance; it will return values in whatever units were used to calculate the distance-per-pulse value. Users thus have complete control over the distance units used. However, units of time are *always* in seconds.

**Note:** The number of pulses used in the distance-per-pulse calculation does *not* depend on the *decoding type* - each “pulse” should always be considered to be a full cycle (four edges).

---

The Encoder class offers a number of configuration methods:

Java

```
// Configures the encoder to return a distance of 4 for every 256 pulses
// Also changes the units of getRate
encoder.setDistancePerPulse(4./256.);

// Configures the encoder to consider itself stopped after .1 seconds
encoder.setMaxPeriod(.1);

// Configures the encoder to consider itself stopped when its rate is below 10
encoder.setMinRate(10);

// Reverses the direction of the encoder
encoder.setReverseDirection(true);

// Configures an encoder to average its period measurement over 5 samples
// Can be between 1 and 127 samples
encoder.setSamplesToAverage(5);
```

C++

```
// Configures the encoder to return a distance of 4 for every 256 pulses
// Also changes the units of getRate
encoder.SetDistancePerPulse(4./256.);

// Configures the encoder to consider itself stopped after .1 seconds
encoder.SetMaxPeriod(.1);

// Configures the encoder to consider itself stopped when its rate is below 10
encoder.SetMinRate(10);

// Reverses the direction of the encoder
encoder.SetReverseDirection(true);

// Configures an encoder to average its period measurement over 5 samples
// Can be between 1 and 127 samples
encoder.SetSamplesToAverage(5);
```

### Reading information from encoders

The Encoder class provides a wealth of information to the user about the motion of the encoder.

### Distance

**Note:** Quadrature encoders measure *relative* distance, not absolute; the distance value returned will depend on the position of the encoder when the robot was turned on or the

encoder value was last *reset*.

---

Users can obtain the total distance traveled by the encoder with the `getDistance()` method:

Java

```
// Configures an encoder to return a distance of 4 for every 256 pulses
encoder.setDistancePerPulse(4./256.);
```

C++

```
// Configures an encoder to return a distance of 4 for every 256 pulses
encoder.SetDistancePerPulse(4./256.);
```

## Rate

---

**Note:** Units of time for the Encoder class are *always* in seconds.

---

Users can obtain the current rate of change of the encoder with the `getRate()` method:

Java

```
// Gets the current rate of the encoder
encoder.getRate();
```

C++

```
// Gets the current rate of the encoder
encoder.GetRate();
```

## Stopped

Users can obtain whether the encoder is stationary with the `getStopped()` method:

Java

```
// Gets whether the encoder is stopped
encoder.getStopped();
```

C++

```
// Gets whether the encoder is stopped
encoder.GetStopped();
```

## Direction

Users can obtain the direction in which the encoder last moved with the `getDirection()` method:

Java



```
// Gets the last direction in which the encoder moved
encoder.getDirection();
```

C++

```
// Gets the last direction in which the encoder moved
encoder.GetDirection();
```

### Period

Users can obtain the period of the encoder pulses (in seconds) with the `getPeriod()` method:

Java

```
// Gets the current period of the encoder
encoder.getPeriod();
```

C++

```
// Gets the current period of the encoder
encoder.GetPeriod();
```

### Resetting an encoder

To reset an encoder to a distance reading of zero, call the `reset()` method. This is useful for ensuring that the measured distance corresponds to the actual desired physical measurement, and is often called during a *homing* routine:

Java

```
// Resets the encoder to read a distance of zero
encoder.reset();
```

C++

```
// Resets the encoder to read a distance of zero
encoder.Reset();
```

## 6.6.2 Using encoders in code

Encoders are some of the most useful sensors in FRC; they are very nearly a requirement to make a robot capable of nontrivially-automated actuations and movement. The potential applications of encoders in robot code are too numerous to summarize fully here, but a few basic examples are provided below:

### Driving to a distance

Encoders can be used on a robot drive to create a simple “drive to distance” routine. This is very useful for robot autonomy:

Java

```
// Creates an encoder on DIO ports 0 and 1
Encoder encoder = new Encoder(0, 1);

// Initialize motor controllers and drive
Spark left1 new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

@Override
public void robotInit() {
    // Configures the encoder's distance-per-pulse
    // The robot moves forward 1 foot per encoder rotation
    // There are 256 pulses per encoder rotation
    encoder.setDistancePerPulse(1./256.);
}

@Override
public void autonomousPeriodic() {
    // Drives forward at half speed until the robot has moved 5 feet, then stops:
    if(encoder.getDistance < 5) {
        drive.tankDrive(.5, .5);
    } else {
        drive.tankDrive(0, 0);
    }
}
}
```

## C++

```
// Creates an encoder on DIO ports 0 and 1.
frc::Encoder encoder{0, 1};

// Initialize motor controllers and drive
frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::RobotInit() {
    // Configures the encoder's distance-per-pulse
    // The robot moves forward 1 foot per encoder rotation
    // There are 256 pulses per encoder rotation
    encoder.SetDistancePerPulse(1./256.);
}

void Robot::AutonomousPeriodic() {
```

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```
// Drives forward at half speed until the robot has moved 5 feet, then stops:
if(encoder.GetDistance < 5) {
    drive.TankDrive(.5, .5);
} else {
    drive.TankDrive(0, 0);
}
}
```

## Stabilizing heading

**Warning:** Like with all control loops, users should be careful to ensure that the sensor direction and the turning direction are consistent. If they are not, the loop will be unstable and the robot will turn wildly.

Encoders can be used to ensure that a robot drives straight in a manner quite similar to *how it is done with a gyroscope*. A simple implementation with a P loop is given below:

Java

```
// The encoders for the drive
Encoder leftEncoder = new Encoder(0,1);
Encoder rightEncoder = new Encoder(2,3);

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive
Spark left1 = new Spark(0);
Spark left2 = new Spark(1);

Spark right1 = new Spark(2);
Spark right2 = new Spark(3);

SpeedControllerGroup leftMotors = new SpeedControllerGroup(left1, left2);
SpeedControllerGroup rightMotors = new SpeedControllerGroup(right1, right2);

DifferentialDrive drive = new DifferentialDrive(leftMotors, rightMotors);

@Override
public void autonomousInit() {
    // Configures the encoders' distance-per-pulse
    // The robot moves forward 1 foot per encoder rotation
    // There are 256 pulses per encoder rotation
    leftEncoder.setDistancePerPulse(1./256.);
    rightEncoder.setDistancePerPulse(1./256.);
}

@Override
public void autonomousPeriodic() {
    // Assuming no wheel slip, the difference in encoder distances is proportional to
    // the heading error
    double error = leftEncoder.getDistance() - rightEncoder.getDistance();
}
```

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```

    // Drives forward continuously at half speed, using the encoders to stabilize the
    ↪ heading
    drive.tankDrive(.5 + kP * error, .5 - kP * error);
}

```

C++

```

// The encoders for the drive
frc::Encoder leftEncoder{0,1};
frc::Encoder rightEncoder{2,3};

// The gain for a simple P loop
double kP = 1;

// Initialize motor controllers and drive
frc::Spark left1{0};
frc::Spark left2{1};
frc::Spark right1{2};
frc::Spark right2{3};

frc::SpeedControllerGroup leftMotors{left1, left2};
frc::SpeedControllerGroup rightMotors{right1, right2};

frc::DifferentialDrive drive{leftMotors, rightMotors};

void Robot::AutonomousInit() {
    // Configures the encoders' distance-per-pulse
    // The robot moves forward 1 foot per encoder rotation
    // There are 256 pulses per encoder rotation
    leftEncoder.SetDistancePerPulse(1./256.);
    rightEncoder.SetDistancePerPulse(1./256.);
}

void Robot::AutonomousPeriodic() {
    // Assuming no wheel slip, the difference in encoder distances is proportional to
    ↪ the heading error
    double error = leftEncoder.GetDistance() - rightEncoder.GetDistance();

    // Drives forward continuously at half speed, using the encoders to stabilize the
    ↪ heading
    drive.TankDrive(.5 + kP * error, .5 - kP * error);
}

```

More-advanced implementations can use more-complicated control loops. Closing a control loop on the encoder difference is roughly analogous to closing it on the heading error, and so PD loops are particularly effective.

## PID Control

Encoders are particularly useful as inputs to PID controllers (the heading stabilization example above is a simple P loop).

## Homing an encoded mechanism

Since encoders measure *relative* distance, it is often important to ensure that their “zero-point” is in the right place. A typical way to do this is a “homing routine,” in which a mechanism is moved until it hits a known position (usually accomplished with a limit switch), or “home,” and then the encoder is reset. The following code provides a basic example:

Java

```
Encoder encoder = new Encoder(0, 1);

Spark spark = new Spark(0);

// Limit switch on DIO 2
DigitalInput limit = new DigitalInput(2);

public void autonomousPeriodic() {
    // Runs the motor backwards at half speed until the limit switch is pressed
    // then turn off the motor and reset the encoder
    if(!limit.get()) {
        spark.set(-.5);
    } else {
        spark.set(0);
        encoder.reset();
    }
}
```

C++

```
frc::Encoder encoder{0,1};

frc::Spark spark{0};

// Limit switch on DIO 2
frc::DigitalInput limit{2};

void AutonomousPeriodic() {
    // Runs the motor backwards at half speed until the limit switch is pressed
    // then turn off the motor and reset the encoder
    if(!limit.Get()) {
        spark.Set(-.5);
    } else {
        spark.Set(0);
        encoder.Reset();
    }
}
```

## 6.7 Analog Inputs - Software

---

**Note:** This section covers analog inputs in software. For a hardware guide to analog inputs, see *Analog Inputs - Hardware*.

---

The roboRIO’s FPGA supports up to 8 analog input channels that can be used to read the value of an analog voltage from a sensor. Analog inputs may be used for any sensor that outputs a

simple voltage.

Analog inputs from the FPGA by default return a 12-bit integer proportional to the voltage, from 0 to 5 volts.

### 6.7.1 The AnalogInput class

**Note:** It is often more convenient to use the *Analog Potentiometers* wrapper class than to use AnalogInput directly, as it supports scaling to meaningful units.

Support for reading the voltages on the FPGA analog inputs is provided through the AnalogInput class (Java, C++).

#### Initializing an AnalogInput

An AnalogInput may be initialized as follows:

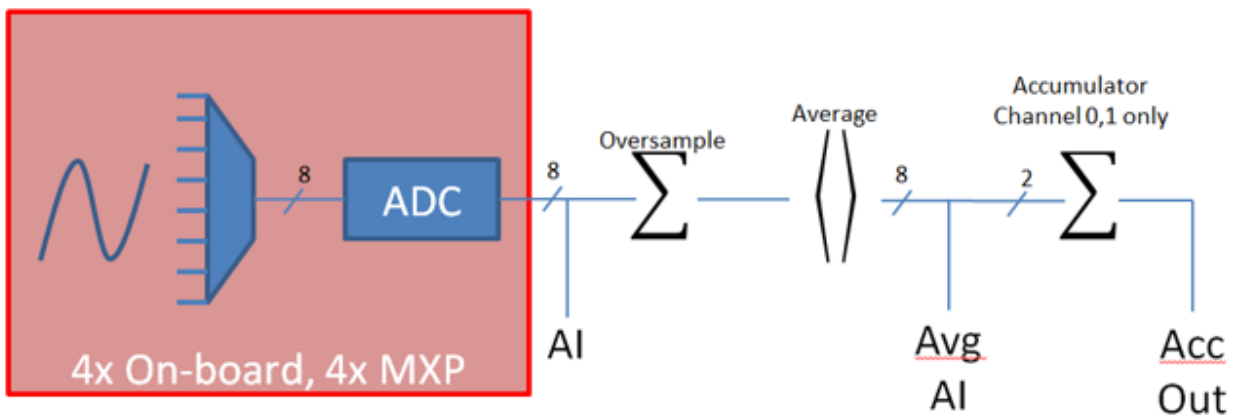
Java

```
// Initializes an AnalogInput on port 0
AnalogInput analog = new AnalogInput(0);
```

C++

```
// Initializes an AnalogInput on port 0
frc::AnalogInput analog{0};
```

#### Oversampling and Averaging



The FPGA's analog input modules supports both oversampling and averaging. These behaviors are highly similar, but differ in a few important ways. Both may be used at the same time.

### Oversampling

When oversampling is enabled, the FPGA will add multiple consecutive samples together, and return the accumulated value. Users may specify the number of *bits* of oversampling - for  $n$  bits of oversampling, the number of samples added together is  $2^n$ :

Java

```
// Sets the AnalogInput to 4-bit oversampling. 16 samples will be added together.  
// Thus, the reported values will increase by about a factor of 16, and the update  
// rate will decrease by a similar amount.  
analog.setOversampleBits(4);
```

C++

```
// Sets the AnalogInput to 4-bit oversampling. 16 samples will be added together.  
// Thus, the reported values will increase by about a factor of 16, and the update  
// rate will decrease by a similar amount.  
analog.SetOversampleBits(4);
```

### Averaging

Averaging behaves much like oversampling, except the accumulated values are divided by the number of samples so that the scaling of the returned values does not change. This is often more-convenient, but occasionally the additional roundoff error introduced by the rounding is undesirable.

Java

```
// Sets the AnalogInput to 4-bit averaging. 16 samples will be averaged together.  
// The update rate will decrease by a factor of 16.  
analog.setAverageBits(4);
```

C++

```
// Sets the AnalogInput to 4-bit averaging. 16 samples will be averaged together.  
// The update rate will decrease by a factor of 16.  
analog.SetAverageBits(4);
```

---

**Note:** When oversampling and averaging are used at the same time, the oversampling is applied *first*, and then the oversampled values are averaged. Thus, 2-bit oversampling and 2-bit averaging used at the same time will increase the scale of the returned values by approximately a factor of 2, and decrease the update rate by approximately a factor of 4.

---

### Reading values from an AnalogInput

Values can be read from an AnalogInput with one of four different methods:

## getValue

The `getValue` method returns the raw instantaneous measured value from the analog input, without applying any calibration and ignoring oversampling and averaging settings. The returned value is an integer.

Java

```
analog.getValue();
```

C++

```
analog.GetValue();
```

## getVoltage

The `getVoltage` method returns the instantaneous measured voltage from the analog input. Oversampling and averaging settings are ignored, but the value is rescaled to represent a voltage. The returned value is a double.

Java

```
analog.getVoltage();
```

C++

```
analog.GetVoltage();
```

## getAverageValue

The `getAverageValue` method returns the averaged value from the analog input. The value is not rescaled, but oversampling and averaging are both applied. The returned value is an integer.

Java

```
analog.getAverageValue();
```

C++

```
analog.GetAverageValue();
```

## getAverageVoltage

The `getAverageVoltage` method returns the averaged voltage from the analog input. Rescaling, oversampling, and averaging are all applied. The returned value is a double.

Java

```
analog.getAverageVoltage();
```

C++



```
analog.GetAverageVoltage();
```

### Accumulator

---

**Note:** The accumulator methods do not currently support returning a value in units of volts - the returned value will always be an integer (specifically, a long).

---

Analog input channels 0 and 1 additionally support an accumulator, which integrates (adds up) the signal indefinitely, so that the returned value is the sum of all past measured values. Oversampling and averaging are applied prior to accumulation.

Java

```
// Sets the initial value of the accumulator to 0
// This is the "starting point" from which the value will change over time
analog.setAccumulatorInitialValue(0);

// Sets the "center" of the accumulator to 0. This value is subtracted from
// all measured values prior to accumulation.
analog.setAccumulatorCenter(0);

// Returns the number of accumulated samples since the accumulator was last started/
↪ reset
analog.getAccumulatorCount();

// Returns the value of the accumulator. Return type is long.
analog.getAccumulatorValue();

// Resets the accumulator to the initial value
analog.resetAccumulator();
```

C++

```
// Sets the initial value of the accumulator to 0
// This is the "starting point" from which the value will change over time
analog.SetAccumulatorInitialValue(0);

// Sets the "center" of the accumulator to 0. This value is subtracted from
// all measured values prior to accumulation.
analog.SetAccumulatorCenter(0);

// Returns the number of accumulated samples since the accumulator was last started/
↪ reset
analog.GetAccumulatorCount();

// Returns the value of the accumulator. Return type is long.
analog.GetAccumulatorValue();

// Resets the accumulator to the initial value
analog.ResetAccumulator();
```

## Obtaining synchronized count and value

Sometimes, it is necessary to obtain matched measurements of the count and the value. This can be done using the `getAccumulatorOutput` method:

Java

```
// Instantiate an AccumulatorResult object to hold the matched measurements
AccumulatorResult result = new AccumulatorResult();

// Fill the AccumulatorResult with the matched measurements
analog.getAccumulatorOutput(result);

// Read the values from the AccumulatorResult
long count = result.count;
long value = result.value;
```

C++

```
// The count and value variables to fill
int_64t count;
int_64t value;

// Fill the count and value variables with the matched measurements
analog.GetAccumulatorOutput(count, value);
```

### 6.7.2 Using analog inputs in code

The `AnalogInput` class can be used to write code for a wide variety of sensors (including potentiometers, accelerometers, gyroscopes, ultrasonics, and more) that return their data as an analog voltage. However, if possible it is almost always more convenient to use one of the other existing WPILib classes that handles the lower-level code (reading the analog voltages and converting them to meaningful units) for you. Users should only directly use `AnalogInput` as a “last resort.”

Accordingly, for examples of how to effectively use analog sensors in code, users should refer to the other pages of this chapter that deal with more-specific classes.

## 6.8 Analog Potentiometers - Software

---

**Note:** This section covers analog potentiometers in software. For a hardware guide to analog potentiometers, see [Analog Potentiometers - Hardware](#).

---

Potentiometers are variable resistors that allow information about position to be converted into an analog voltage signal. This signal can be read by the roboRIO to control whatever device is attached to the potentiometer.

While it is possible to read information from a potentiometer directly with an [Analog Inputs - Software](#), WPILib provides an `AnalogPotentiometer` class (Java, C++) that handles re-scaling the values into meaningful units for the user. It is strongly encouraged to use this class.

In fact, the `AnalogPotentiometer` name is something of a misnomer - this class should be used for the vast majority of sensors that return their signal as a simple, linearly-scaled analog voltage.

### 6.8.1 The `AnalogPotentiometer` class

---

**Note:** The “full range” or “scale” parameters in the `AnalogPotentiometer` constructor are scale factors from a range of 0-1 to the actual range, *not* from 0-5. That is, they represent a native fractional scale, rather than a voltage scale.

---

An `AnalogPotentiometer` can be initialized as follows:

Java

```
// Initializes an AnalogPotentiometer on analog port 0
// The full range of motion (in meaningful external units) is 0-180 (this could be
↪degrees, for instance)
// The "starting point" of the motion, i.e. where the mechanism is located when the
↪potentiometer reads 0v, is 30.

AnalogPotentiometer pot = new AnalogPotentiometer(0, 180, 30);
```

C++

```
// Initializes an AnalogPotentiometer on analog port 0
// The full range of motion (in meaningful external units) is 0-180 (this could be
↪degrees, for instance)
// The "starting point" of the motion, i.e. where the mechanism is located when the
↪potentiometer reads 0v, is 30.

frc::AnalogPotentiometer pot{0, 180, 30};
```

### Customizing the underlying `AnalogInput`

---

**Note:** If the user changes the scaling of the `AnalogInput` with oversampling, this must be reflected in the scale setting passed to the `AnalogPotentiometer`.

---

If the user would like to apply custom settings to the underlying `AnalogInput` used by the `AnalogPotentiometer`, an alternative constructor may be used in which the `AnalogInput` is injected:

Java

```
// Initializes an AnalogInput on port 0, and enables 2-bit averaging
AnalogInput input = new AnalogInput(0);
input.setAverageBits(2);

// Initializes an AnalogPotentiometer with the given AnalogInput
// The full range of motion (in meaningful external units) is 0-180 (this could be
↪degrees, for instance)
// The "starting point" of the motion, i.e. where the mechanism is located when the
↪potentiometer reads 0v, is 30.
```

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```
AnalogPotentiometer pot = new AnalogPotentiometer(input, 180, 30);
```

C++

```
// Initializes an AnalogInput on port 0, and enables 2-bit averaging
frc::AnalogInput input{0};
input.SetAverageBits(2);

// Initializes an AnalogPotentiometer with the given AnalogInput
// The full range of motion (in meaningful external units) is 0-180 (this could be
↪ degrees, for instance)
// The "starting point" of the motion, i.e. where the mechanism is located when the
↪ potentiometer reads 0v, is 30.

frc::AnalogPotentiometer pot{input, 180, 30};
```

### Reading values from the AnalogPotentiometer

The scaled value can be read by simply calling the `get` method:

Java

```
pot.get();
```

C++

```
pot.Get();
```

## 6.8.2 Using AnalogPotentiometers in code

Analog sensors can be used in code much in the way other sensors that measure the same thing can be. If the analog sensor is a potentiometer measuring an arm angle, it can be used similarly to an *encoder*. If it is an ultrasonic sensor, it can be used similarly to other *ultrasonics*.

It is very important to keep in mind that actual, physical potentiometers generally have a limited range of motion. Safeguards should be present in both the physical mechanism and the code to ensure that the mechanism does not break the sensor by traveling past its maximum throw.

## 6.9 Digital Inputs - Software

**Note:** This section covers digital inputs in software. For a hardware guide to digital inputs, see *Digital Inputs - Hardware*.

The roboRIO's FPGA supports up to 26 digital inputs. 10 of these are made available through the built-in DIO ports on the RIO itself, while the other 16 are available through the MXP breakout port.

Digital inputs read one of two states - “high” or “low.” By default, the built-in ports on the RIO will read “high” due to internal pull-up resistors (for more information, see [Digital Inputs - Hardware](#)). Accordingly, digital inputs are most-commonly used with switches of some sort. Support for this usage is provided through the `DigitalInput` class ([Java](#), [C++](#)).

### 6.9.1 The `DigitalInput` class

A `DigitalInput` can be initialized as follows:

Java

```
// Initializes a DigitalInput on DIO 0
DigitalInput input = new DigitalInput(0);
```

C++

```
// Initializes a DigitalInput on DIO 0
frc::DigitalInput input{0};
```

### Reading the value of the `DigitalInput`

The state of the `DigitalInput` can be polled with the `get` method:

Java

```
// Gets the value of the digital input. Returns true if the circuit is open.
input.get();
```

C++

```
// Gets the value of the digital input. Returns true if the circuit is open.
input.Get();
```

### 6.9.2 Creating a `DigitalInput` from an `AnalogInput`

---

**Note:** An `AnalogTrigger` constructed with a port number argument can share that analog port with a separate `AnalogInput`, but two `AnalogInput` objects may not share the same port.

---

Sometimes, it is desirable to use an analog input as a digital input. This can be easily achieved using the `AnalogTrigger` class ([Java](#), [C++](#)).

An `AnalogTrigger` may be initialized as follows. As with `AnalogPotentiometer`, an `AnalogInput` may be passed explicitly if the user wishes to customize the sampling settings:

Java

```
// Initializes an AnalogTrigger on port 0
AnalogTrigger trigger0 = new AnalogTrigger(0);

// Initializes an AnalogInput on port 1 and enables 2-bit oversampling
AnalogInput input = new AnalogInput(1);
```

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```
input.setAverageBits(2);

// Initializes an AnalogTrigger using the above input
AnalogTrigger trigger1 = new AnalogTrigger(input);
```

C++

```
// Initializes an AnalogTrigger on port 0
frc::AnalogTrigger trigger0{0};

// Initializes an AnalogInput on port 1 and enables 2-bit oversampling
frc::AnalogInput input{1};
input.SetAverageBits(2);

// Initializes an AnalogTrigger using the above input
frc::AnalogTrigger trigger1{input};
```

## Setting the trigger points

**Note:** For details on the scaling of “raw” AnalogInput values, see [Analog Inputs - Software](#).

To convert the analog signal to a digital one, it is necessary to specify at what values the trigger will enable and disable. These values may be different to avoid “dithering” around the transition point:

Java

```
// Sets the trigger to enable at a raw value of 3500, and disable at a value of 1000
trigger.setLimitsRaw(1000, 3500);

// Sets the trigger to enable at a voltage of 4 volts, and disable at a value of 1.5
↳volts
trigger.setLimitsVoltage(1.5, 4);
```

C++

```
// Sets the trigger to enable at a raw value of 3500, and disable at a value of 1000
trigger.SetLimitsRaw(1000, 3500);

// Sets the trigger to enable at a voltage of 4 volts, and disable at a value of 1.5
↳volts
trigger.SetLimitsVoltage(1.5, 4);
```

## 6.9.3 Using DigitalInputs in code

As almost all switches on the robot will be used through a DigitalInput, this class is extremely important for effective robot control.

### Limiting the motion of a mechanism

Nearly all motorized mechanisms (such as arms and elevators) in FRC should be given some form of “limit switch” to prevent them from damaging themselves at the end of their range of motions. A short example is given below:

Java

```
Spark spark = new Spark(0);

// Limit switch on DIO 2
DigitalInput limit = new DigitalInput(2);

public void autonomousPeriodic() {
    // Runs the motor forwards at half speed, unless the limit is pressed
    if(!limit.get()) {
        spark.set(.5);
    } else {
        spark.set(0);
    }
}
```

C++

```
// Motor for the mechanism
frc::Spark spark{0};

// Limit switch on DIO 2
frc::DigitalInput limit{2};

void AutonomousPeriodic() {
    // Runs the motor forwards at half speed, unless the limit is pressed
    if(!limit.Get()) {
        spark.Set(.5);
    } else {
        spark.Set(0);
    }
}
```

### Homing an encoded mechanism

Limit switches are very important for being able to “home” an encoded mechanism. For an example of this, see [Homing an encoded mechanism](#).

## 7.1 Using CAN Devices

CAN has many advantages over other methods of connection between the robot controller and peripheral devices.

- CAN connections are daisy-chained from device to device, which often results in much shorter wire runs than having to wire each device to the RIO itself.
- Much more data can be sent over a CAN connection than over a PWM connection - thus, CAN motor controllers are capable of a much more expansive feature-set than are PWM motor controllers.
- CAN is bi-directional, so CAN motor controllers can send data back to the RIO, again facilitating a more expansive feature-set than can be offered by PWM Controllers.

Supported CAN peripherals include:

- CAN speed controllers
- The Power Distribution Panel (PDP)
- The Pneumatics Control Module (PCM)

For instructions on wiring CAN devices, see the relevant section of the *robot wiring guide*.

CAN devices generally have their own WPILib classes. The following sections will describe the use of several of these classes.

## 7.2 Pneumatics Control Module

The Pneumatics Control Module (PCM) is a CAN-based device that provides complete control over the compressor and up to 8 solenoids per module. The PCM is integrated into WPILib through a series of classes that make it simple to use.

The closed loop control of the Compressor and Pressure switch is handled by the Compressor class (Java, C++), and the Solenoids are handled by the Solenoid (Java, C++) and DoubleSolenoid (Java, C++) classes.



An additional PCM module can be used where the modules corresponding solenoids are differentiated by the module number in the constructors of the Solenoid and Compressor classes.

For more information on controlling the compressor, see [Operating a Compressor for Pneumatics](#).

For more information on controlling solenoids, see [Operating Pneumatic Cylinders](#).

## 7.3 Power Distribution Panel

The Power Distribution Panel (PDP) can use its CAN connectivity to communicate a wealth of status information regarding the robot's power use to the roboRIO, for use in user code. The PDP has the capability to report its current temperature, the bus voltage, the total robot current draw, the total robot energy use, and the individual current draw of each device power channel. These data can be used for a number of advanced control techniques, such as motor torque limiting and brownout avoidance.

### 7.3.1 Creating a PDP Object

To use the PDP, create an instance of the `PowerDistributionPanel` class (Java, C++):

C++

```
PowerDistributionPanel examplePDP{0};
```

Java

```
PowerDistributionPanel examplePDP = new PowerDistributionPanel(0);
```

Note: it is not necessary to create a `PowerDistributionPanel` object unless you need to read values from it. The board will work and supply power on all the channels even if the object is never created.

**Warning:** To enable voltage and current logging in the Driver Station, the CAN ID for the PDP *must* be 0.

### 7.3.2 Reading the Bus Voltage

Java

```
examplePDP.getVoltage();
```

C++

```
examplePDP.GetVoltage();
```

Monitoring the bus voltage can be useful for (among other things) detecting when the robot is near a brownout, so that action can be taken to avoid brownout in a controlled manner.

### 7.3.3 Reading the Temperature

Java

```
examplePDP.getTemperature();
```

C++

```
examplePDP.GetTemperature();
```

Monitoring the temperature can be useful for detecting if the robot has been drawing too much power and needs to be shut down for a while, or if there is a short or other wiring problem.

### 7.3.4 Reading the Total Current and Energy

Java

```
examplePDP.getTotalCurrent();  
examplePDP.getTotalEnergy();
```

C++

```
examplePDP.GetTotalCurrent();  
examplePDP.GetTotalEnergy();
```

Monitoring the total current and total energy (the total energy is simply the total current multiplied by the bus voltage) can be useful for controlling how much power is being drawn from the battery, both for preventing brownouts and ensuring that mechanisms have sufficient power available to perform the actions required.

### 7.3.5 Reading Individual Channel Currents

The PDP also allows users to monitor the current drawn by the individual device power channels. For example, to read the current on channel 0:

Java

```
examplePDP.getCurrent(0);
```

C++

```
examplePDP.GetCurrent(0);
```

Monitoring individual device current draws can be useful for detecting shorts or stalled motors.

## 7.4 Third-Party CAN Devices

A number of FRC vendors offer their own CAN peripherals. As CAN devices offer expansive feature-sets, vendor CAN devices require similarly expansive code libraries to operate. As a result, these libraries are not maintained as an official part of WPILib, but are instead

maintained by the vendors themselves. For a guide to installing third-party libraries, see [3rd Party Libraries](#)

A list of common third-party CAN devices from various vendors, along with links to corresponding external documentation, is provided below:

### 7.4.1 Cross-the-Road Electronics

Cross-the-Road Electronics (CTRE) offers several CAN peripherals with external libraries:

#### CTRE Motor Controllers

- **Talon SRX**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)
- **Victor SPX**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)

#### CTRE Sensors

- **Pigeon IMU**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)
- **CANifier**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)

### 7.4.2 REV Robotics

REV Robotics currently offers the SPARK MAX motor controller, which has a similar feature-set to the Talon SRX.

#### REV Motor Controllers

- **SPARK MAX**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)

### 7.4.3 Playing With Fusion

Playing With Fusion (PWF) offers the Venom integrated motor/controller as well as a Time-of-Flight distance sensor:

#### PWF Motor Controllers

- **Venom**
  - [API Documentation \(Java, C++\)](#)
  - [Technical Manual](#)

#### PWF Sensors

- **Time of Flight Sensor**
  - [API Documentation\(Java, C++\)](#)
  - [Technical Manual](#)

## 7.5 FRC CAN Device Specifications

This document seeks to describe the basic functions of the current FRC CAN system and the requirements for any new CAN devices seeking to work with the system.

### 7.5.1 Addressing

FRC CAN nodes assign arbitration IDs based on a pre-defined scheme that breaks the ID into 5 components:

#### Device Type

This is a 5-bit value describing the type of device being addressed. A table of currently assigned device types can be found below. If you wish to have a new device type assigned from the Reserved pool, please submit a request to FIRST.

Device Types	
Broadcast Messages	0
Robot Controller	1
Motor Controller	2
Relay Controller	3
Gyro Sensor	4
Accelerometer	5
Ultrasonic Sensor	6
Gear Tooth Sensor	7
Power Distribution Module	8
Pneumatics Controller	9
Miscellaneous	10
IO Breakout	11
Reserved	12-30
Firmware Update	31

## Manufacturer

This is an 8-bit value indicating the manufacturer of the CAN device. Currently assigned values can be found in the table below. If you wish to have a manufacturer ID assigned from the Reservedpool, please submit a request to FIRST.

Manufacturer	
Broadcast	0
NI	1
Luminary Micro	2
DEKA	3
CTR Electronics	4
REV Robotics	5
Grapple	6
MindSensors	7
Team Use	8
Kauai Labs	9
Copperforge	10
Playing With Fusion	11
Studica	12
Reserved	13-255

## API/Message Identifier

The API or Message Identifier is a 10-bit value that identifies a particular command or message type. These identifiers are unique for each Manufacturer + Device Type combination (so an API identifier that may be a “Voltage Set” for a Luminary Micro Motor Controller may be a “Status Get” for a CTR Electronics Motor Controller or Current Get for a CTR Power Distribution Module).

The Message identifier is further broken down into 2 sub-fields: the 6-bit API Class and the 4-bit API Index.

## API Class

The API Class is a 6-bit identifier for an API grouping. Similar messages are grouped into a single API Class. An example of the API Classes for the Jaguar Motor Controller is shown in the table below.

API Class	
Voltage Control Mode	0
Speed Control Mode	1
Voltage Compensation Mode	2
Position Control Mode	3
Current Control Mode	4
Status	5
Periodic Status	6
Configuration	7
Ack	8

## API Index

The API Index is a 4-bit identifier for a particular message within an API Class. An example of the API Index values for the Jaguar Motor Controller Speed Control API Class is shown in the table below.

API Index	
Enable Control	0
Disable Control	1
Set Setpoint	2
P Constant	3
I Constant	4
D Constant	5
Set Reference	6
Trusted Enable	7
Trusted Set No Ack	8
Trusted Set Setpoint No Ack	10
Set Setpoint No Ack	11

## Device Number

Device Number is a 6-bit quantity indicating the number of the device of a particular type. Devices should default to device ID 0 to match other components of the FRC Control System. Device 0x3F may be reserved for device specific broadcast messages.

### Example

Speed Control Mode Disable from Luminary Micro Jaguar Speed Controller (dev # 4)

	Device Type					Manufacturer Code								API						Device Number									
Field Value	2					2								1						1		4							
Bits	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0		
Bit Position	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

## 7.5.2 Protected Frames

FRC CAN Nodes which implement actuator control capability (motor controllers, relays, pneumatics controllers, etc.) must implement a way to verify that the robot is enabled and that commands originate with the main robot controller (i.e. the roboRIO).

## 7.5.3 Broadcast Messages

Broadcast messages are messages sent to all nodes by setting the device type and manufacturer fields to 0. The API Class for broadcast messages is 0. The currently defined broadcast messages are shown in the table below:

Description	
Disable	0
System Halt	1
System Reset	2
Device Assign	3
Device Query	4
Heartbeat	5
Sync	6
Update	7
Firmware Version	8
Enumerate	9
System Resume	10

Devices should disable immediately when receiving the Disable message (arbID 0), implementation of other broadcast messages is optional.

## 7.5.4 Requirements for FRC CAN Nodes

For CAN Nodes to be accepted for use in the FRC System, they must:

- Communicate using Arbitration IDs which match the prescribed FRC format:
  - A valid, issued CAN Device Type (per Table 1 - CAN Device Types)
  - A valid, issued Manufacturer ID (per Table 2 - CAN Manufacturer Codes)
  - API Class(es) and Index(s) assigned and documented by the device manufacturer

- A user selectable device number if multiple units of the device type are intended to co-exist on the same network.
- Support the minimum Broadcast message requirements as detailed in the Broadcast Messages section.
- If controlling actuators, utilize a scheme to assure that the robot is issuing commands, is enabled, and is still present
- Provide software library support for LabVIEW, C++, and Java or arrange with FIRST or FIRSTs Control System Partners to provide such interfaces.





## 8.1 Git Version Control Introduction

---

**Important:** A more in-depth guide on Git is available on the [Git website](#).

---

[Git](#) is a Distributed Version Control System (VCS) created by Linus Torvalds, also known for creating and maintaining the linux kernel. Version Control is a system for tracking changes of code for developers. The advantages of Git Version Control are:

- Separate testing environments into *branches*
- Ability to navigate to a particular *commit* without removing history
- Ability to manage *commits* in various ways, including combining them
- Various other features, see [here](#)

### 8.1.1 Prerequisites

---

**Important:** This tutorial uses the Windows operating system

---

You have to download and install Git from the following links:

- [Windows](#)
- [macOS](#)
- [Linux](#)

---

**Note:** You may need to add Git to your [path](#)

---

### 8.1.2 Git Vocabulary

Git revolves around several core commands:

- **Repository:** the data structure of your code, including a `.git` folder in the root directory
- **Commit:** a particular saved state of the repository, this includes all files and additions
- **Branch:** a means of separating various commits, having a unique history. This is primarily used for separating development and stable branches.
- **Push:** update the remote repository with your local changes
- **Pull:** update your local repository with the remote changes
- **Clone:** retrieving a local copy of a repository to modify
- **Fork:** duplicating a pre-existing repository to modify, and to compare against the original
- **Merge:** combining various changes from different branches/commits/forks into a single history

### 8.1.3 Repository

A Git repository is a data structure containing the structure, history, and files of a project.

Git repositories usually consist of:

- A `.git` folder. This folder contains the various information about the repository.
- A `.gitignore` file. This file contains the files or directories that you do *not* want included when you commit.
- Files and folders. This is the main content of the repository.

### Creating the repository

You can store the repository locally, or through a remote. A remote being the cloud, or possibly another storage medium that hosts your repository. [Github](#) is a popular free hosting service. Numerous developers use it, and that's what this tutorial will use.

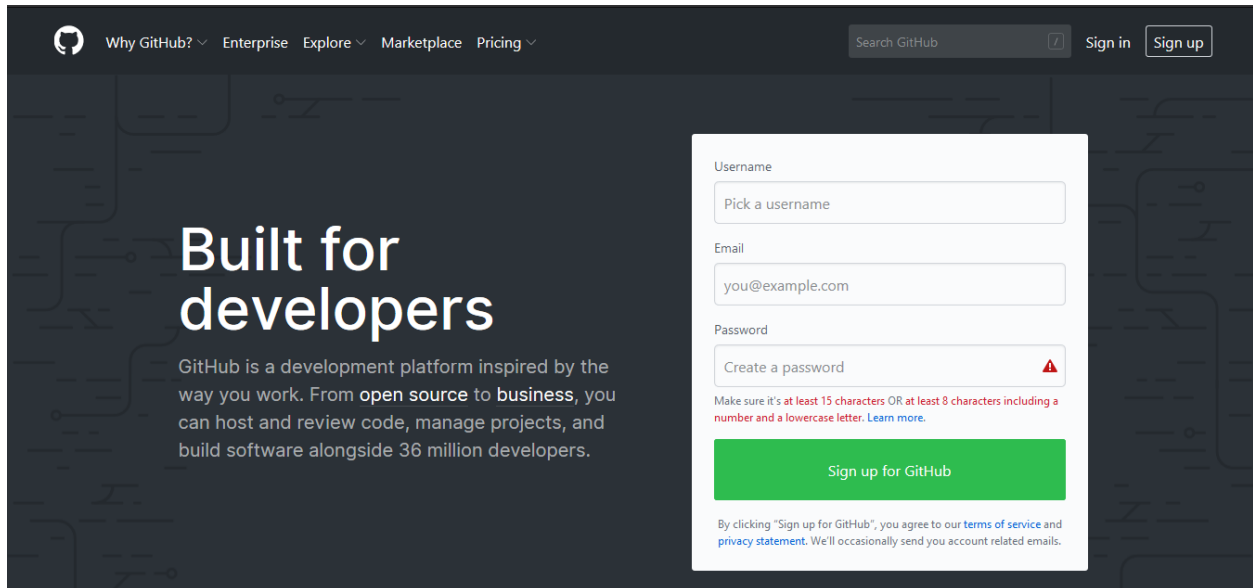
---

**Note:** There are various providers that can host repositories. [Gitlab](#), [Bitbucket](#), and [Cloud-forge](#) are a few alternatives to Github

---

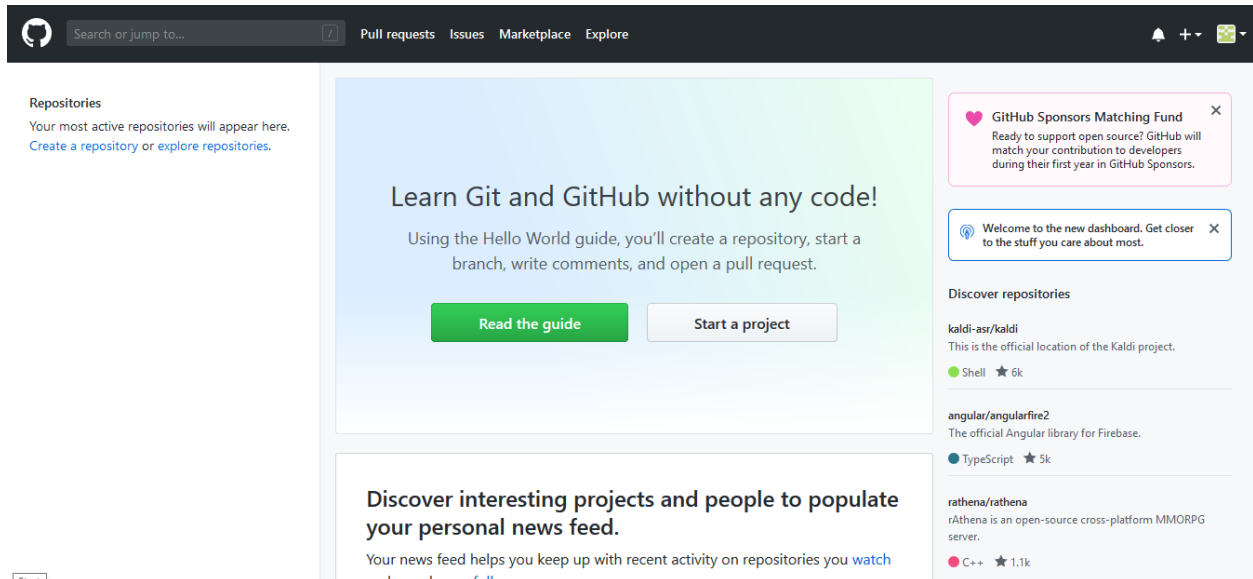
### Creating a Github Account

Go ahead and create a Github account by visiting the [website](#) and following the own screen prompts.

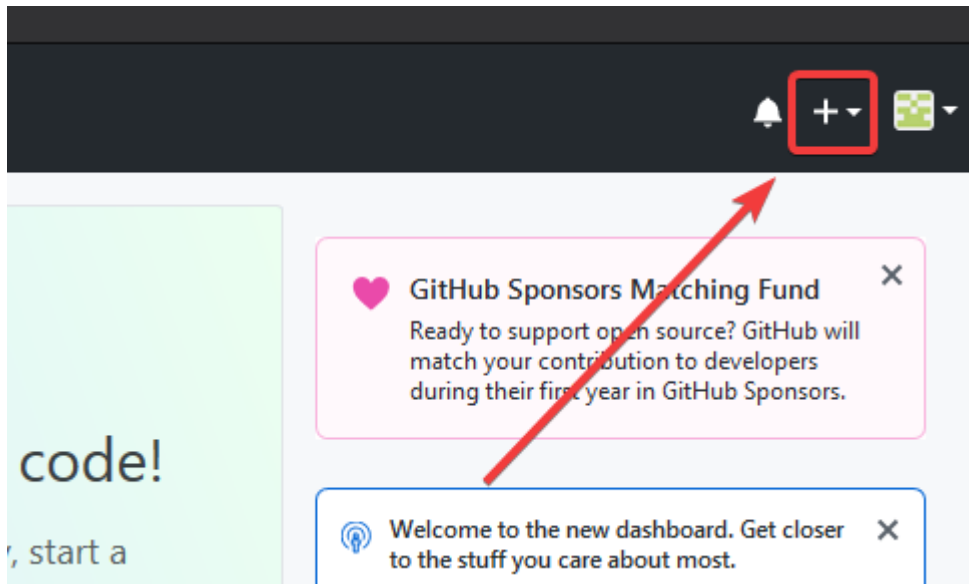


## Local Creation

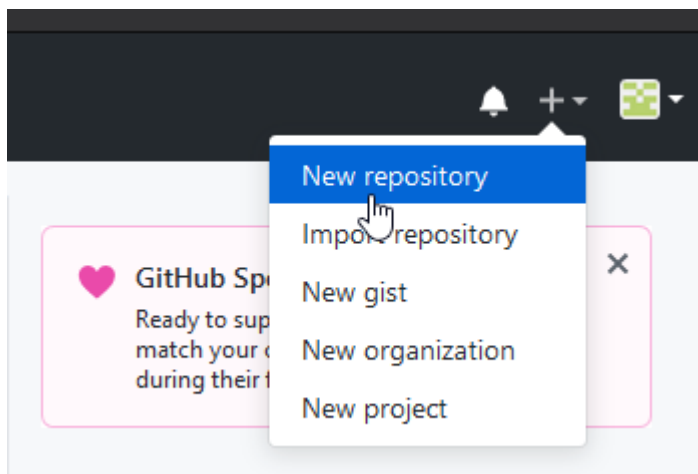
After creating and verifying your account, you'll want to visit the homepage. It'll look similar to the shown image.



Click the plus icon in the top right.



Then click “New Repository”




Fill out the appropriate information, and then click “Create repository”

## Create a new repository

A repository contains all project files, including the revision history. Already have a project repository elsewhere? [Import a repository.](#)



Owner

Repository name \*

 ExampleUser9007 ▾ / ExampleRepo ✓

Great repository names are short and memorable. Need inspiration? How about [reimagined-palm-tree](#)?


Description (optional)

- ☒  **Public**  
Anyone can see this repository. You choose who can commit.
- ☐  **Private**  
You choose who can see and commit to this repository.

☐ **Initialize this repository with a README**

This will let you immediately clone the repository to your computer. Skip this step if you're importing an existing repository.



Add .gitignore: **None** ▾

Add a license: **None** ▾ 

Create repository

You should see a screen similar to this


### Quick setup — if you've done this kind of thing before

 Set up in Desktop or **HTTPS** **SSH** `https://github.com/ExampleUser9007/ExampleRepo.git` 

Get started by [creating a new file](#) or [uploading an existing file](#). We recommend every repository include a [README](#), [LICENSE](#), and [.gitignore](#).


### ...or create a new repository on the command line

```
echo "# ExampleRepo" >> README.md
git init
git add README.md
git commit -m "first commit"
git remote add origin https://github.com/ExampleUser9007/ExampleRepo.git
git push -u origin master
```



### ...or push an existing repository from the command line

```
git remote add origin https://github.com/ExampleUser9007/ExampleRepo.git
git push -u origin master
```



### ...or import code from another repository

You can initialize this repository with code from a Subversion, Mercurial, or TFS project.

Import code

---

**Note:** The keyboard shortcut `ctrl + ~` can be used to open a terminal in Visual Studio Code.

---

Now you'll want to open a powershell window and navigate to your project directory. An excellent tutorial on powershell can be found [here](#). Please consult your search engine on how to open a terminal on alternative operating systems.

#### Windows PowerShell

```
PS C:\Users\daltz\Documents\Example Folder>
```

In the below example, we created a file called `README.md` with the contents of `# Example Repo`. More details on the various commands can be found in the subsequent sections.

```
> cd "C:\Users\ExampleUser9007\Documents\Example Folder"
> git init
```

(continues on next page)

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```
Initialized empty Git repository in C:/Users/ExampleUser9007/Documents/Example Folder/
↪.git/
> echo "# ExampleRepo" >> README.md
> git add README.md
> git commit -m "First commit"
[master (root-commit) fafafa] First commit
 1 file changed, 1 insertions(+), 0 deletions(-)
 create mode 100644 README.md
> git remote add origin https://github.com/ExampleUser9007/ExampleRepo.git
> git push -u origin master
```

### 8.1.4 Commits

Repositories are primarily composed of commits. Commits are saved states or *versions* of code.

In the previous example, we created a file called README.md. Open that file in your favorite text editor and edit a few lines. After tinkering with the file for a bit, simply save and close. Navigate to powershell and type the following commands.

```
> git add README.md
> git commit -m "Adds a description to the repository"
[master bcbcbc] Adds a description to the repository
 1 file changed, 2 insertions(+), 0 deletions(-)
> git push
```

---

**Note:** Writing good commit messages is a key part of a maintainable project. A guide on writing commit messages can be found [here](#).

---

### Git Pull

---

**Note:** `git fetch` can be used when the user does not wish to automatically merge into the current working branch

---

This command retrieves the history or commits from the remote repository. When the remote contains work you do not have, it will attempt to automatically merge. See [Merging](#).

Run: `git pull`

### Git Add

This command adds a selected file(s) to a commit. To commit every file/folder that isn't excluded via *gitignore*.

Run: `git add FILENAME.txt` where FILENAME.txt is the name and extension of the file to add to a commit. Run: `git add .` will add every untracked, unexcluded file when ran in the root of the repository.



## Git Commit

This command creates the commit and stores it locally. This saves the state and adds it to the repositories history.

Run: `git commit -m "type message here"`

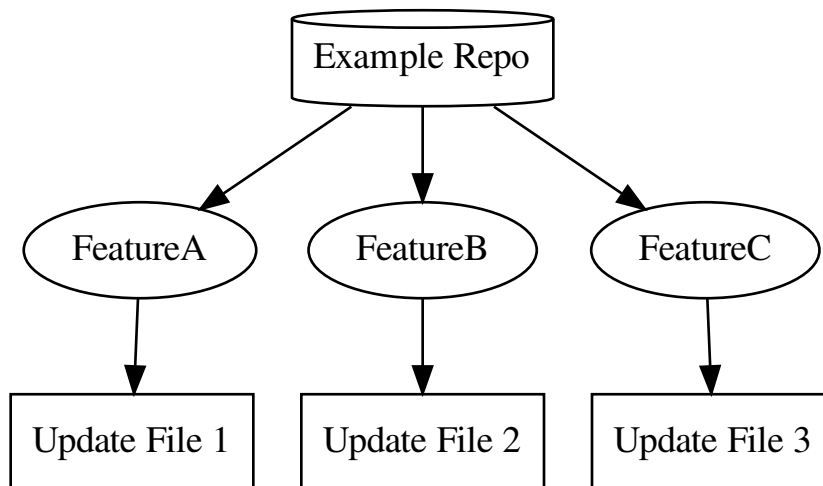
## Git Push

Upload (Push) your local changes to the remote (Cloud)

Run: `git push`

### 8.1.5 Branches

Branches are a similar to parallel worlds to Git. They start off the same, and then they can “branch” out into different varying paths. Consider the Git control flow to look similar to this.



In the above example, FeatureB was merged into FeatureA. This is what is called a merge. You are “merging” the changes from one branch into another.

## Creating a Branch

Run: `git branch branch-name` where branch-name is the name of the branch to create. The new branch history will be created from the current active branch.

## Entering a Branch

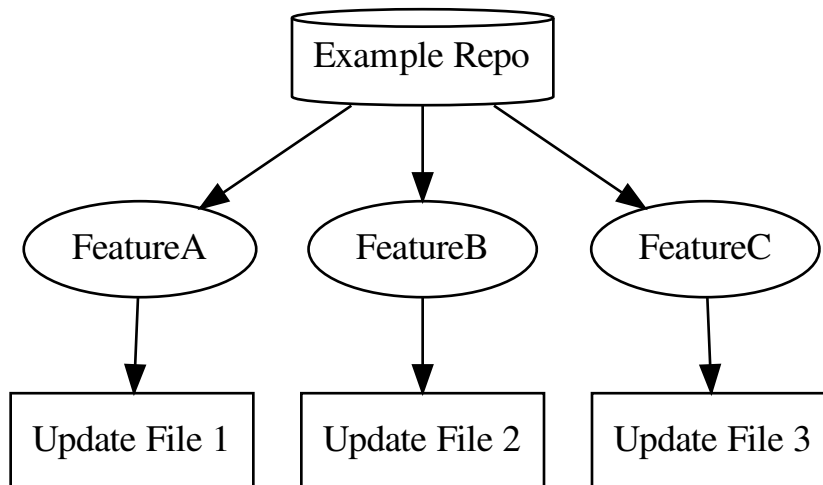
Once a branch is created, you have to then enter the branch.

Run: `git checkout branch-name` where `branch-name` is the branch that was previously created.

### 8.1.6 Merging

In scenarios where you want to copy one branches history into another, you can merge them. A merge is done by calling `git merge branch-name` with `branch-name` being the name of the branch to merge from. It is automatically merged in the current active branch.

It's common for a remote repository to contain work (history) that you do not have. Whenever you run `git pull`, it will attempt to automatically merge those commits. That merge may look like the below.



However, in the above example, what if File 1 was modified by both branch FeatureA and FeatureB? This is called a **merge conflict**. A merge conflict will can be resolved by editing the conflicting file. In the example, we would need to edit File 1 to keep the history or changes that we want. After that has been done. Simply re-add, re-commit, and then push your changes.

### 8.1.7 Resets

Sometimes history needs to be reset, or a commit needs to be undone. This can be done multiple ways.

### Reverting the Commit

---

**Note:** You cannot revert a merge, as git does not know which branch or origin it should choose.

---

To revert history leading up to a commit run `git revert commit-id`. The commit IDs can be shown using the `git log` command.

### Resetting the Head

**Warning:** Forcibly resetting the head is a dangerous command. It permanently erases all history past the target. You have been warned!

Run: `git reset --hard commit-id`.

### 8.1.8 Forks

Forks can be treated similarly to branches. You can merge the upstream (original repository) into the origin (forked repository).

#### Updating a Fork

1. Add the upstream: `git remote add upstream https://github.com/ORIGINAL_OWNER/ORIGINAL_REPOSITORY.git`
2. Confirm it was added via: `git remote -v`
3. Pull changes from upstream: `git fetch upstream`
4. Merge the changes into head: `git merge upstream/upstream-branch-name`

### 8.1.9 Gitignore

---

**Important:** It is extremely important that teams **do not** modify the `.gitignore` file that is included with their robot project. This can lead to offline deployment not working.

---

A `.gitignore` file is commonly used as a list of files to not automatically commit with `git add`. Any files or directory listed in this file will **not** be committed. They will also not show up with `git status`.

Additional Information can be found [here](#)

## Hiding a Folder

Simply add a new line containing the folder to hide, with a forward slash at the end

EX: directory-to-exclude/

## Hiding a File

Add a new line with the name of the file to hide, including any prepending directory relative to the root of the repository.

EX: directory/file-to-hide.txt

EX: file-to-hide2.txt

### 8.1.10 Additional Information

A much more in-depth tutorial can be found at the official [git](#) website.

A guide for correcting common mistakes can be found at the [git flight rules](#) repository.

## 8.2 The C++ Units Library

The 2020 release of WPILib is coupled with a [Units](#) library for C++ teams. This library leverages the C++ [type system](#) to enforce proper dimensionality for method parameters, automatically perform unit conversions, and even allow users to define arbitrary defined unit types. Since the C++ type system is enforced at compile-time, the library has essentially no runtime cost.

### 8.2.1 Using the Units Library

The units library is a header-only library. You must include the `units.h` header in your code files.

```
#include <units/units.h>
```

### Unit Types and Container Types

The C++ units library is based around two sorts of type definitions: unit types and container types.

### Unit Types

Unit types correspond to the abstract concept of a unit, without any actual stored value. Unit types are the fundamental “building block” of the units library - all unit types are defined constructively (using the `compound_unit` template) from a small number of “basic” unit types (such as meters, seconds, etc).

While unit types cannot contain numerical values, their use in building other unit types means that when a type or method uses a [template parameter](#) to specify its dimensionality, that parameter will be a unit type.

### Container Types

Container types correspond to an actual quantity dimensioned according to some unit - that is, they are what actually hold the numerical value. Container types are constructed from unit types with the `unit_t` template. Most unit types have a corresponding container type that has the same name suffixed by `_t` - for example, the unit type `units::meter` corresponds to the container type `units::meter_t`.

Whenever a specific quantity of a unit is used (as a variable or a method parameter), it will be an instance of the container type. By default, container types will store the actual value as a `double` - advanced users may change this by calling the `unit_t` template manually.

A full list of unit and container types can be found in the [documentation](#).

### Creating Instances of Units

To create an instance of a specific unit, we create an instance of its container type:

```
// The variable speed has a value of 5 meters per second.
units::meter_per_second_t speed{5.0};
```

Alternatively, the units library has [type literals](#) defined for some of the more common container types. These can be used in conjunction with type inference via `auto` to define a unit more succinctly:

```
// The variable speed has a value of 5 meters per second.
auto speed = 5_mps;
```

Units can also be initialized using a value of an another container type, as long as the types can be converted between one another. For example, a `meter_t` value can be created from a `foot_t` value.

```
auto feet = 6_ft;
units::meter_t meters{feet};
```

In fact, all container types representing convertible unit types are *implicitly convertible*. Thus, the following is perfectly legal:

```
units::meter_t distance = 6_ft;
```

In short, we can use *any* unit of length in place of *any other* unit of length, anywhere in our code; the units library will automatically perform the correct conversion for us.

### Performing Arithmetic with Units

Container types support all of the ordinary arithmetic operations of their underlying data type, with the added condition that the operation must be *dimensionally* sound. Thus, addition must always be performed on two compatible container types:

```
// Add two meter_t values together
auto sum = 5_m + 7_m; // sum is 12_m

// Adds meters to feet; both are length, so this is fine
auto sum = 5_m + 7_ft;

// Tries to add a meter_t to a second_t, will throw a compile-time error
auto sum = 5_m + 7_s;
```

Multiplication may be performed on any pair of container types, and yields the container type of a compound unit:

**Note:** When a calculation yields a compound unit type, this type will only be checked for validity at the point of operation if the result type is specified explicitly. If `auto` is used, this check will not occur. For example, when we divide distance by time, we may want to ensure the result is, indeed, a velocity (i.e. `units::meter_per_second_t`). If the return type is declared as `auto`, this check will not be made.

```
// Multiply two meter_t values, result is square_meter_t
auto product = 5_m * 7_m; // product is 35_sq_m
```

```
// Divide a meter_t value by a second_t, result is a meter_per_second_t
units::meter_per_second_t speed = 6_m / 0.5_s; // speed is 12_mps
```

## <cmath> Functions

Some `std` functions (such as `clamp`) are templated to accept any type on which the arithmetic operations can be performed. Quantities stored as container types will work with these functions without issue.

However, other `std` functions work only on ordinary numerical types (e.g. `double`). The units library's `units::math` namespace contains wrappers for several of these functions that accept units. Examples of such functions include `sqrt`, `pow`, etc.

```
auto area = 36_sq_m;
units::meter_t sideLength = units::math::sqrt(area);
```

## Removing the Unit Wrapper

To convert a container type to a raw numeric value, the `to<...>()` method can be used, where the template argument is the underlying type.

```
units::meter_t distance = 6.5_m;
double distanceMeters = distance.to<double>();
```

## 8.2.2 Example of the Units Library in WPILib Code

Several arguments for methods in new features of WPILib (ex. *kinematics*) use the units library. Here is an example of *sampling a trajectory*.

```
// Sample the trajectory at 1.2 seconds. This represents where the robot
// should be after 1.2 seconds of traversal.
Trajectory::State point = trajectory.Sample(1.2_s);

// Since units of time are implicitly convertible, this is exactly equivalent to the
↪above code
Trajectory::State point = trajectory.Sample(1200_ms);
```

Some WPILib classes represent objects that could naturally work with multiple choices of unit types - for example, a motion profile might operate on either linear distance (e.g. meters) or angular distance (e.g. radians). For such classes, the unit type is required as a template parameter:

```
// Creates a new set of trapezoidal motion profile constraints
// Max velocity of 10 meters per second
// Max acceleration of 20 meters per second squared
frc::TrapezoidProfile<units::meters>::Constraints{10_mps, 20_mps_sq};

// Creates a new set of trapezoidal motion profile constraints
// Max velocity of 10 radians per second
// Max acceleration of 20 radians per second squared
frc::TrapezoidProfile<units::radians>::Constraints{10_rad_per_s, 20__rad_per_s / 1_s};
```

For more detailed documentation, please visit the official [GitHub page](#) for the units library.

## Support Resources

In addition to the documentation here, there are a variety of other resources available to FRC® teams to help understand the Control System and software.

### 9.1 Other Documentation

In addition to this site there are a few other places teams may check for documentation:

- [NI FRC Community Documents Section](#)
- [FIRST Inspires Technical Resources Page](#)
- [CTRE Product Pages](#)

### 9.2 Forums

Stuck? Have a question not answered by the documentation? Official Support is provided on these forums:

- [NI FRC Community Discussion Section](#) (roboRIO, LabVIEW and Driver Station software questions)
- [FIRST Inspires Control System Forum](#) (wiring, hardware and Driver Station questions)
- [FIRST Inspires Programming Forum](#) (programming questions for C++, Java, or LabVIEW)

### 9.3 NI Phone Support

Have a LabVIEW, roboRIO, or Driver Station question? NI provides phone support for FRC teams during the build season at +1 (866) 511-6285 1:00-7:00 PM CST Monday - Friday.



## 9.4 CTRE Support

Support for Cross The Road Electronics components (Pneumatics Control Module, Power Distribution Panel, Talon SRX, and Voltage Regulator Module) is provided via the e-mail address [support@crosstheroadelectronics.com](mailto:support@crosstheroadelectronics.com)

## 9.5 Bug Reporting

Found a bug? Let us know by reporting it in the Issues section of the appropriate WPILibSuite project on Github: <https://github.com/wpilibsuite>

## 10.1 Imaging your Classmate (Veteran Image Download)

---

**Note:** Veteran teams are not required to re-image their classmate

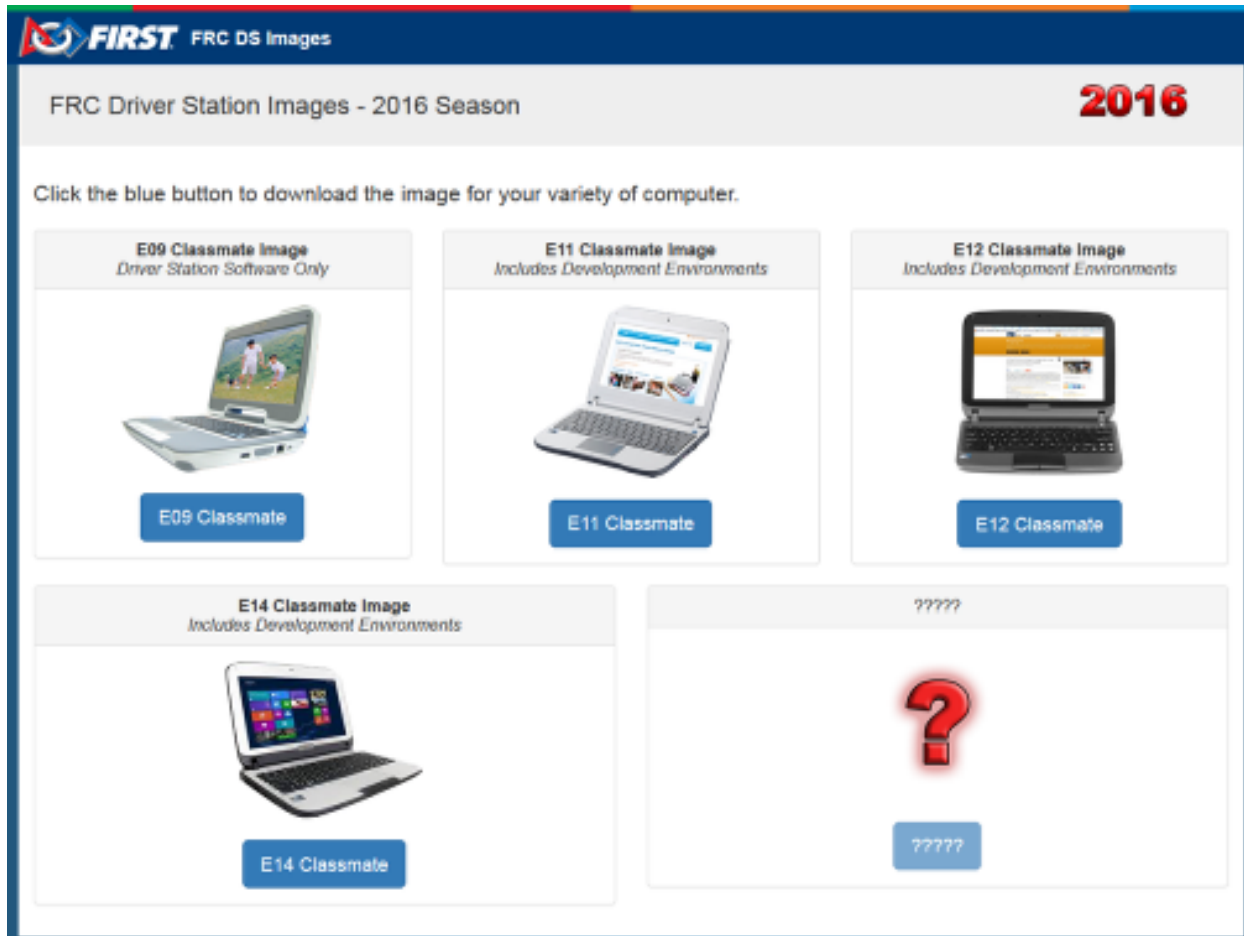
---

This document describes the procedure for creating a bootable USB drive to restore the FRC image on a Classmate computer. If you do not wish to re-image your Classmate then you can start with the appropriate document for C++/Java, LabVIEW, or DS only.

### 10.1.1 Prerequisites

1. E09, E11, E12, or E14 Classmate computer or Acer ES1 computer
2. 16GB or larger USB drive
3. 7-Zip software installed (download [here](#)). As of the writing of this document, the current released version is 19.00 (2019-02-21).
4. RMprepUSB software installed (download [here](#)). Scroll down the page and select the stable (Full) version download link. As of the writing of this document, the current stable version is 2.1.743e.

### 10.1.2 Download the Computer Image



Download the image from the [FIRST FRC Driver Station System Image Portal](#). There are several computer images available, one for each model. On the download site, select the option that matches your computer by clicking the button below the image. Due to the limited size of the hard drive in the E09, it is supported with a DS/Utilities image only and does not have the IDEs for LabVIEW or C++/Java installed. All other images have the LabVIEW base installation already present.

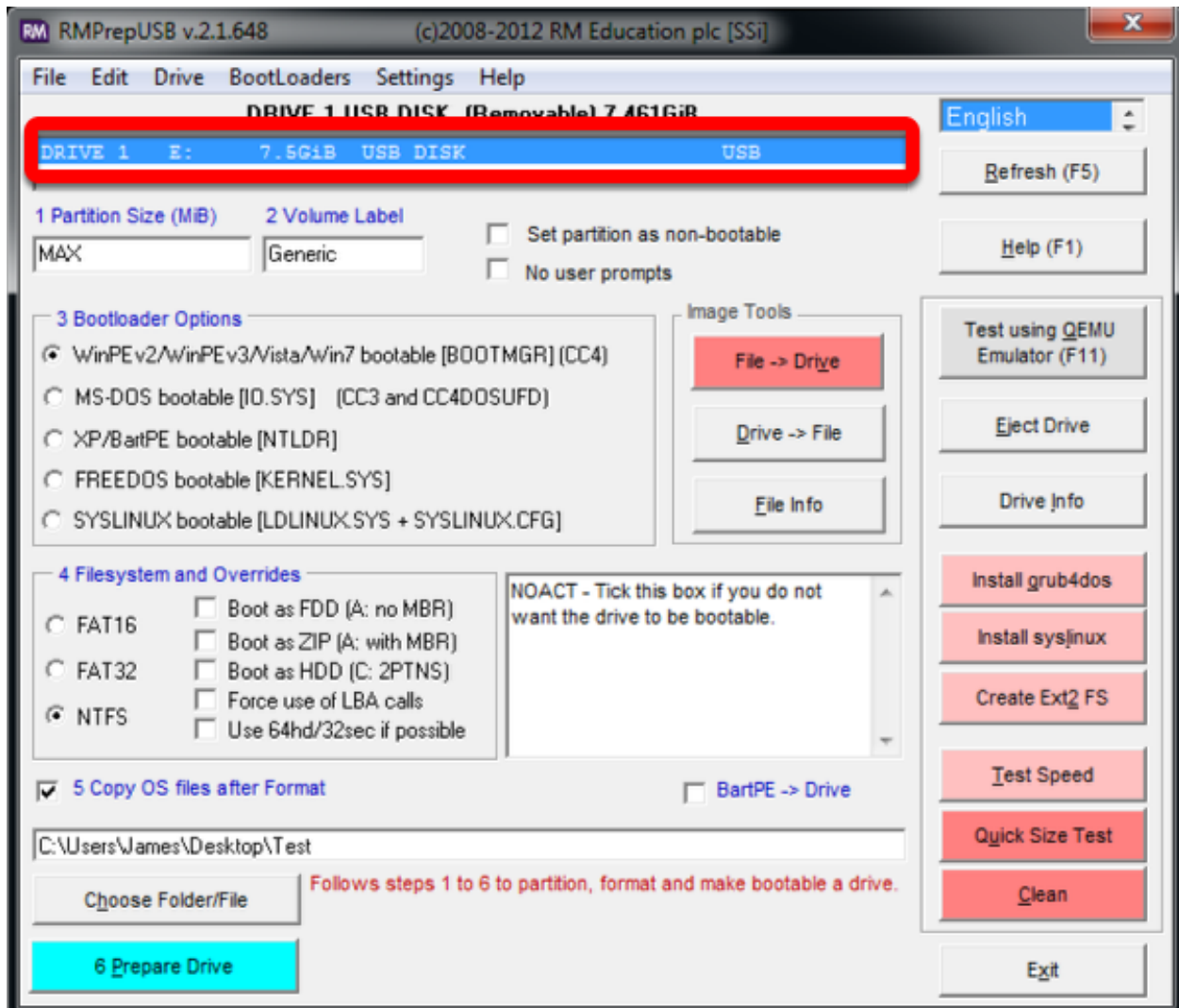
**Note:** These images only install the prerequisite core FRC software, it is still necessary to install the FRC specific updates. See the Update Software step for more information.

**Warning:** Due to computer availability, the E14 image provided is the 2018 image. If using this image, teams may need to remove the old IDE (LabVIEW or Eclipse) and install the new IDE.

### 10.1.3 Preparation

1. Place the image file downloaded from the site to a folder on your root drive (e.g. C:\2016\_Image).
2. Connect 16GB or larger USB Flash drive to the PC to use as the new restoration drive.

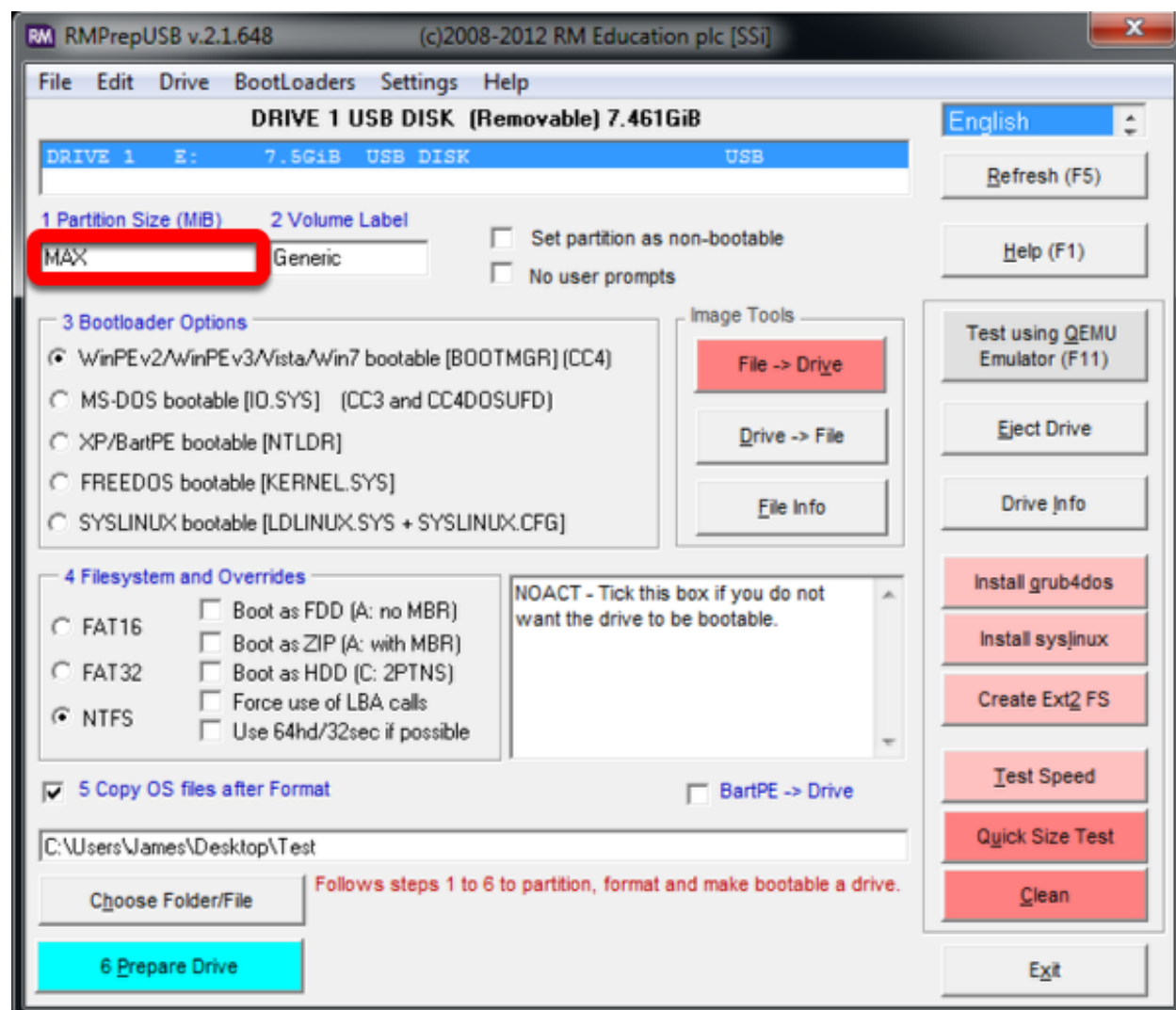
### 10.1.4 RMPrep



Start/Run RMPrepUSB

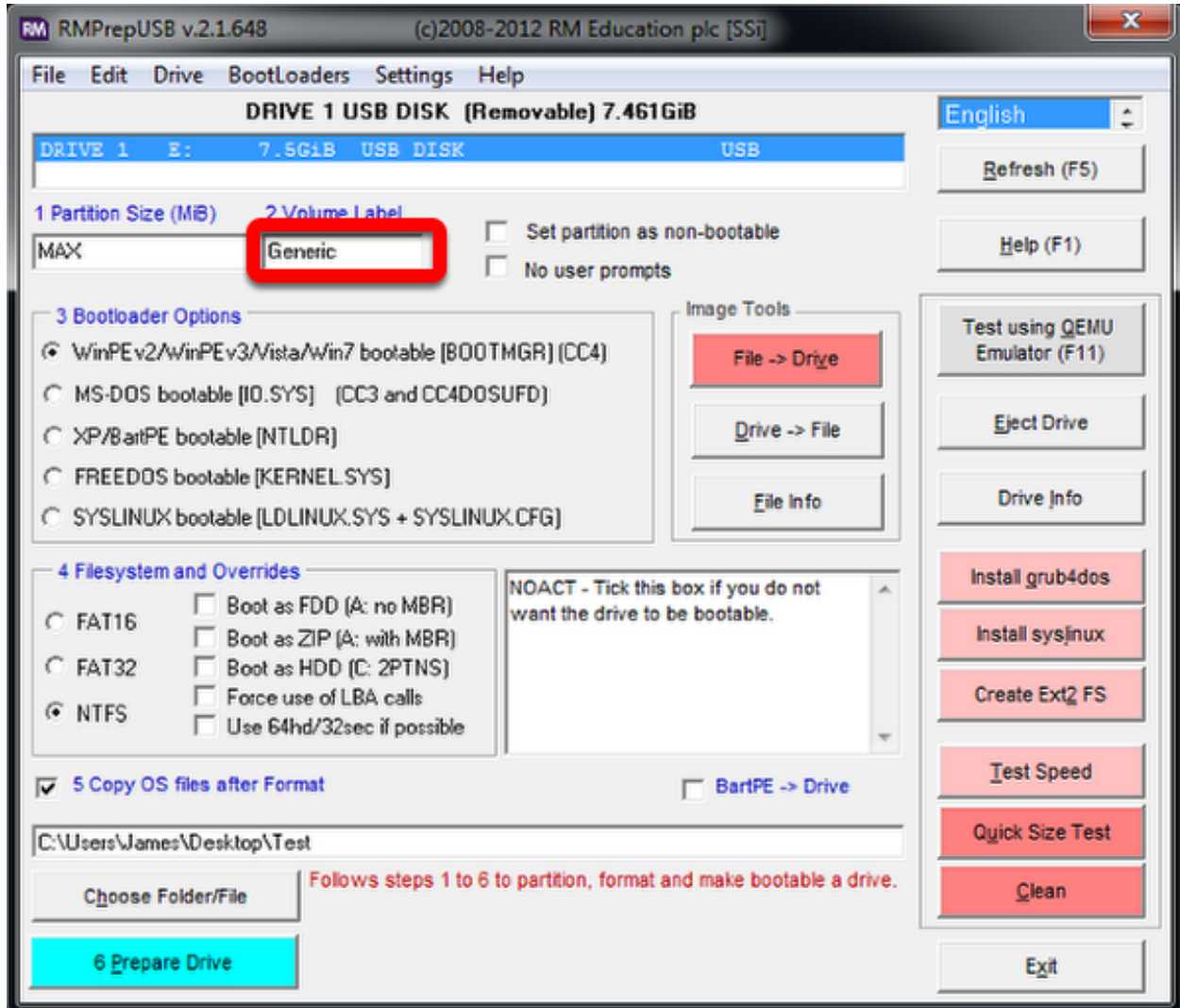
Select USB Drive

## Set Partition Size



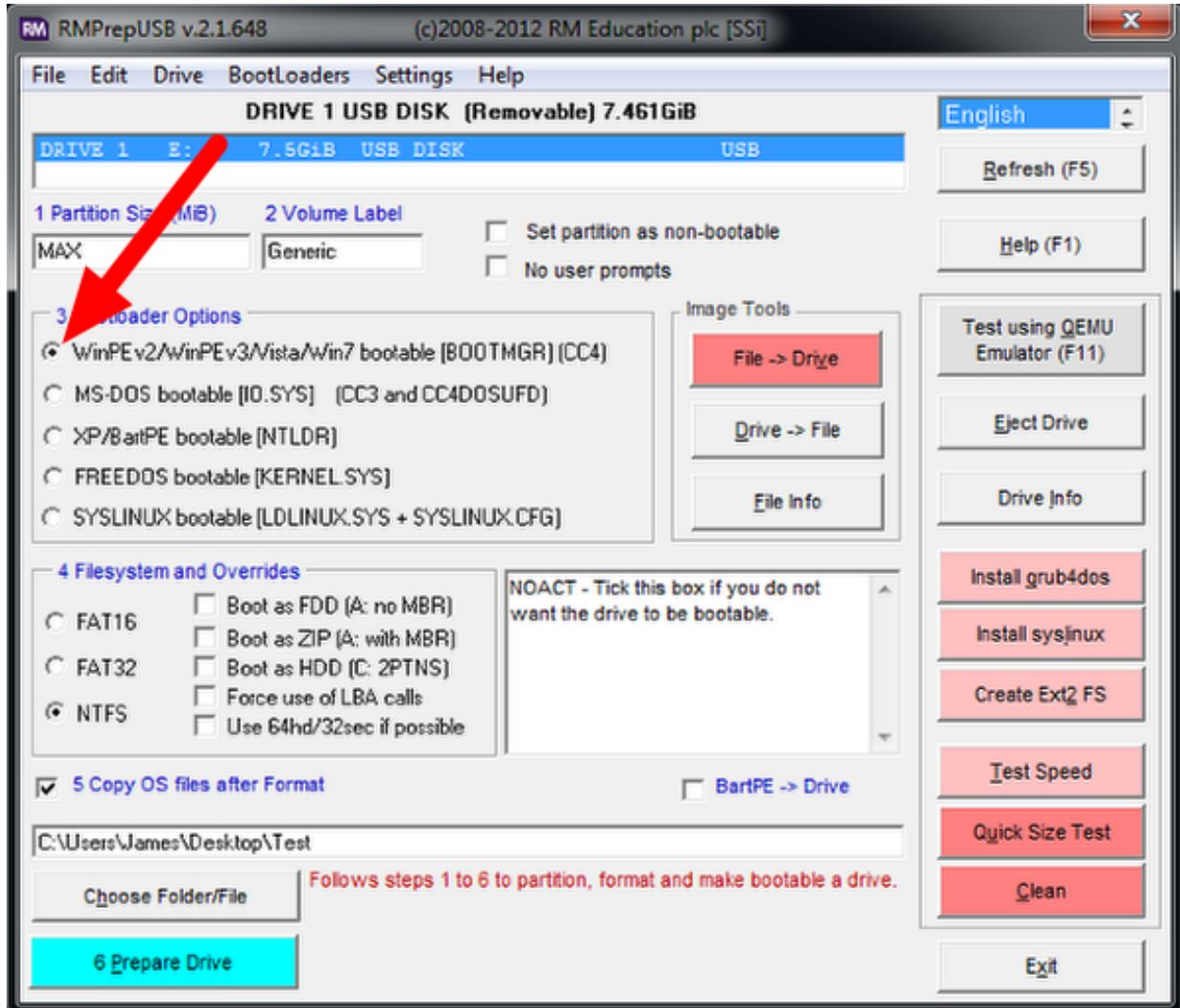
Set Partition Size to MAX

## Set Volume Label



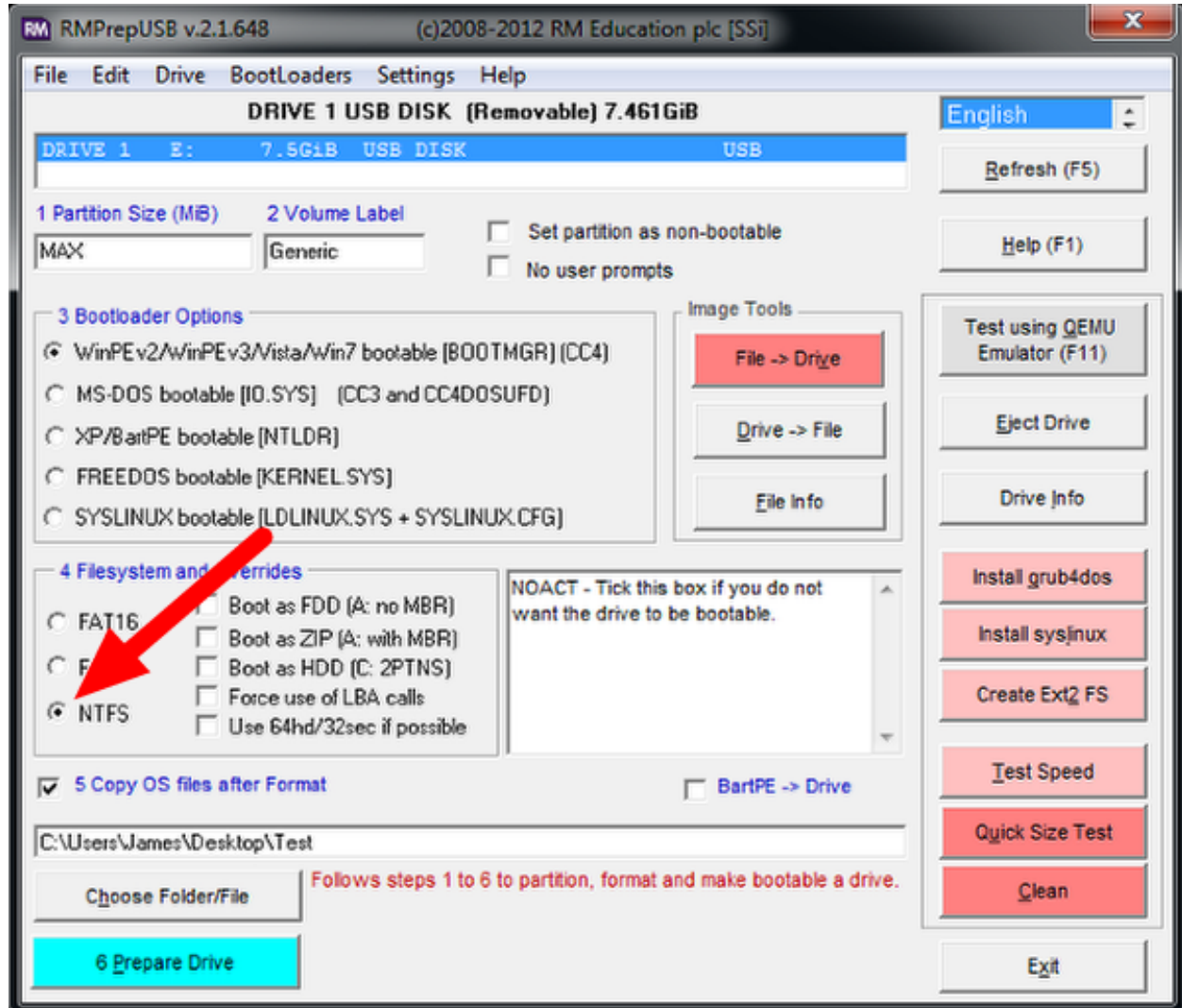
Set Volume Label to Generic

## Set Bootloader Option



Select Bootloader Option “WinPE v2/WinPE v3/Vista/Win7 bootable”

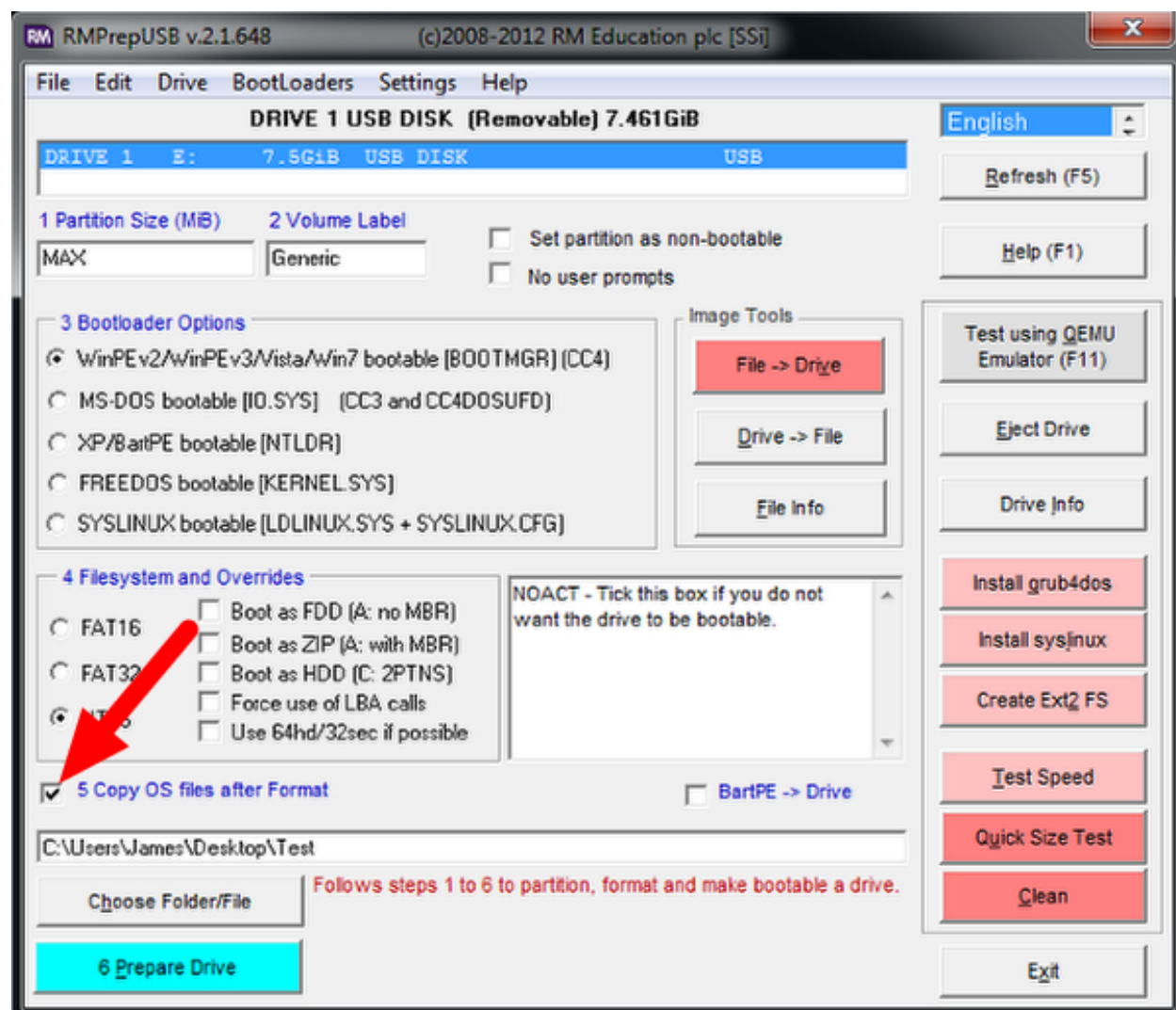
## Select Filesystem



Select NTFS Filesystem

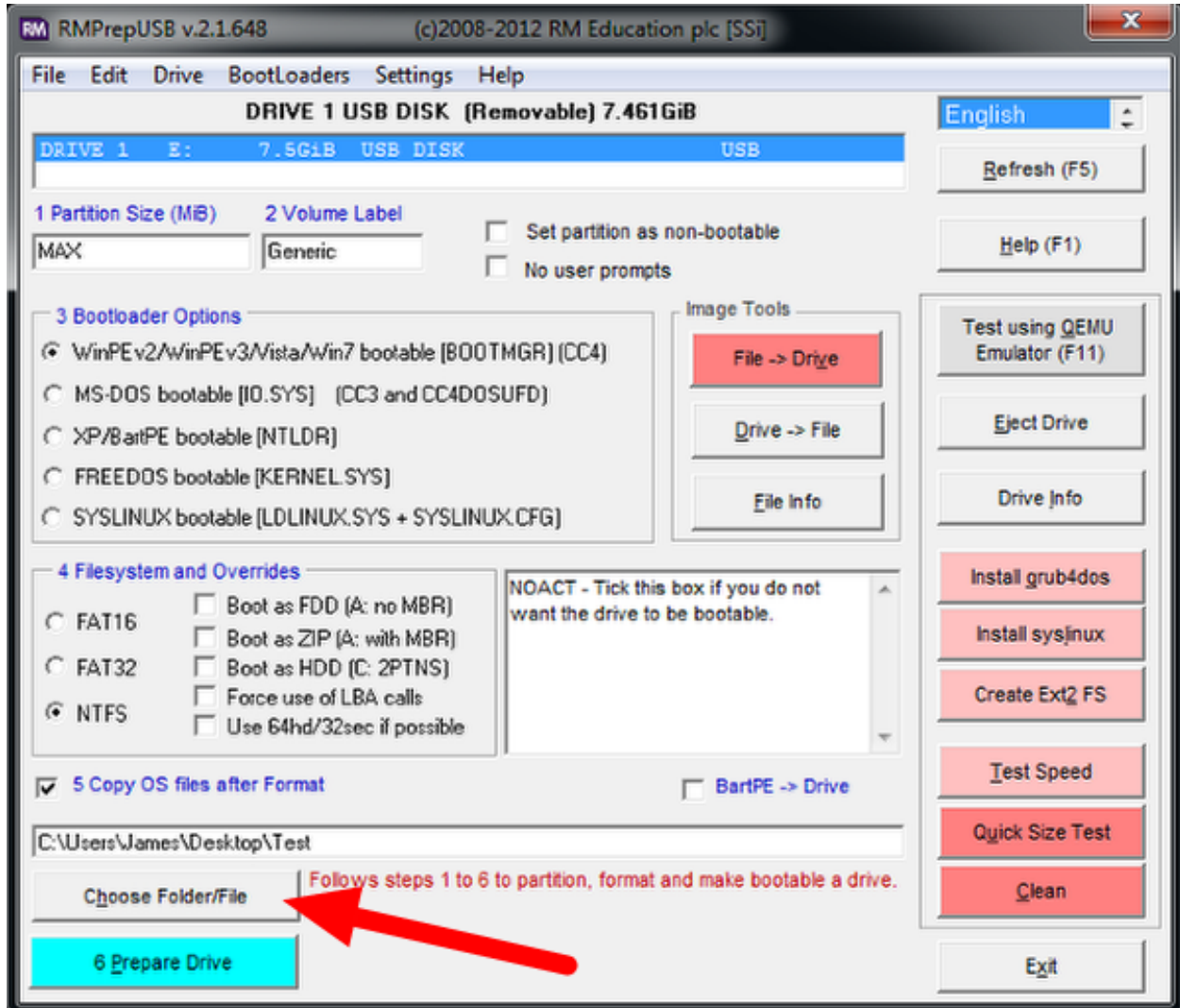


## Copy OS Files Option



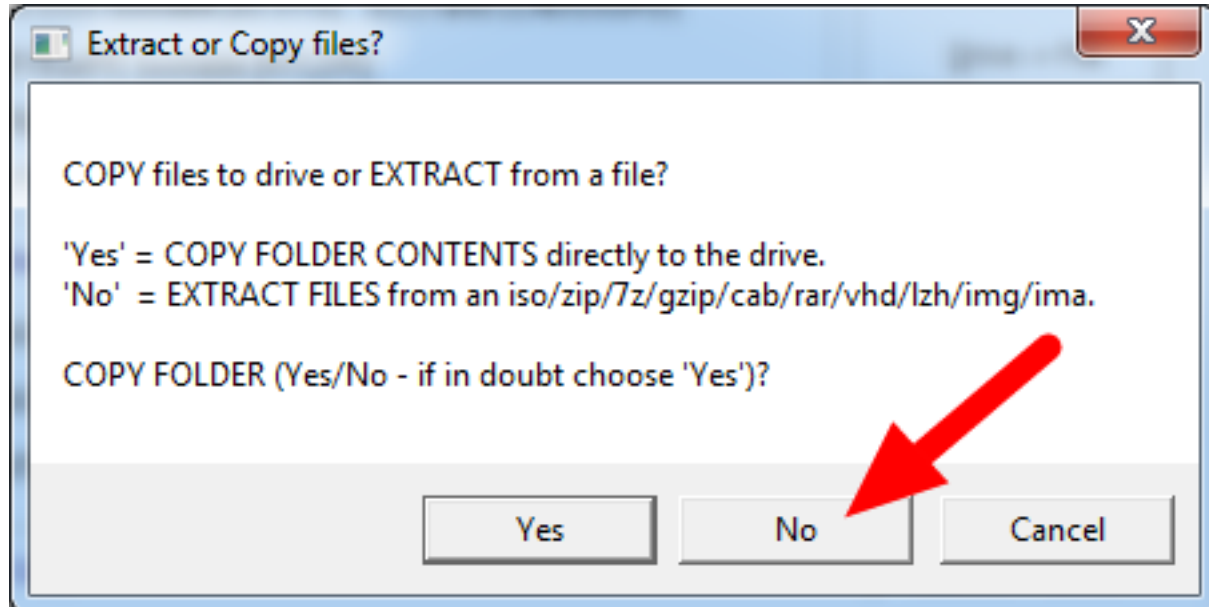
Ensure the “Copy OS files after Format” box is checked

## Locate Image



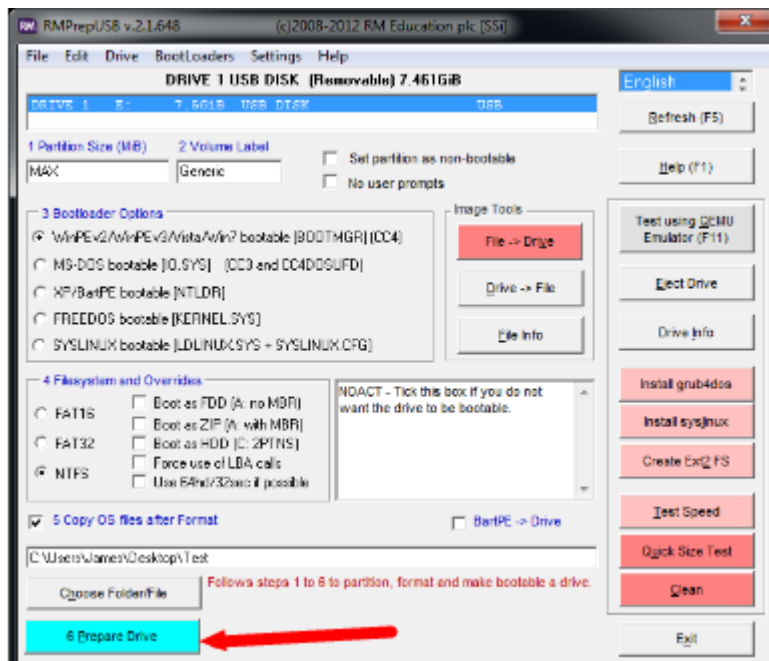
Select the "Choose Folder/File" button

### Copy Files Dialog

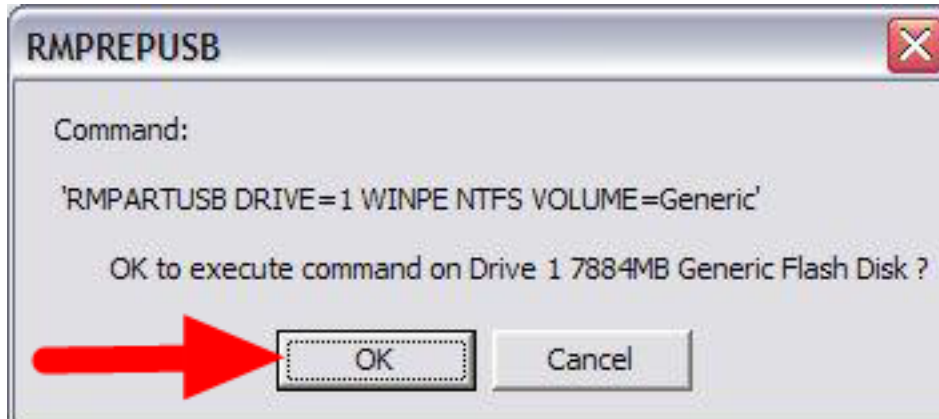


Choose “No” and select your .7z image

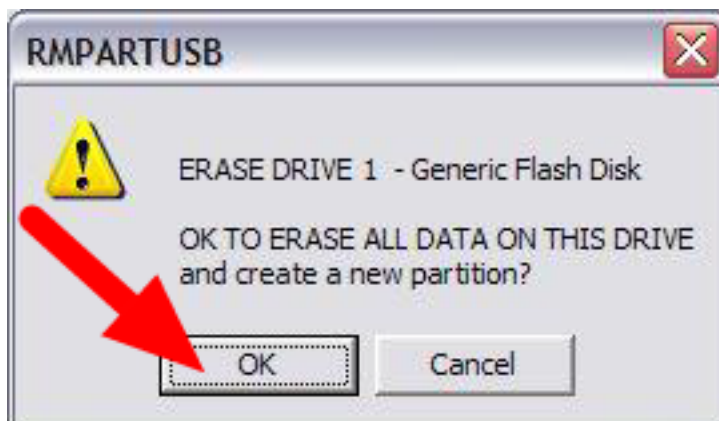
### Prepare Drive



All configuration settings are now complete. Select “Prepare Drive” to begin the process

**Confirmation Dialog 1**

Click "OK" to execute the command on the selected USB Flash drive. A Command Prompt will open showing the progress

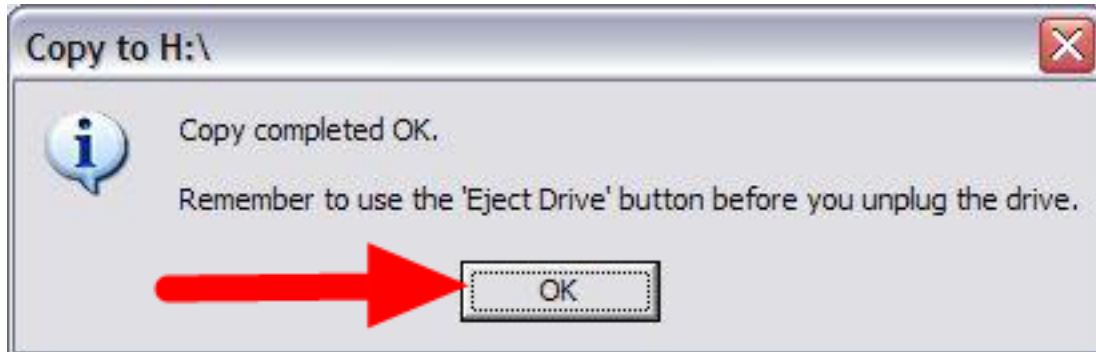
**Confirmation Dialog 2**

Click "OK" to format the USB drive

**Danger: ALL DATA ON THE DRIVE WILL BE ERASED!**

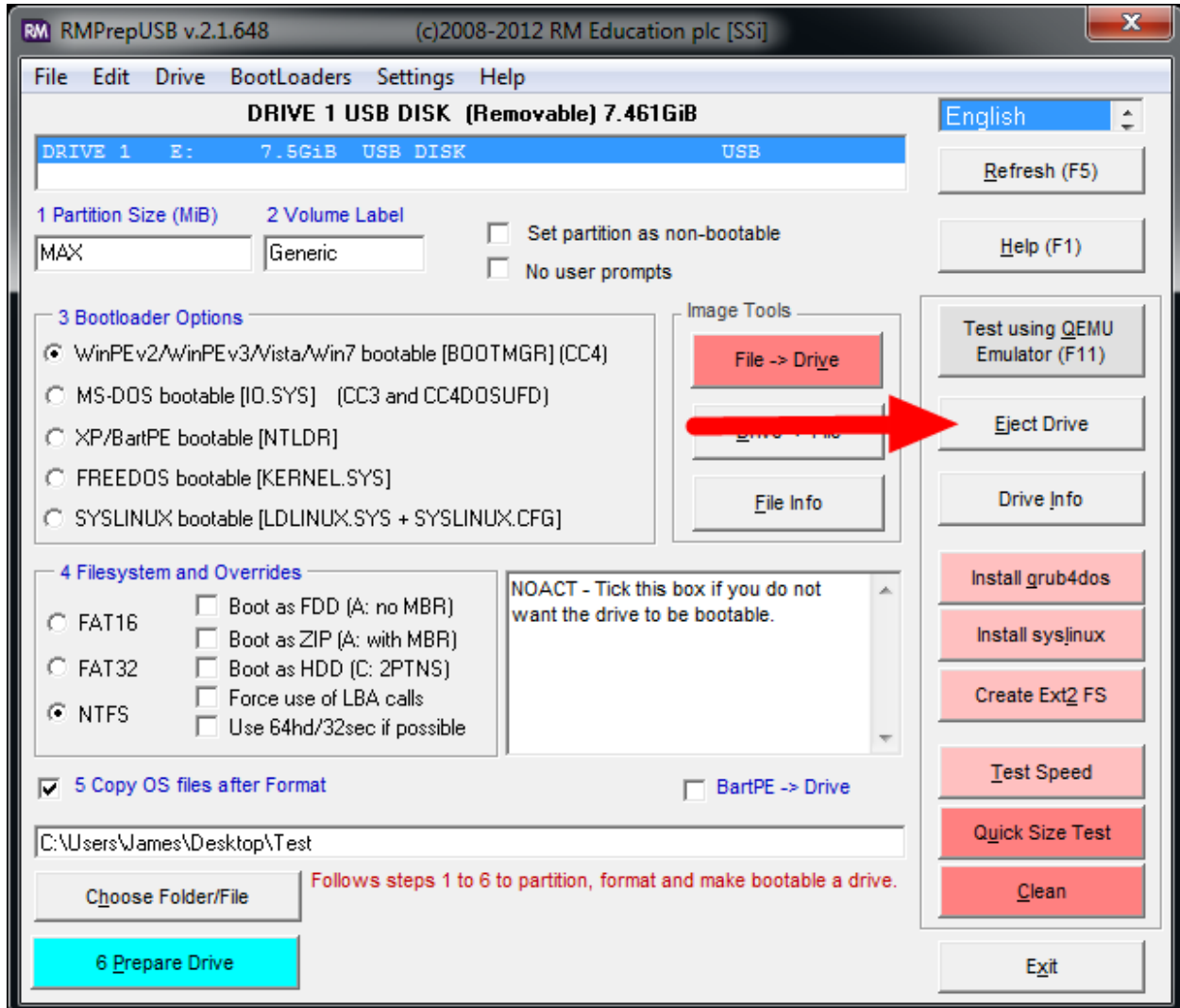
**Decryption**

**Note:** If you are using an encrypted version of the image downloaded before kickoff you will be prompted to enter the decryption key found at the end of the Kickoff video.

**Copy Complete**

Once formatting is complete, the restoration files will be extracted and copied to the USB drive. This process should take ~15 minutes when connected to a USB 2.0 port. When all files have been copied, this message will appear, press OK to continue.

## Eject Drive



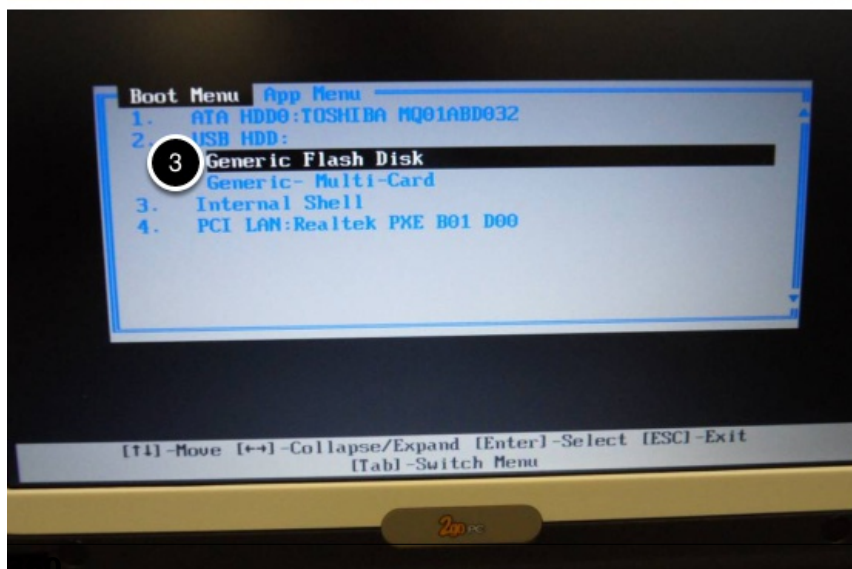
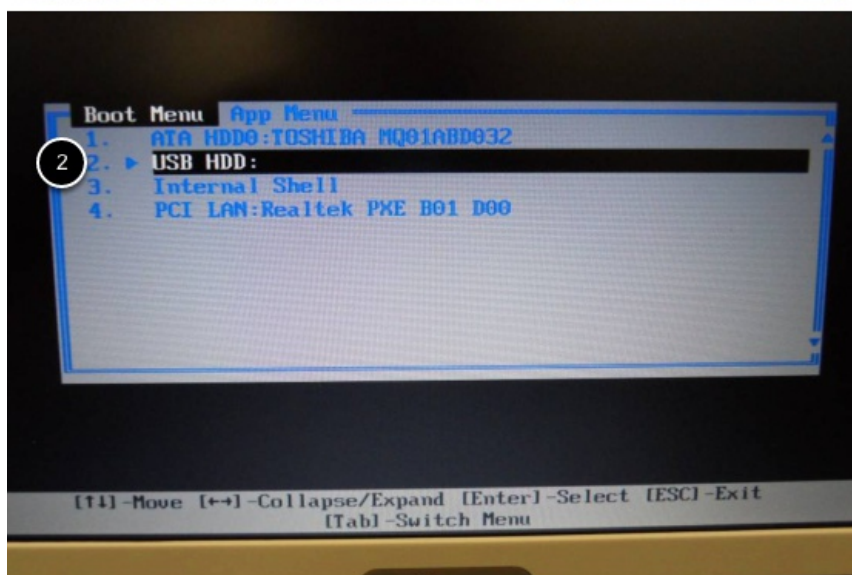
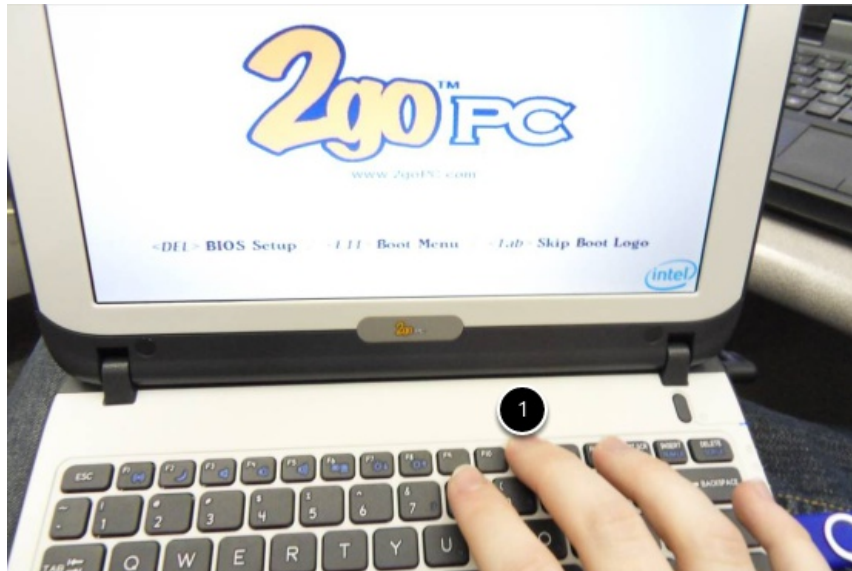
Press the “Eject Drive” button to safely remove the USB drive. The USB drive is now ready to be used to restore the image onto the PC.

### 10.1.5 Hardware Setup

1. Make sure the computer is turned off, but plugged in.
2. Insert the USB Thumb Drive into a USB port on the Driver Station computer.



### Boot to USB



**Classmate:**

1. Power on the Classmate and tap the F11 key on the keyboard. Tapping the F11 key during boot will bring up the boot menu.
2. Use the up/down keys to select the **USB HDD:** entry on the menu, then press the right arrow to expand the listing
3. Use the up/down arrow keys on the keyboard to select the USB device (it will be called "Generic Flash Disk"). Press the ENTER key when the USB device is highlighted.

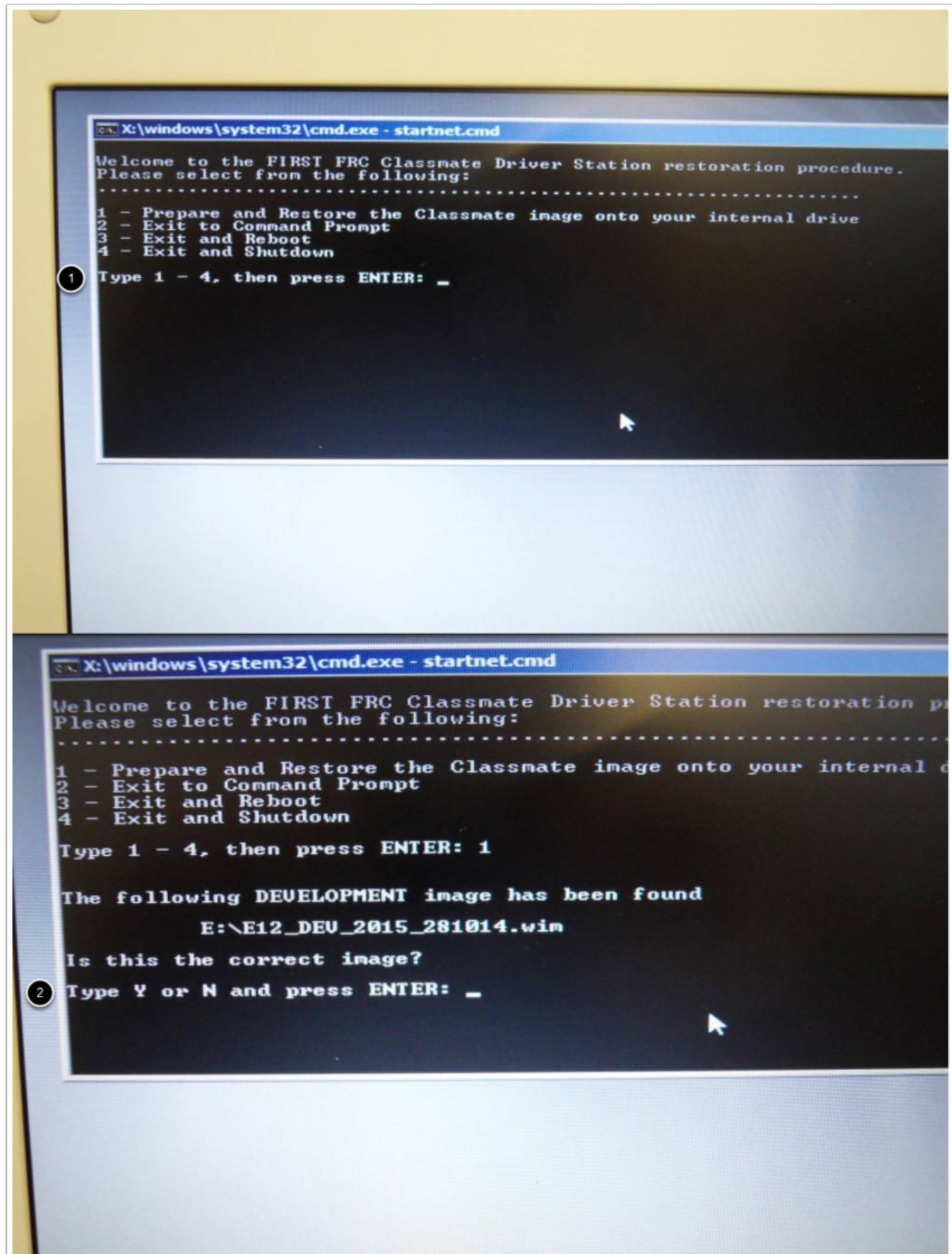
**Acer ES1:**

1. Power on the computer and tap the F12 key on the keyboard. Tapping the F12 key during boot will bring up the boot menu.
2. Use the up/down keys to select the **USB HDD: Generic** entry on the menu, then press the ENTER key when the USB device is highlighted.

**Acer ES1: If pressing F12 does not pull up the boot menu or if the USB device is not listed in the boot menu, see "Checking BIOS Settings" at the bottom of this article.**



## Image the Classmate



1. To confirm that you want to reimage the Classmate, type “1” and press ENTER.
2. Then, type “Y” and press ENTER. The Classmate will begin re-imaging. The installation will take 15-30 minutes.
3. When the installation is complete, remove the USB drive.
4. Restart the Classmate. The Classmate will boot into Windows.

### **10.1.6 Initial Driver Station Boot**

The first time the Classmate is turned on, there are some unique steps, listed below, that you’ll need to take. The initial boot may take several minutes; make sure you do not cycle power during the process.

---

**Note:** These steps are only required during original startup.

---

#### **Enter Setup**

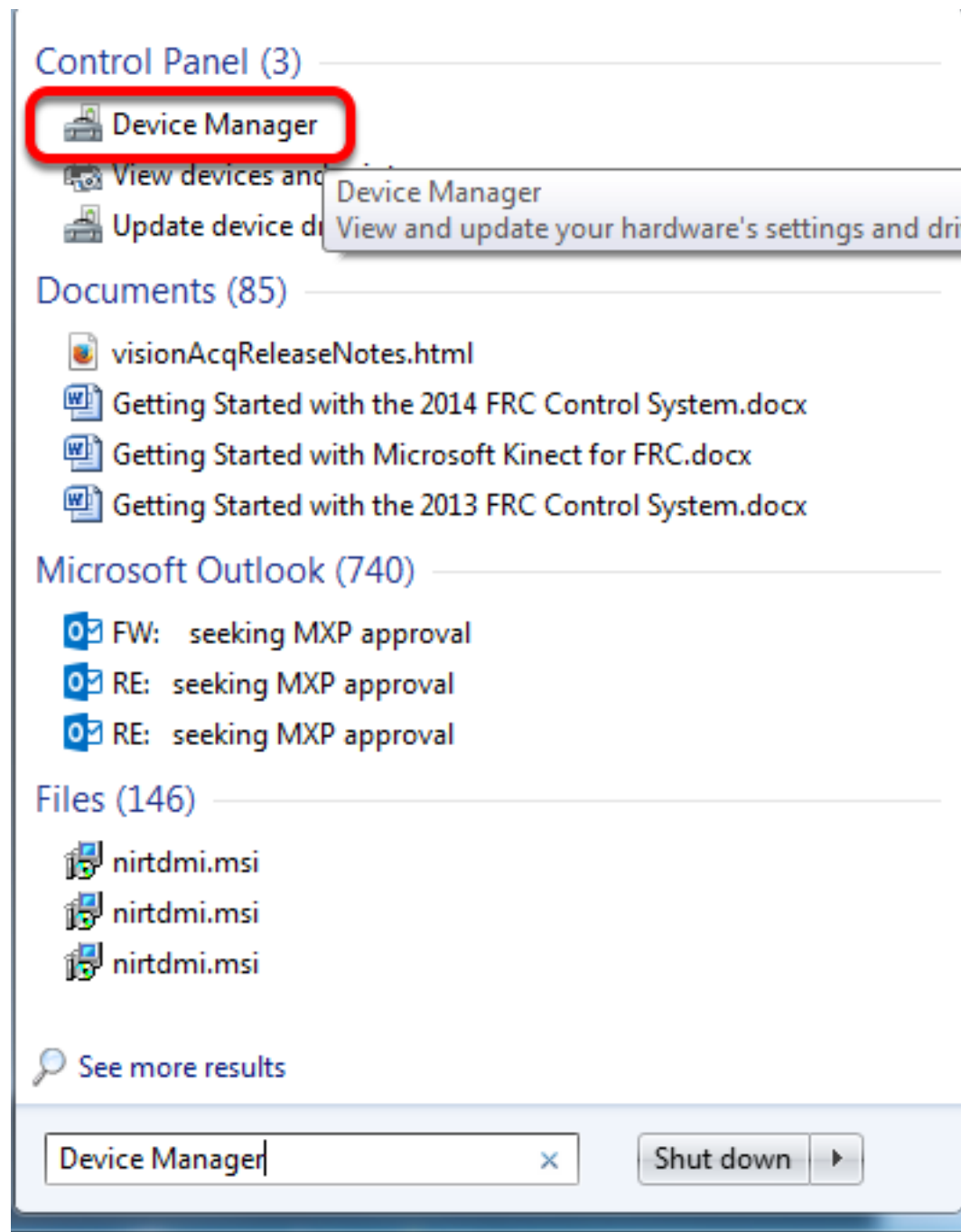
1. Log into the Developer account.
2. Click “Ask me later”.
3. Click “OK”. The computer now enters a Set Up that may take a few minutes.

#### **Activate Windows**

1. Establish an Internet connection.
2. Once you have an Internet connection, click the Start menu, right click “Computer” and click “Properties”.
3. Scroll to the bottom section, “Windows activation”, and Click “Activate Windows now”
4. Click “Activate Windows online now”. The activation may take a few minutes.
5. When the activation is complete, close all of the windows.

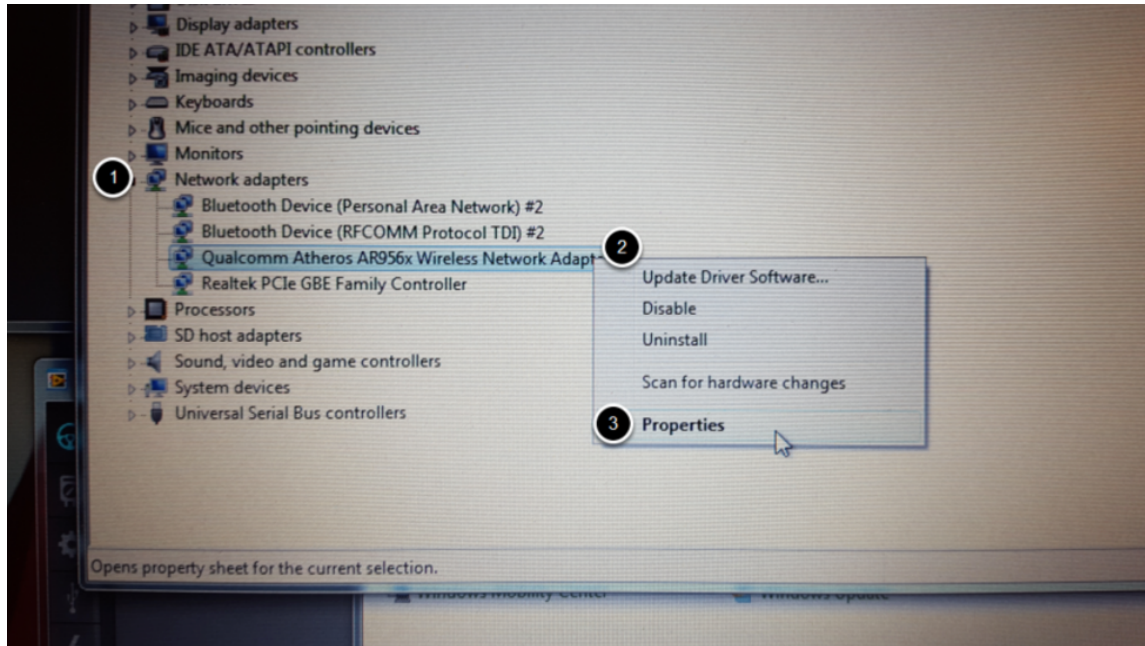
#### **Microsoft Security Essentials**

Navigate through the Microsoft Security Essentials Setup Wizard. Once it is complete, close all of the windows.

**Acer ES1: Fix Wireless Driver****Acer ES1 PC only!**

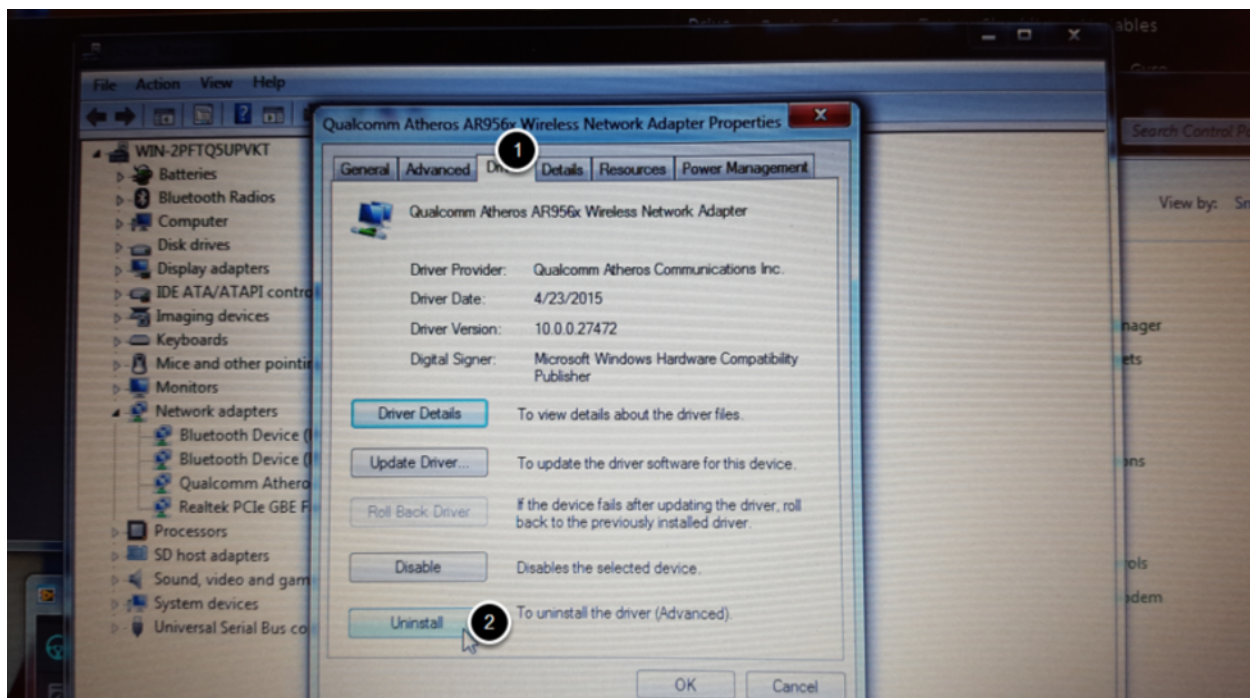
The default wireless driver in the image may have issues with intermittent communication with the robot radio. The correct driver is in the image, but could not be set to load by default. To load the correct driver, open the Device Manager by clicking start, typing "Device Manager" in the box and clicking Device Manager.

## Open Wireless Device Properties



Click on the arrow next to Network Adapters to expand it and locate the Wireless Network Adapter. Right click the adapter and select Properties.

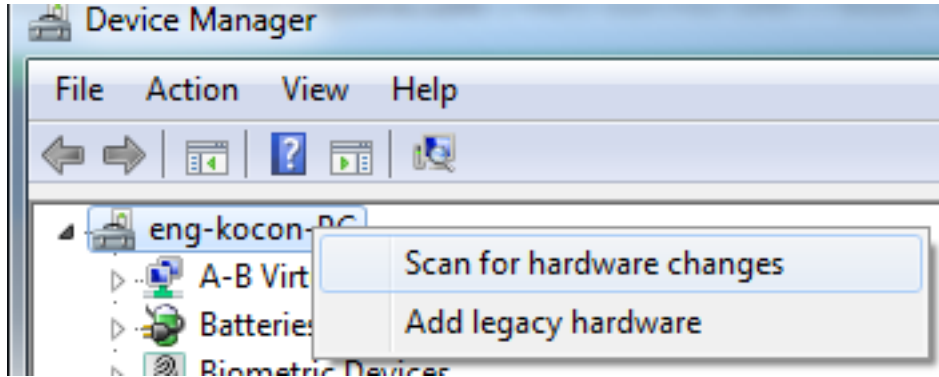
## Uninstall-Driver



Click on the Driver tab, then click the Uninstall button. Click Yes at any prompts.



## Scan for New Hardware

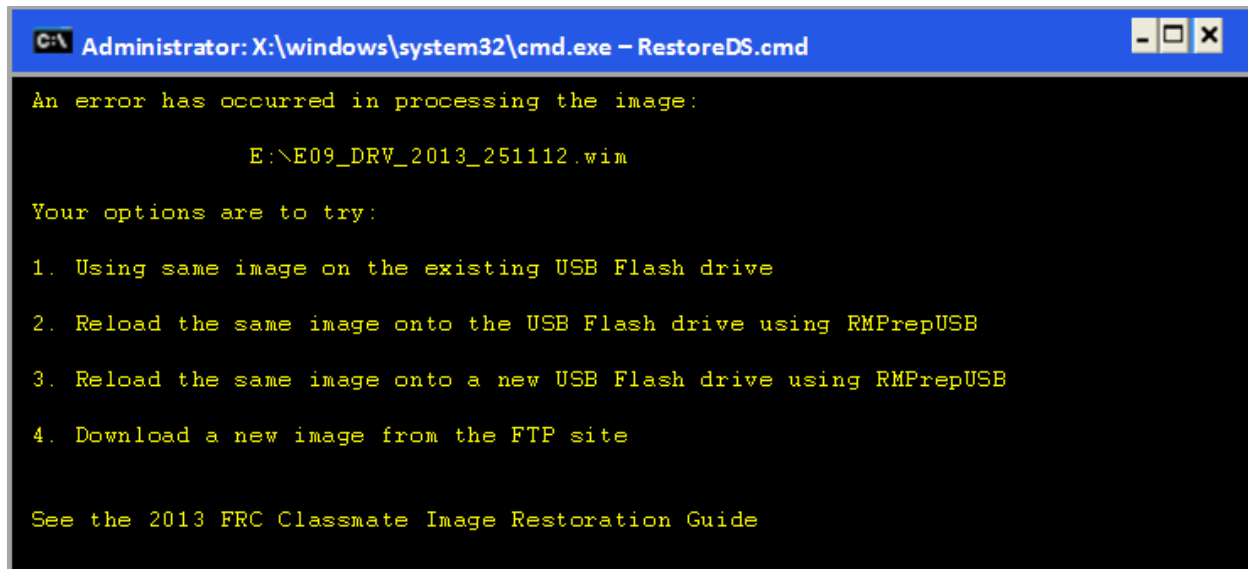


Right click on the top entry of the tree and click “Scan for hardware changes”. The wireless adapter should automatically be re-detected and the correct driver should be installed.

### 10.1.7 Update Software

In order for the Classmate images to be prepared on time, they are created before the final versions of the software were ready. To use the software for FRC some additional components will need to be installed. LabVIEW teams should continue with Installing the FRC Game Tools (All Languages). C++ or Java teams should continue Installing C++ and Java Development Tools for FRC.

### 10.1.8 Errors during Imaging Process



If an error is detected during the imaging process, the following screen will appear. Note that the screenshot below shows the error screen for the Driver Station-only image for the E09. The specific image filename shown will vary depending on the image being applied.

The typical reason for the appearance of this message is due to an error with the USB device on which the image is stored. Each option is listed below with further details as to the actions

you can take in pursuing a solution. Pressing any key once this error message is shown will return the user to the menu screen shown in Image the Classmate.

### **Option 1**

**Using same image on the existing USB Flash drive** To try this option, press any key to return to the main menu and select #1. This will run the imaging process again.

### **Option 2**

**Reload the same image onto the USB Flash drive using RMPrepUSB** It's possible the error message was displayed due to an error caused during the creation of the USB Flash drive (e.g. file copy error, data corruption, etc.) Press any key to return to the main menu and select #4 to safely shutdown the Classmate then follow the steps starting with RMPrep to create a new USB Restoration Key using the same USB Flash drive.

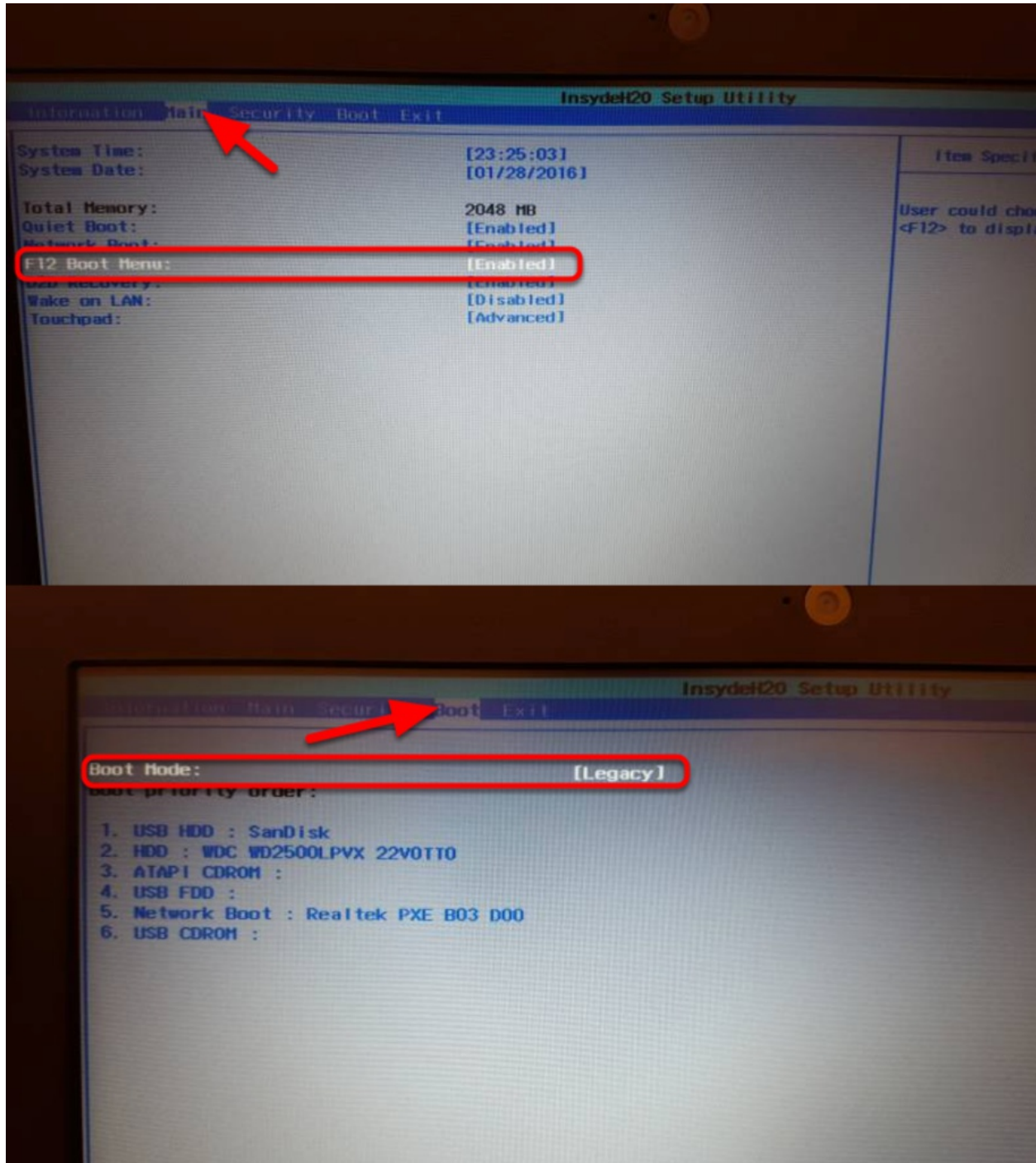
### **Option 3**

**Reload the same image onto a new USB Flash drive using RMPrepUSB** The error message displayed may also be caused by an error with the USB Flash drive itself. Press any key to return to the main menu and select #4 to safely shutdown the Classmate. Select a new USB Flash drive and follow the steps starting with RMPrep.

### **Option 4**

**Download a new image** An issue with the downloaded image may also cause an error when imaging. Press any key to return to the main menu and select #4 to safely shutdown the Classmate. Starting with Download the Classmate Image create a new copy of the imaging stick.

### Checking BIOS Settings



If you are having difficulty booting to USB, check the BIOS settings to insure they are correct. To do this:

- Repeatedly tap the **F2** key while the computer is booting to enter the BIOS settings
- Once the BIOS settings screen has loaded, use the right and left arrow keys to select the "Main" tab, then check if the line for "F12 Boot Menu" is set to "Enabled". If it is not, use the Up/Down keys to highlight it, press Enter, use Up/Down to select "Enabled" and

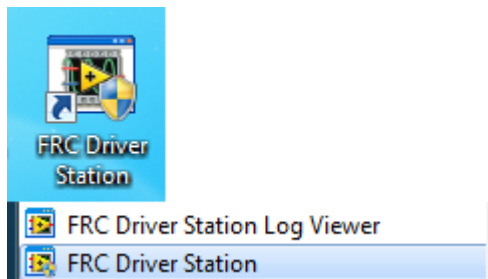
press Enter again.

- Next, use the Left/Right keys to select the “Boot” tab. Make sure that the “Boot Mode” is set to “Legacy”. If it is not, highlight it using UpDown, press Enter, highlight “Legacy” and press Enter again. Press Enter to move through any pop-up dialogs you may see.
- Press F10 to save any changes and exit.

## 10.2 FRC Driver Station Powered by NI LabVIEW

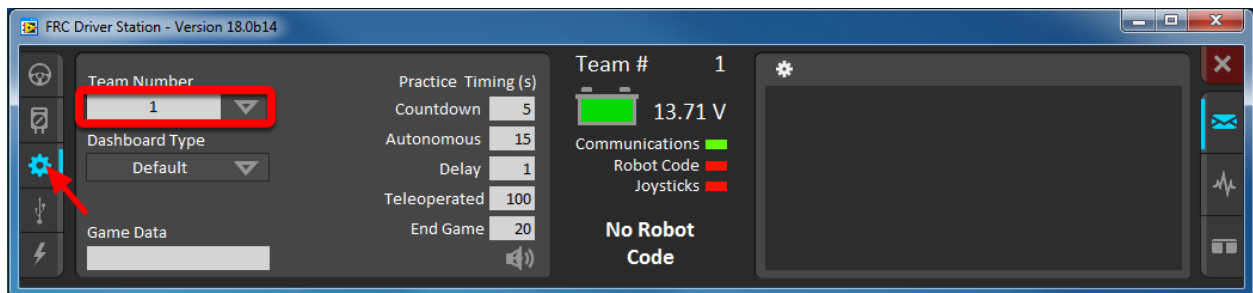
This article describes the use and features of the FRC Driver Station Powered by NI LabVIEW. For information on installing the Driver Station software see [this document](#).

### 10.2.1 Starting the FRC Driver Station



The FRC Driver Station can be launched by double-clicking the icon on the Desktop or by selecting Start->All Programs->FRC Driver Station.

### 10.2.2 Setting Up the Driver Station

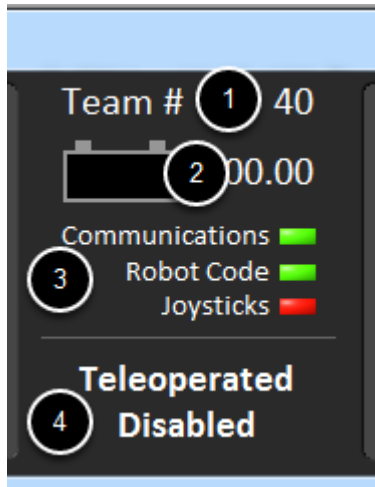


The DS must be set to your team number in order to connect to your robot. In order to do this click the Setup tab then enter your team number in the team number box. Press return or click outside the box for the setting to take effect.

PCs will typically have the correct network settings for the DS to connect to the robot already, but if not, make sure your Network adapter is set to DHCP.



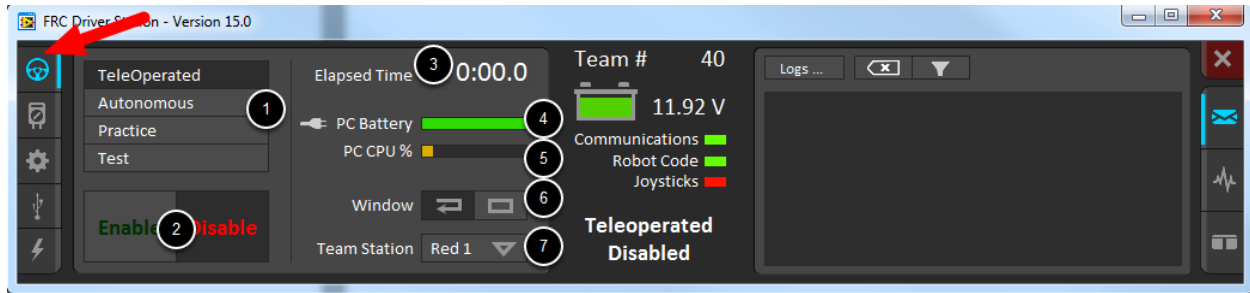
### 10.2.3 Status Pane



The Status Pane of the Driver Station is located in the center of the display and is always visible regardless of the tab selected. It displays a selection of critical information about the state of the DS and robot:

1. **Team #** - The Team number the DS is currently configured for. This should match your FRC team number. To change the team number see the Setup Tab.
2. **Battery Voltage** - If the DS is connected and communicating with the roboRIO this displays current battery voltage as a number and with a small chart of voltage over time in the battery icon. The background of the numeric indicator will turn red when the roboRIO brownout is triggered. See [roboRIO Brownout and Understanding Current Draw](#) for more information.
3. **Major Status Indicators** - These three indicators display major status items for the DS. The “Communications” indicates whether the DS is currently communicating with the FRC Network Communications Task on the roboRIO (it is split in half for the TCP and UDP communication). The “Robot Code” indicator shows whether the team Robot Code is currently running (determined by whether or not the Driver Station Task in the robot code is updating the battery voltage), The “Joysticks” indicator shows if at least one joystick is plugged in and recognized by the DS.
4. **Status String** - The Status String provides an overall status message indicating the state of the robot, some examples are “No Robot Communication”, “No Robot Code”, “Emergency Stopped”, and “Teleoperated Enabled”. When the roboRIO brownout is triggered this will display “Voltage Brownout”.

### 10.2.4 Operation Tab

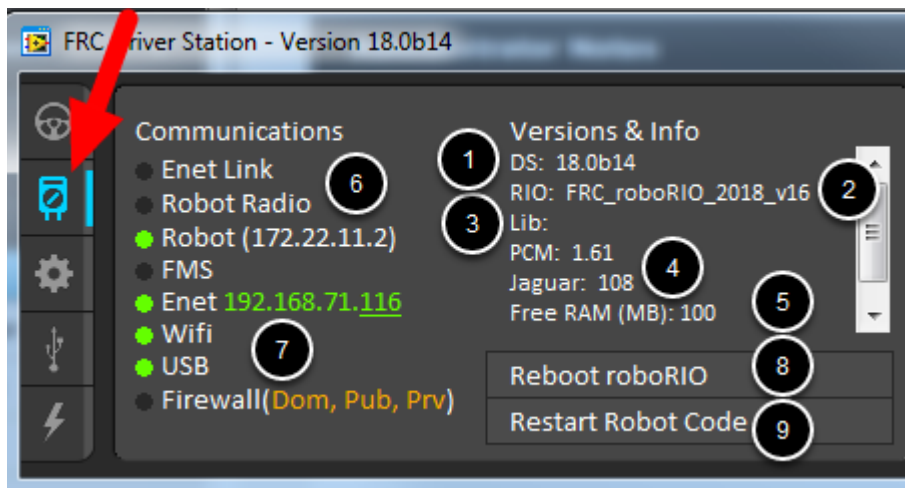


The Operations Tab is used to control the mode of the robot and provide additional key status indicators while the robot is running.

1. Robot Mode - This section controls the Robot Mode. Practice Mode causes the robot to cycle through the same transitions as an FRC match after the Enable button is pressed (timing for practice mode can be found on the setup tab).
2. Enable/Disable - These controls enable and disable the robot. See also [Driver Station Key Shortcuts](#)
3. Elapsed Time - Indicates the amount of time the robot has been enabled
4. PC Battery - Indicates current state of DS PC battery and whether the PC is plugged in
5. PC CPU% - Indicates the CPU Utilization of the DS PC
6. Window Mode - When not on the Driver account on the Classmate allows the user to toggle between floating (arrow) and docked (rectangle)
7. Team Station - When not connected to FMS, sets the team station to transmit to the robot.

**Note:** When connected to the Field Management System the controls in sections 1, and 2 will be replaced by the words FMS Connected and the control in Section 7 will be greyed out.

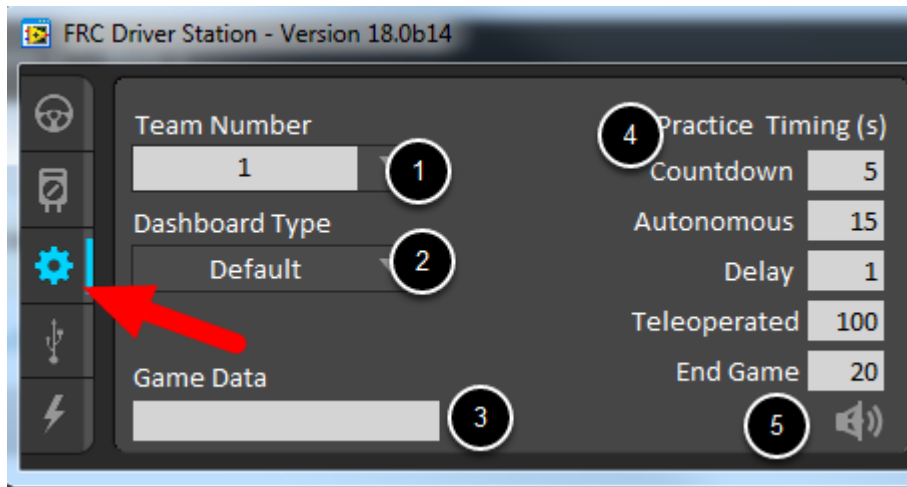
### 10.2.5 Diagnostics Tab



The Diagnostics Tab contains additional status indicators that teams can use to diagnose issues with their robot:

1. DS Version - Indicates the Driver Station Version number
2. roboRIO Image Version - String indicating the version of the roboRIO Image
3. WPILib Version - String indicating the version of WPILib in use
4. CAN Device Versions - String indicating the firmware version of devices connected to the CAN bus. These items may not be present if the CTRE Phoenix framework has not been loaded
5. Memory Stats - This section shows stats about the roboRIO memory
6. Connection Indicators - The top half of these indicators show connection status to various components.
  - “Enet Link” indicates the computer has something connected to the ethernet port.
  - “Robot Radio” indicates the ping status to the robot wireless bridge at 10.XX.YY.1.
  - “Robot” indicates the ping status to the roboRIO using mDNS (with a fallback of a static 10.TE.AM.2 address).
  - “FMS” indicates if the DS is receiving packets from FMS (this is NOT a ping indicator).
7. Network Indicators - The second section of indicators indicates status of network adapters and firewalls. These are provided for informational purposes, communication may be established with one or more unlit indicators in this section
  - “Enet” indicates the IP address of the detected Ethernet adapter
  - “WiFi” indicates if a wireless adapter has been detected as enabled
  - “USB” indicates if a roboRIO USB connection has been detected
  - “Firewall” indicates if any firewalls are detected as enabled. Enabled firewalls will show in orange ( Dom = Domain, Pub = Public, Prv = Private)
8. Reboot roboRIO - This button attempts to perform a remote reboot of the roboRIO (after clicking through a confirmation dialog)
9. Restart Robot Code - This button attempts to restart the code running on the robot (but not restart the OS)

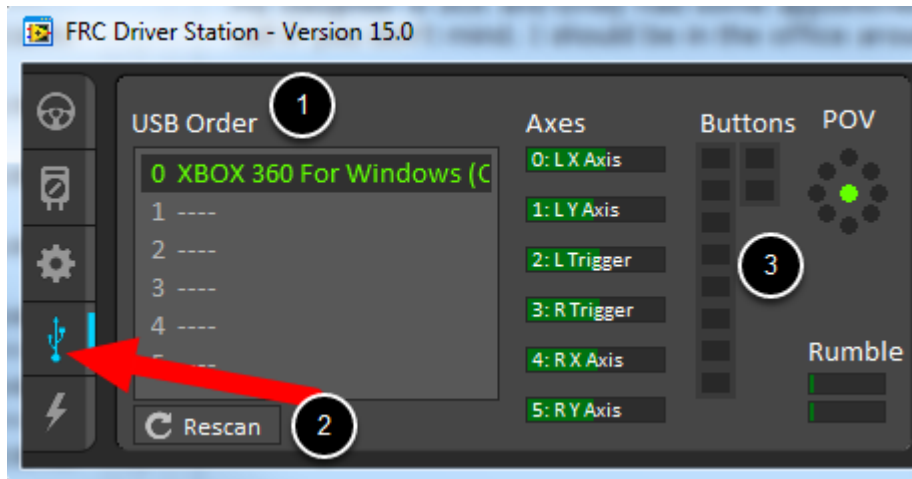
### 10.2.6 Setup Tab



The Setup Tab contains a number of buttons teams can use to control the operation of the Driver Station:

1. Team Number - Should contain your FRC Team Number. This controls the mDNS name that the DS expects the robot to be at. Shift clicking on the dropdown arrow will show all roboRIO names detected on the network for troubleshooting purposes.
2. Dashboard Type - Controls what Dashboard is launched by the Driver Station. Default launches the file pointed to by the "FRC DS Data Storage.ini" file, by default this is Dashboard.exe in the Program Files\FRC Dashboard folder. LabVIEW attempts to launch a dashboard at the default location for a custom built LabVIEW dashboard, but will fall back to the default if no dashboard is found. SmartDashboard and Shuffleboard launch the respective dashboards included with the C++ and Java WPILib installation.
3. Game Data - This box can be used for at home testing of the Game Data API. Text entered into this box will appear in the Game Data API on the Robot Side. When connected to FMS, this data will be populated by the field automatically.
4. Practice Mode Timing - These boxes control the timing of each portion of the practice mode sequence. When the robot is enabled in practice mode the DS automatically proceeds through the modes indicated from top to bottom.
5. Audio Control - This button controls whether audio tones are sounded when the Practice Mode is used.

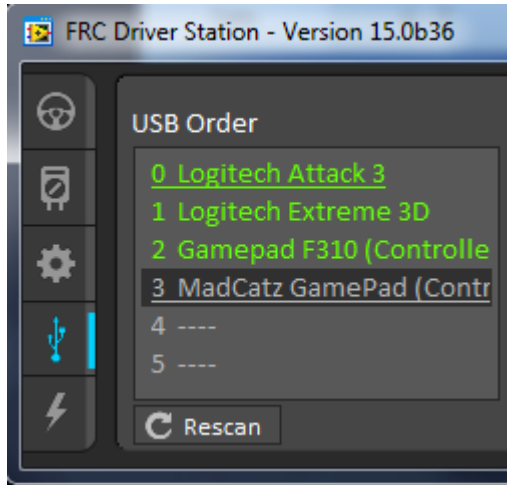
## 10.2.7 USB Devices Tab



The USB Devices tab includes the information about the USB Devices connected to the DS

1. USB Setup List - This contains a list of all compatible USB devices connected to the DS. Pressing a button on a device will highlight the name in green and put 2 \*s before the device name
2. Rescan - This button will force a Rescan of the USB devices. While the robot is disabled, the DS will automatically scan for new devices and add them to the list. To force a complete re-scan or to re-scan while the robot is Enabled (such as when connected to FMS during a match) press F1 or use this button.
3. Device indicators - These indicators show the current status of the Axes, buttons and POV of the joystick.
4. Rumble - For XInput devices (such as X-Box controllers) the Rumble control will appear. This can be used to test the rumble functionality of the device. The top bar is "Right Rumble" and the bottom bar is "Left Rumble". Clicking and holding anywhere along the bar will activate the rumble proportionally (left is no rumble = 0, right is full rumble = 1). This is a control only and will not indicate the Rumble value set in robot code.

## Re-Arranging and Locking Devices



The Driver Station has the capability of “locking” a USB device into a specific slot. This is done automatically if the device is dragged to a new position and can also be triggered by double clicking on the device. “Locked” devices will show up with an underline under the device. A locked device will reserve its slot even when the device is not connected to the computer (shown as grayed out and underlined). Devices can be unlocked (and unconnected devices removed) by double clicking on the entry.

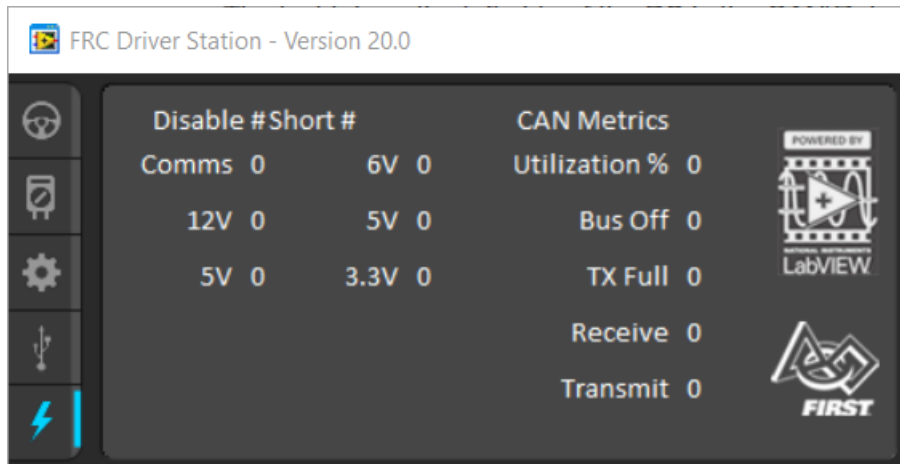
**Note:** If you have two or more of the same device, they should maintain their position as long as all devices remain plugged into the computer in the same ports they were locked in. If you switch the ports of two identical devices the lock should follow the port, not the device. If you re-arrange the ports (take one device and plug it into a new port instead of swapping) the behavior is not determinate (the devices may swap slots). If you unplug one or more of the set of devices, the positions of the others may move, they should return to the proper locked slots when all devices are reconnected.

Example: The image above shows 4 devices:

- A Locked “Logitech Attack 3” joystick. This device will stay in this position unless dragged somewhere else or unlocked
- An unlocked “Logitech Extreme 3D” joystick
- An unlocked “Gamepad F310 (Controller)” which is a Logitech F310 gamepad
- A Locked, but disconnected “MadCatz GamePad (Controller)” which is a MadCatz Xbox 360 Controller

In this example, unplugging the Logitech Extreme 3D joystick will result in the F310 Gamepad moving up to slot 1. Plugging in the MadCatz Gamepad (even if the devices in Slots 1 and 2 are removed and those slots are empty) will result in it occupying Slot 3.

### 10.2.8 CAN/Power Tab

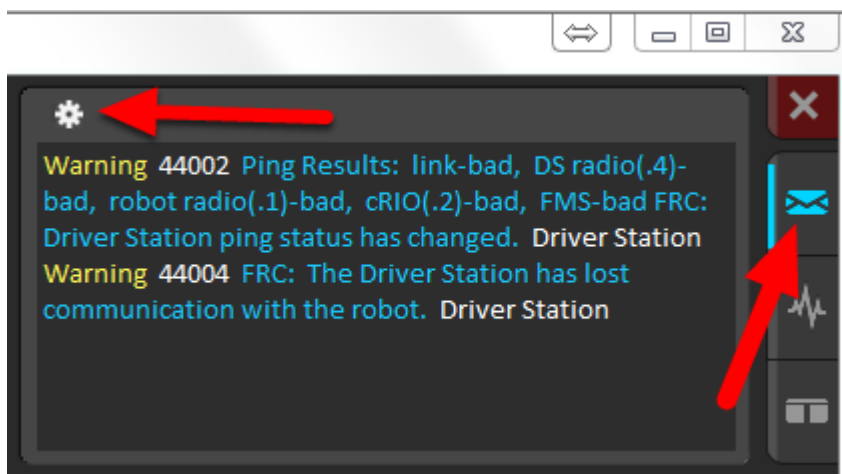


The last tab on the left side of the DS is the CAN/Robot Power Tab. This tab contains information about the power status of the roboRIO and the status of the CAN bus:

1. Comms Faults - Indicates the number of Comms faults that have occurred since the DS has been connected
2. 12V Faults - Indicates the number of input power faults (Brownouts) that have occurred since the DS has been connected
3. 6V/5V/3.3V Faults - Indicates the number of faults (typically cause by short circuits) that have occurred on the User Voltage Rails since the DS has been connected
4. CAN Bus Utilization - Indicates the percentage utilization of the CAN bus
5. CAN faults - Indicates the counts of each of the 4 types of CAN faults since the DS has been connected

If a fault is detected, the indicator for this tab (shown in blue in the image above) will turn red.

### 10.2.9 Messages Tab



The Messages tab displays diagnostic messages from the DS, WPILib, User Code, and/or the roboRIO. The messages are filtered by severity. By default, only Errors are displayed.

To access settings for the Messages tab, click the Gear icon. This will display a menu that will allow you to select the detail level (Errors, Errors+Warnings or Errors+Warnings+Prints), Clear the box, launch a larger Console window for viewing messages, or launch the DS Log Viewer.

### 10.2.10 Charts Tab



The Charts tab plots and displays advanced indicators of robot status to help teams diagnose robot issues:

1. The top graph charts trip time in milliseconds in green (against the axis on the right) and lost packets per second in orange (against the axis on the left)
2. The bottom graph plots battery voltage in yellow (against the axis on the left), roboRIO CPU in red (against the axis on the right), DS Requested mode as a continuous line on the bottom of the chart and robot mode as a discontinuous line above it.
3. This key shows the colors used for the DS Requested and Robot Reported modes in the bottom chart.
4. Chart scale - These controls change the time scale of the DS Charts
5. This button launches the *DS Log File Viewer*

The DS Requested mode is the mode that the Driver Station is commanding the robot to be in. The Robot Reported mode is what code is actually running based on reporting methods contained in the coding frameworks for each language.

### 10.2.11 Both Tab

The last tab on the right side is the Both tab which displays Messages and Charts side by side

### 10.2.12 Driver Station Key Shortcuts

- *F1* - Force a Joystick refresh.



- `[ + ] + \` - Enable the robot (the 3 keys above Enter on most keyboards)
- *Enter* - Disable the Robot
- *Space* - Emergency Stop the robot. After an emergency stop is triggered the roboRIO will need to be rebooted before the robot can be enabled again.

---

**Note:** Space bar will E-Stop the robot regardless of if the Driver Station window has focus or not

---

## 10.3 Programming Radios for FMS Offseason

When using the FMS Offseason software, the typical networking setup is to use a single access point with a single SSID and WPA key. This means that the radios should all be programmed to connect to this network, but with different IPs for each team. The Team version of the FRC Bridge Configuration Utility has an FMS-Lite mode that can be used to do this configuration.

Before you begin using the software:

1. Disable WiFi connections on your computer, as it may prevent the configuration utility from properly communicating with the bridge
2. Make sure no devices are connected to your computer via ethernet, other than the wireless bridge.

### 10.3.1 Pre-Requisites

---

**Note:** Even though WPILib uses Java 11, the FRC Radio Configuration Utility requires Java 8.

---

The FRC Radio Configuration Utility requires the Java Runtime Engine (JRE). If you do not have Java installed, you can download the JRE from [here](#).

The FRC Radio Configuration Utility requires Administrator privileges to configure the network settings on your machine. The program should request the necessary privileges automatically (may require a password if run from a non-Administrator account), but if you are having trouble try running it from an Administrator account.

### 10.3.2 Application Notes

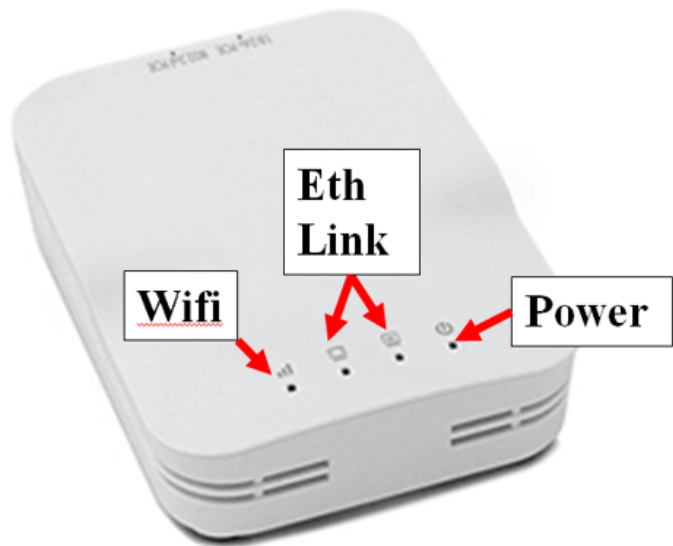
The Radio Kiosk will program the radio to enforce the 4 Mbps bandwidth limit on traffic exiting the radio over the wireless interface. In the home configuration (AP mode) this is a total, not a per client limit. This means that streaming video to multiple clients is not recommended.

The Kiosk has been tested on Windows 7, 8, and 10. It may work on other operating systems, but has not been tested.

## Programmed Configuration

<b>Power</b>	
Blue	On or Powering up
Blue Blinking	Powering up
<b>Eth Link</b>	
Blue	Link Up
Blue Blinking	Traffic present
<b>WiFi</b>	
Red	Bridge Mode, unlinked
Yellow\Orange	Bridge Mode, Linked
Green	AP Mode
Off	Unprogrammed

**WiFi light only works after radio has been power cycled.**



The Radio Configuration Utility programs a number of configuration settings into the radio when run. These settings apply to the radio in all modes (including at events). These include:

- Set a static IP of 10.TE.AM.1
- Set an alternate IP on the wired side of 192.168.1.1 for future programming
- Bridge the wired ports so they may be used interchangeably
- The LED configuration noted in the graphic above
- 4Mb/s bandwidth limit on the outbound side of the wireless interface
- QoS rules for internal packet prioritization (affects internal buffer and which packets to discard if bandwidth limit is reached). These rules are Robot Control and Status (UDP 1110, 1115, 1150) >> Robot TCP & Network Tables (TCP 1735, 1740) >> Bulk (All other traffic).

When programmed with the team version of the Radio Configuration - Utility, the user accounts will be left at (or set to) the firmware - defaults **for the DAPs only**:

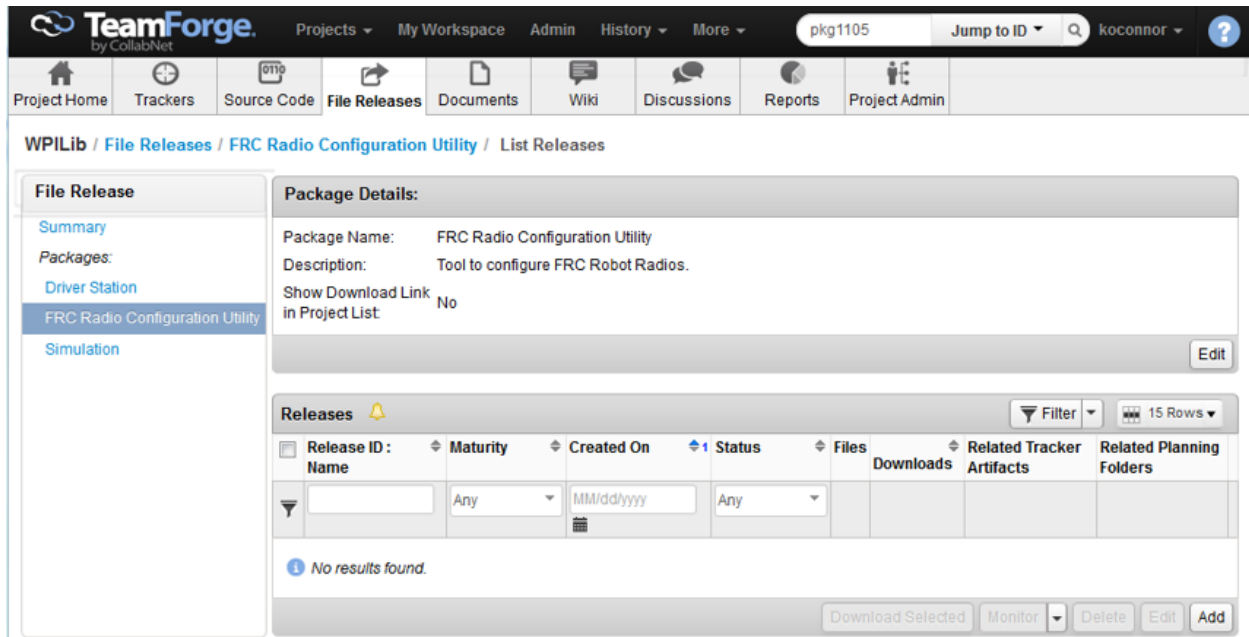
- Username: root
- Password: root

---

**Note:** It is not recommended to modify the configuration manually

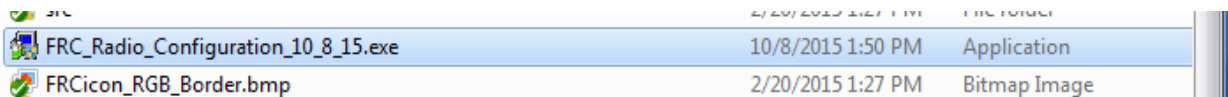
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### 10.3.3 Download the software



Download the latest FRC Radio Configuration Utility Installer from the [WPILib project File Releases](#).

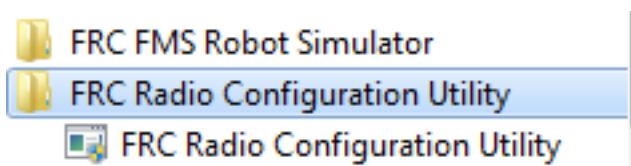
### 10.3.4 Install the software



Double click on FRC\_Radio\_Configuration\_MM\_DD\_YY.exe to launch the installer. Follow the prompts to complete the installation.

Part of the installation prompts will include installing WinPCap if it is not already present. The WinPCap installer contains a checkbox (checked by default) to start the WinPCap driver on boot. You should leave this box checked.

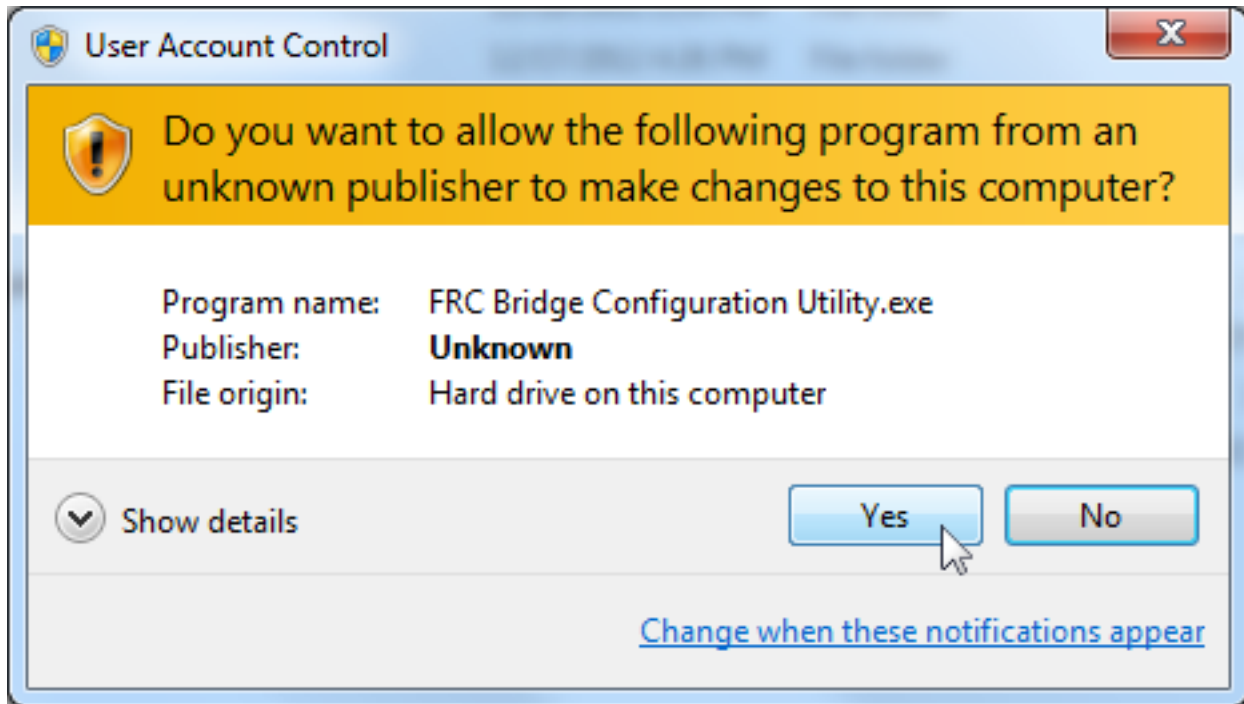
### 10.3.5 Launch the software



Use the Start menu or desktop shortcut to launch the program.

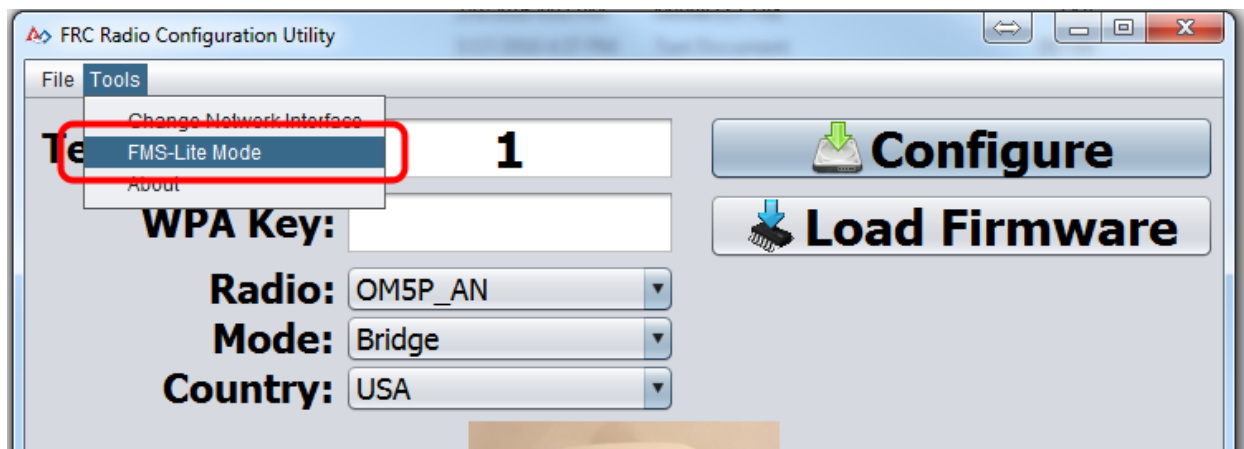
**Note:** If you need to locate the program it is installed to C:/Program Files (x86)/FRC Radio Configuration Utility. For 32-bit machines the path is C:/Program Files/FRC

### 10.3.6 Allow the program to make changes, if prompted



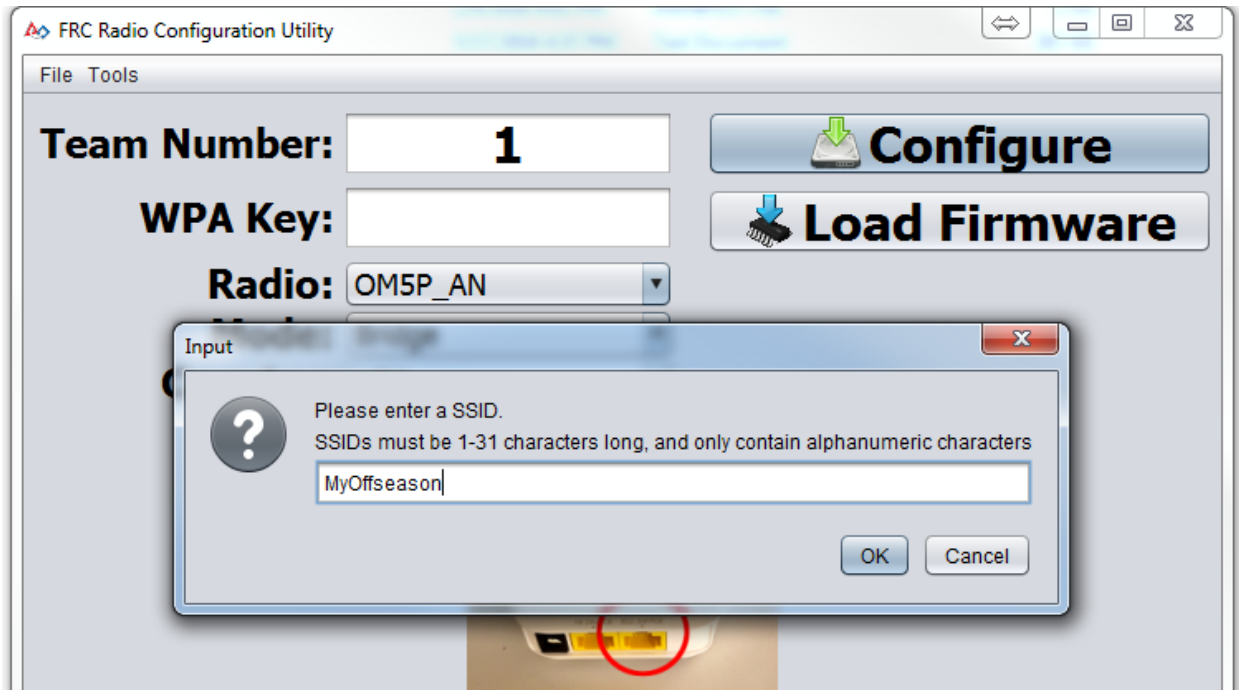
If the your computer is running Windows Vista or Windows 7, a prompt may appear about allowing the configuration utility to make changes to the computer. Click "Yes" if the prompt appears.

### 10.3.7 Enter FMS-Lite Mode



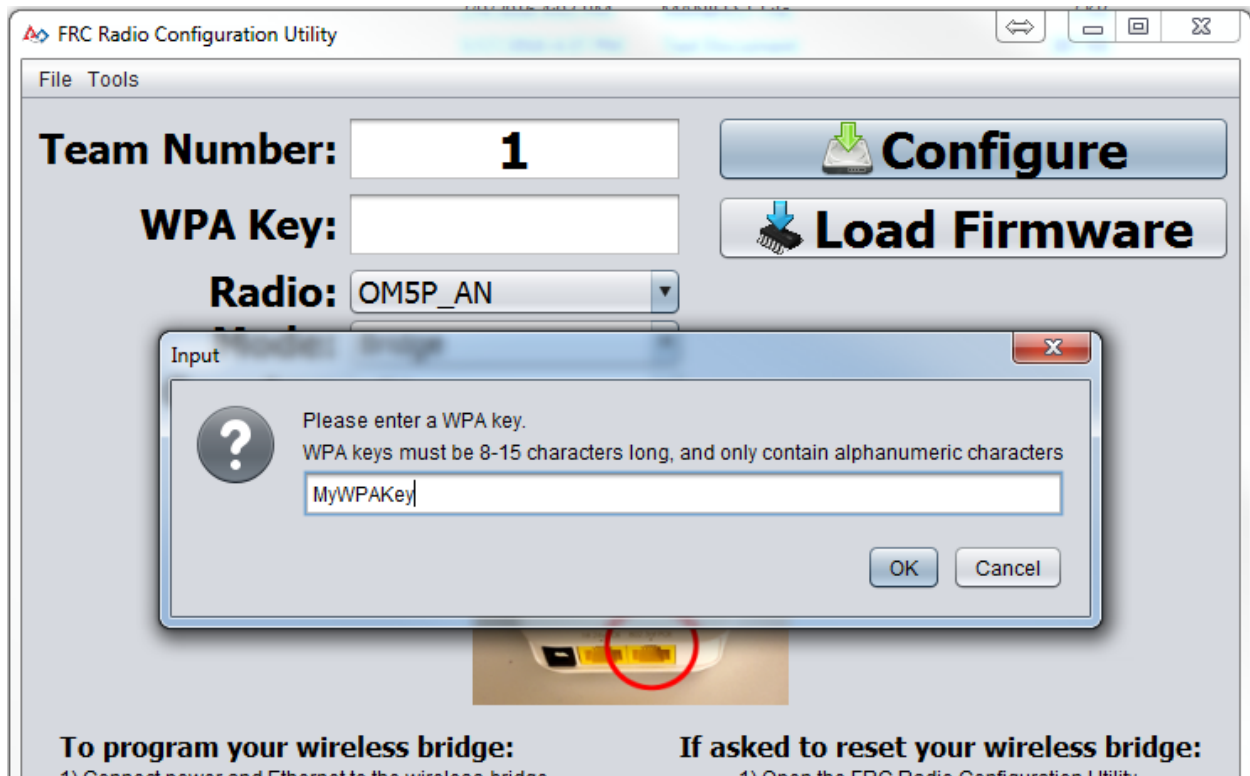
Click Tools -> FMS-Lite Mode to enter FMS-Lite Mode.

### 10.3.8 Enter SSID



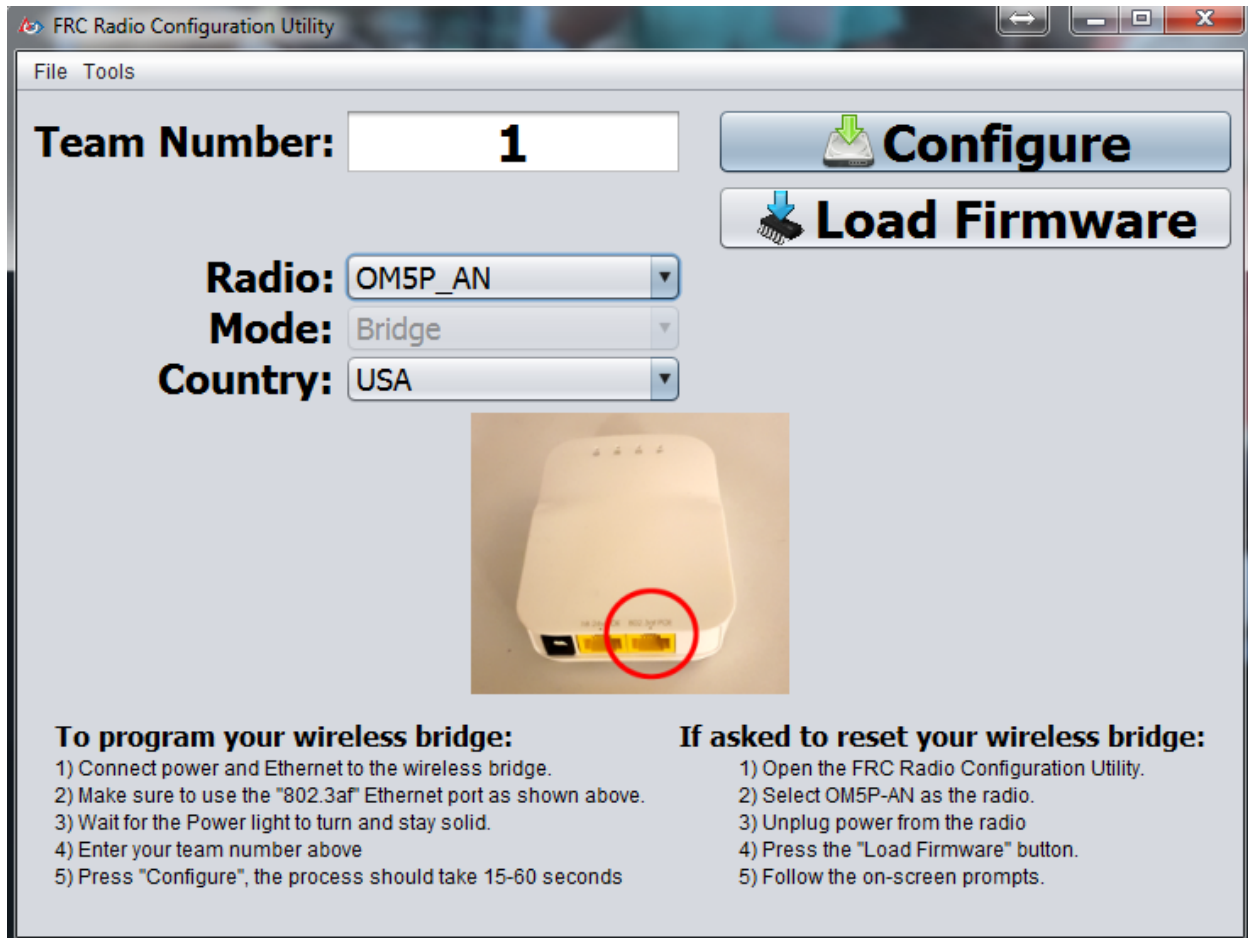
Enter the SSID (name) of your wireless network in the box and click OK.

### 10.3.9 Enter WPA Key



Enter the WPA key for your network in the box and click OK. Leave the box blank if you are using an unsecured network.

### 10.3.10 Program Radios



The Kiosk is now ready to program any number of radios to connect to the network entered. To program each radio, connect the radio to the Kiosk, set the Team Number in the box, and click Configure.

The kiosk will program OpenMesh, D-Link Rev A or D-Link Rev B radios to work on an offseason FMS network by selecting the appropriate option from the "Radio" dropdown.

**Note:** Bandwidth limitations and QoS will not be configured on the D-Link radios in this mode.

### 10.3.11 Changing SSID or Key

If you enter something incorrectly or need to change the SSID or WPA Key, go to the Tools menu and click FMS-Lite Mode to take the kiosk out of FMS-Lite Mode. When you click again to put the Kiosk back in FMS-Lite Mode, you will be re-prompted for the SSID and Key.

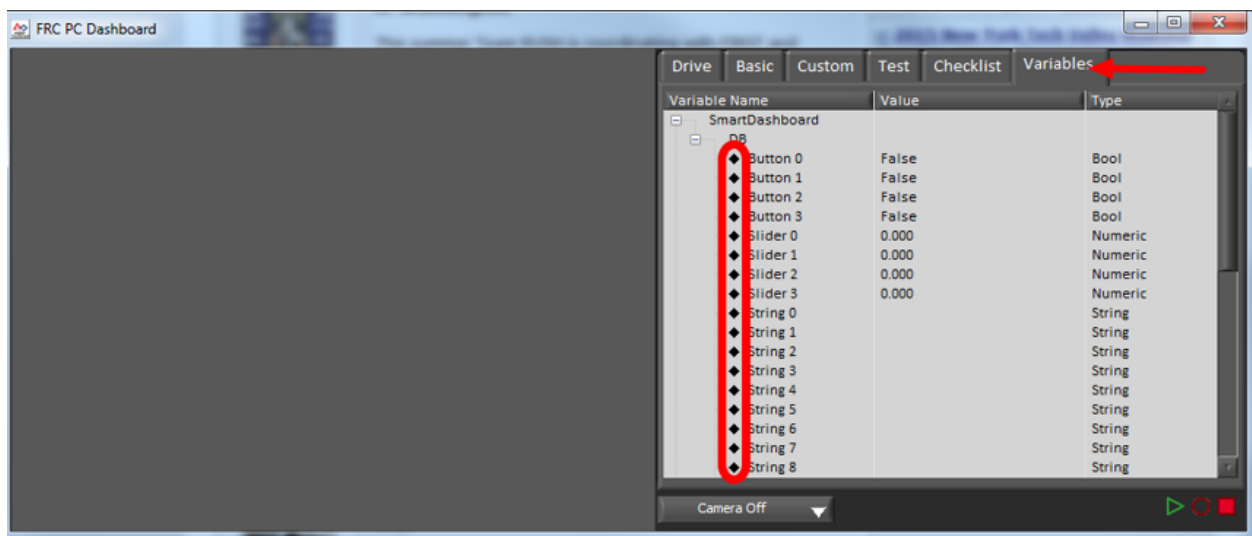
## 10.4 Troubleshooting Dashboard Connectivity

We have received a number of reports of Dashboard connectivity issues from events. This document will help explain how to recognize if the Dashboard is not connected to your robot, steps to troubleshoot this condition and a code modification you can make.

### 10.4.1 LabVIEW Dashboard

This section discusses connectivity between the robot and LabVIEW dashboard

#### Recognizing LabVIEW Dashboard Connectivity



If you have an indicator on your dashboard that you expect to be changing it may be fairly trivial to recognize if the Dashboard is connected. If not, there is a way to check without making any changes to your robot code. On the Variables tab of the Dashboard, the variables are shown with a black diamond when they are not synced with the robot. Once the Dashboard connects to the robot and these variables are synced, the diamond will disappear.

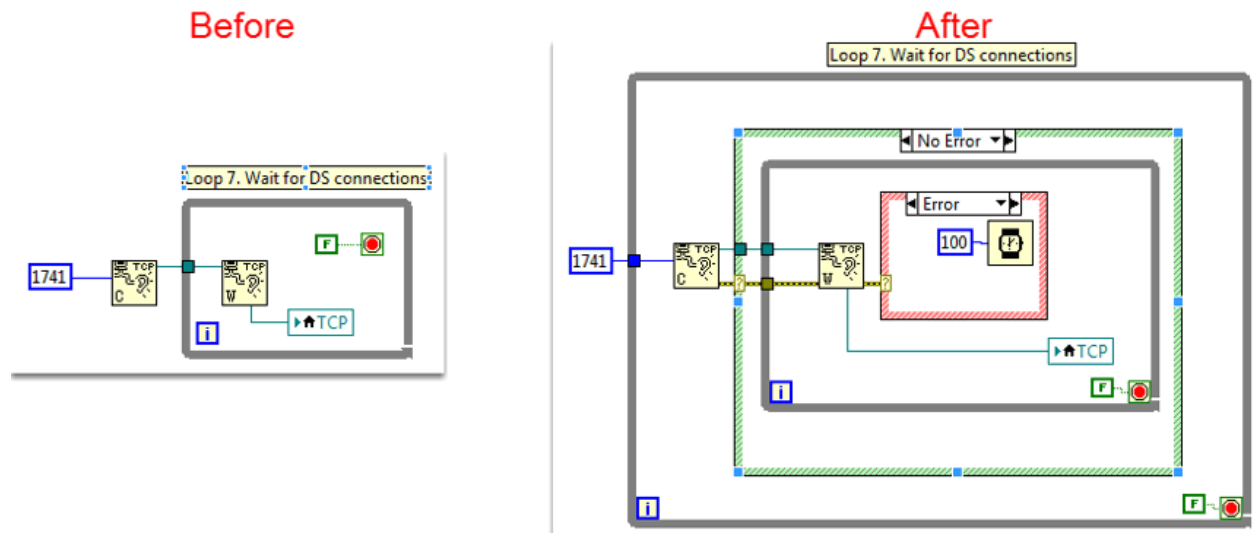
#### Troubleshooting LabVIEW Dashboard Connectivity

If the Dashboard does not connect to the Robot (after the Driver Station has connected to the robot) the recommended troubleshooting steps are:

1. Close the Driver Station and Dashboard, then re-open the Driver Station (which should launch the Dashboard).
2. If that doesn't work, restart the Robot Code using the Restart Robot Code button on the Diagnostics tab of the Driver Station



## Improving Reliability of a Custom Dashboard

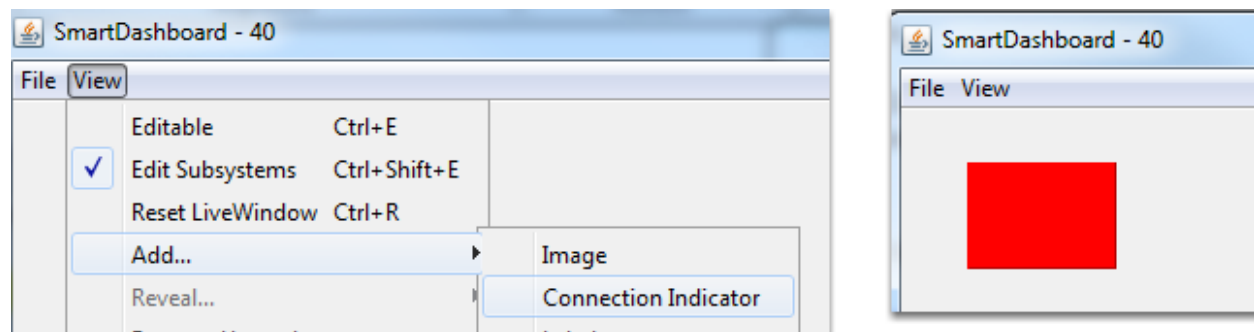


If you have created a custom LabVIEW dashboard there is a tweak you can make to the code to improve reliability of the initial connection. Locate the loop labeled Loop 7 in the Dashboard Main VI. Modify the loop according to the image above by adding a loop around the listener, 2 case statements, a Wait block and error wiring.

### 10.4.2 SmartDashboard

This section discusses connectivity between the robot and Java SmartDashboard

#### Recognizing SmartDashboard Connectivity



The typical way to recognize connectivity with the Java SmartDashboard is to add a Connection Indicator widget and to make sure your code is writing at least one key during initialization or disabled to trigger the connection indicator. The connection indicator can be moved or re-sized if the Editable checkbox is checked.

## Troubleshooting SmartDashboard Connectivity

If the Dashboard does not connect to the Robot (after the Driver Station has connected to the robot) the recommended troubleshooting steps are:

1. Restart the SmartDashboard (there is no need to restart the Driver Station software for the Java SmartDashboard)
2. If that doesn't work, restart the Robot Code using the Restart Robot Code button on the Diagnostics tab of the Driver Station
3. If it still doesn't connect verify that the Team Number is set properly in the Dashboard and that your Robot Code writes a SmartDashboard value during initialization or disabled

## 10.5 Driver Station Best Practices

This document was created by Steve Peterson, with contributions from Juan Chong, James Cole-Henry, Rick Kosbab, Greg McKaskle, Chris Picone, Chris Roadfeldt, Joe Ross, and Ryan Sjostrand. The original post and follow-up posts can be found here: <https://www.chiefdelphi.com/t/paper-driver-station-best-practices/164429> and a mirror of the document can be found [here](#).

Want to ensure the driver station isn't a stopper for your team at the FIRST Robotics Competition (FRC) field? Building and configuring a solid driver station laptop is an easy project for the time between stop build day and your competition. Read on to find lessons learned by many teams over thousands of matches.

### 10.5.1 Prior To Departing For The Competition

1. Dedicate a laptop to be used solely as a driver station. Many teams do. A dedicated machine allows you manage the configuration for one goal – being ready to compete at the field. Dedicated means no other software except the FRC-provided Driver Station software and associated Dashboard installed or running.
2. Use a business-class laptop for your driver station. Why? They're much more durable than the \$300 Black Friday special at Best Buy. They'll survive being banged around at the competition. Business-class laptops have higher quality device drivers, and the drivers are maintained for a longer period than consumer laptops. This makes your investment last longer. Lenovo ThinkPad T series and Dell Latitude are two popular business-class brands you'll commonly see at competitions. There are thousands for sale every day on eBay. The laptop provided in recent rookie kits is a good entry level machine. Teams often graduate from it to bigger displays as they do more with vision and dashboards.
3. Consider used laptops rather than new. The FRC Driver Station and dashboard software uses very few system resources, so you don't need to buy a new laptop – instead, buy a cheap 4-5 year old used one. You might even get one donated by a used computer store in your area.
4. Laptop recommended features
  - a. RAM – 2GB of RAM is minimum, if you have a SSD.
  - b. A display size of 13" or greater, with minimum resolution of 1440x1050.

- c. Ports
  - i. A built-in Ethernet port is highly preferred. Ensure that it's a full-sized port. The hinged Ethernet ports don't hold up to repeated use.
  - ii. Use an Ethernet port saver to make your Ethernet connection. This extends the life of the port on the laptop. This is particularly important if you have a consumer-grade laptop with a hinged Ethernet port.
  - iii. If the Ethernet port on your laptop is dodgy, either replace the laptop (recommended) or buy a USB Ethernet dongle from a reputable brand. Many teams find that USB Ethernet is less reliable than built-in Ethernet, primarily due to cheap hardware and bad drivers. The dongles given to rookies in the KOP have a reputation for working well.
  - iv. 2 USB ports minimum
- d. A keyboard. It's hard to quickly do troubleshooting on touch-only computers at the field.
- e. A solid-state disk (SSD). If the laptop has a rotating disk, spend \$50 and replace it with a SSD.
- f. Updated to the current release of Windows 10. Being the most common OS now seen at competitions, bugs are more likely to be found and fixed for Windows 10 than on older Windows versions.
- 5. Install all Windows updates a week before the competition. This allows you time to ensure the updates will not interfere with driver station functions. To do so, open the Windows Update settings page and see that you're up-to-date. Install pending updates if not. Reboot and check again to make sure you're up to date.
- 6. Change "Active Hours" for Windows Updates to prevent updates from installing during competition hours. Navigate to Start -> Settings -> Update & Security -> Windows Update, then select Change active hours. If you're traveling to a competition, take time zone differences into account. This will help ensure your driver station does not reboot or fail due to update installing on the field.
- 7. Remove any 3rd party antivirus or antimalware software. Instead, use Windows Defender on Windows 10. Since you're only connecting to the internet for Windows and FRC software updating, the risk is low. Only install software on your driver station that's needed for driving. Your goal here is to eliminate variables that might interfere with proper operation. Remove any unneeded preinstalled software ("crapware") that came with the machine. Don't use the laptop as your Steam machine for gaming back at the hotel the night before the event. Many teams go as far as having a separate programming laptop.
- 8. Avoid managed Windows 10 installations from the school's IT department. These deployments are built for the school environment and often come with unwanted software that interferes with your robot's operation.
- 9. Laptop battery / power
  - a. Turn off Put the computer to sleep in your power plan for both battery and powered operation.
  - b. Turn off USB Selective Suspend:
    - i. Right click on the battery/charging icon in the tray, then select Power Options.
    - ii. Edit the plan settings of your power plan.

- iii. Click the Change advanced power settings link.
  - iv. Scroll down in the advanced settings and disable the USB selective suspend setting for both Battery and Plugged in.
  - c. Ensure the laptop battery can hold a charge for at least an hour after making the changes above. This allows plenty of time for the robot and drive team to go through the queue and reach the alliance station without mains power.
10. Bring a trusted USB and Ethernet cable for use connecting to the roboRIO.
  11. Add retention/strain relief to prevent your joystick/gamepad controllers from falling on the floor and/or yanking on the USB ports. This helps prevent issues with intermittent controller connections.
  12. The Windows user account you use to drive must be a member of the Administrator group.

### **10.5.2 At The Competition**

1. Turn off Windows firewall using these instructions.
2. Turn off the Wi-Fi adapter, either using the dedicated hardware Wi-Fi switch or by disabling it in the Adapter Settings control panel.
3. Charge the driver station when it's in the pit.
4. Remove login passwords or ensure everyone on the drive team knows the password. You'd be surprised at how often drivers arrive at the field without knowing the password for the laptop.
5. Ensure your LabView code is deployed permanently and set to "run as startup", using the instructions in the LabView Tutorial. If you must deploy code every time you turn the robot on, you're doing it wrong.
6. Limit web browsing to FRC related web sites. This minimizes the chance of getting malware during the competition.
7. Don't plan on using internet access to do software updates. There likely won't be any in the venue, and hotel Wi-Fi varies widely in quality. If you do need updates, contact a Control System Advisor in the pit.

### **10.5.3 Before Each Match**

1. Make sure the laptop is on and logged in prior to the end of the match before yours.
2. Close programs that aren't needed during the match - e.g., Eclipse or LabView - when you are competing.
3. Bring your laptop charger to the field. Power is provided for you in each player station.
4. Fasten your laptop with hook-and-loop tape to the player station shelf. You never know when your alliance partner will have an autonomous programming issue and blast the wall.
5. Ensure joysticks and controllers are assigned to the correct USB ports.
  - a. In the USB tab in the FRC Driver Station software, drag and drop to assign joysticks as needed.

- b. Use the rescan button (F1) if joysticks / controllers do not appear green
- c. Use the rescan button (F1) during competition if joystick or controllers become unplugged and then are plugged back in or otherwise turn gray during competition.

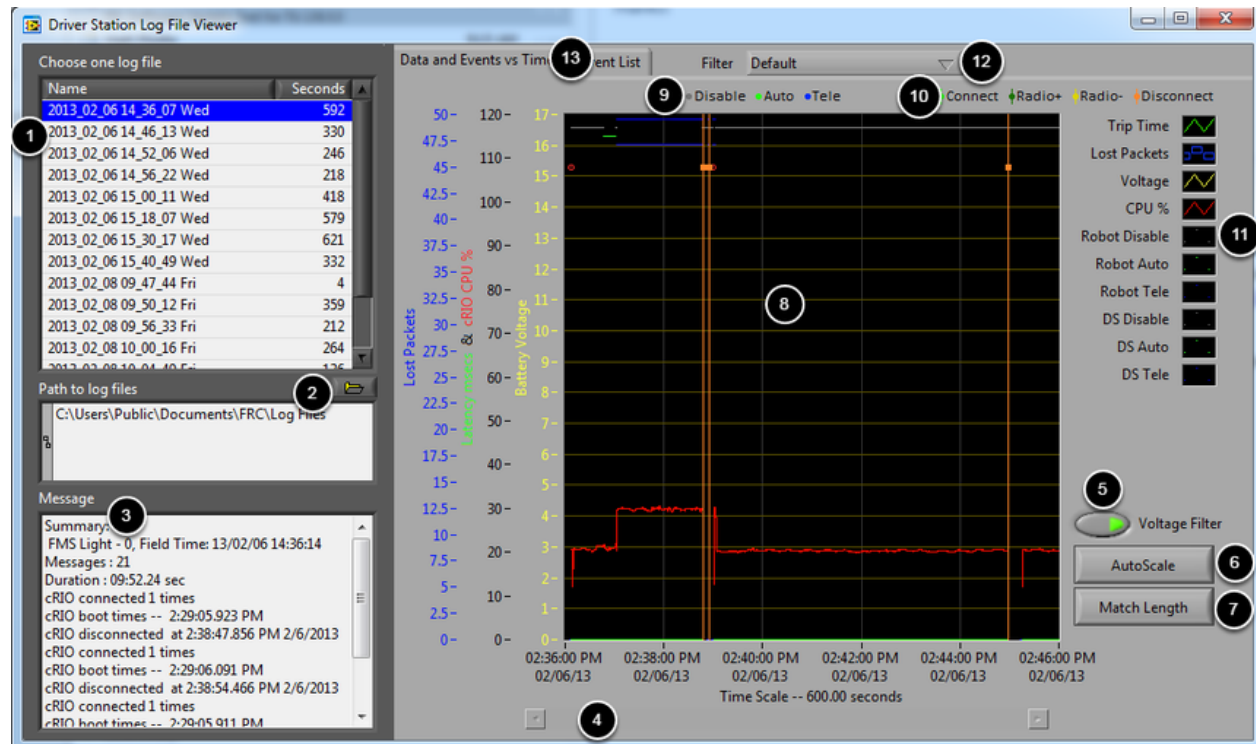
## 10.6 Driver Station Log File Viewer

In an effort to provide information to aid in debugging, the FRC Driver Station creates log files of important diagnostic data while running. These logs can be reviewed later using the FRC Driver Station Log Viewer. The Log Viewer can be found via the shortcut installed in the Start menu or in the FRC Driver Station folder in Program Files.

### 10.6.1 Event Logs

The Driver Station logs all messages sent to the Messages box on the Diagnostics tab (not the User Messages box on the Operation tab) into a new Event Log file. When viewing Log Files with the Driver Station Log File Viewer, the Event Log and DSLog files are overlaid in a single display.

### 10.6.2 Log Viewer UI

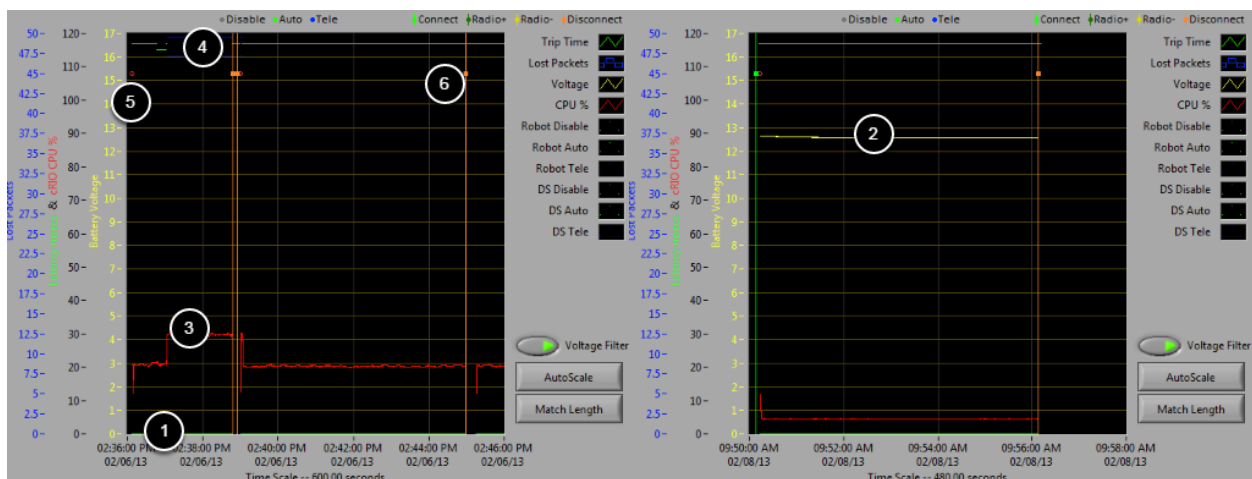


The Log Viewer contains a number of controls and displays to aid in the analysis of the Driver Station log files:

1. File Selection Box - This window displays all available log files in the currently selected folder. Click on a log file in the list to select it.

2. Path to Log Files - This box displays the current folder the viewer is looking in for log files. This defaults to the folder that the Driver Station stores log files in. Click the folder icon to browse to a different location.
3. Message Box - This box displays a summary of all messages from the Event Log. When hovering over an event on the graph this box changes to display the information for that event.
4. Scroll Bar - When the graph is zoomed in, this scroll bar allows for horizontal scrolling of the graph.
5. Voltage Filter - This control turns the Voltage Filter on and off (defaults to on). The Voltage Filter filters out data such as CPU %, robot mode and trip time when no Battery Voltage is received (indicating that the DS is no in communication with the roboRIO).
6. AutoScale - This button zooms the graph out to show all data in the log.
7. Match Length - This button scales the graph to approximately the length of an FRC match (2 minutes and 30 seconds shown). It does not automatically locate the start of the match, you will have to scroll using the scroll bar to locate the beginning of the Autonomous mode.
8. Graph - This display shows graph data from the DS Log file (voltage, trip time, roboRIO CPU%, Lost Packets, and robot mode) as well as overlaid event data (shown as dots on the graph with select events showing as vertical lines across the entire graph). Hovering over event markers on the graph displays information about the event in the Messages window in the bottom left of the screen.
9. Robot Mode Key - Key for the Robot Mode displayed at the top of the screen
10. Major event key - Key for the major events, displayed as vertical lines on the graph
11. Graph key - Key for the graph data
12. Filter Control - Drop-down to select the filter mode (filter modes explained below)
13. Tab Control - Control to switch between the Graph (Data and Events vs. Time) and Event List displays.

### 10.6.3 Using the Graph display



The Graph Display contains the following information:

1. Graphs of Trip Time in ms (green line) and Lost Packets per second (displayed as blue vertical bars). In these example images Trip Time is a flat green line at the bottom of the graph and there are no lost packets
  2. Graph of Battery voltage displayed as a yellow line.
  3. Graph of roboRIO CPU % as a red line
  4. Graph of robot mode and DS mode. The top set of the display shows the mode commanded by the Driver Station. The bottom set shows the mode reported by the robot code. In this example the robot is not reporting it's mode during the disabled and autonomous modes, but is reported during Teleop.
  5. Event markers will be displayed on the graph indicating the time the event occurred. Errors will display in red; warnings will display in yellow. Hovering over an event marker will display information about the event in the Messages box at the bottom left of the screen.
  6. Major events are shown as vertical lines across the graph display.
- To zoom in on a portion of the graph, click and drag around the desired viewing area. You can only zoom the time axis, you cannot zoom vertically.

### 10.6.4 Event List

DS Time	Event Message Text
2:36:07.288 PM	WARNING <Code> 44007 occurred at FRC_NetworkCommunications <secondsSinceReboot> 421.365 Warning <Code> 44001 occurred at No Change to Network Configuration: "Local Area Connection" <noNIC> FRC: Time since robot boot. Driver Station <time> 2/6/2013 2:36:07 PM<unique#> 3 ERROR <Code> -44009 occurred at Driver Station <time> 2/6/2013 2:36:06 PM<unique#> 2 FRC: A joystick was disconnected while the robot was enabled. Warning <Code> 44006 occurred at Driver Station <time> 2/6/2013 2:36:06 PM<unique#> 1 FRC: Custom I/O is not enabled or is not connected to the driver station.
2:36:07.328 PM	FMS Connected: FMS Light - 0, Field Time: 13/02/06 14:36:14
2:36:10.441 PM	WARNING <Code> 44008 occurred at FRC_NetworkCommunications <radioLostEvents> 173.563 <radioSec> FRC: Robot radio detection times.
2:37:01.461 PM	Watchdog Expiration: System 1, User 0
2:38:47.856 PM	Warning <Code> 44004 occurred at Driver Station <time> 2/6/2013 2:38:47 PM<unique#> 4 FRC: The Driver Station has lost communication with the robot.
2:38:49.356 PM	Warning <Code> 44002 occurred at Ping Results: link-GOOD, DS radio(4)-GOOD, robot radio(1)-GOOD, <time> 2/6/2013 2:38:49 PM<unique#> 5 FRC: Driver Station ping status has changed.
2:38:53.460 PM	WARNING <Code> 44007 occurred at FRC_NetworkCommunications <secondsSinceReboot> 587.369 FRC: Time since robot boot.
2:38:54.466 PM	Warning <Code> 44004 occurred at Driver Station <time> 2/6/2013 2:38:53 PM<unique#> 6 FRC: The Driver Station has lost communication with the robot.
2:38:55.468 PM	Warning <Code> 44002 occurred at Ping Results: link-GOOD, DS radio(4)-GOOD, robot radio(1)-GOOD, <time> 2/6/2013 2:38:55 PM<unique#> 7 FRC: Driver Station ping status has changed.
2:38:59.278 PM	WARNING <Code> 44008 occurred at FRC_NetworkCommunications <radioLostEvents> 339.065 <radioSec> FRC: Robot radio detection times. WARNING <Code> 44007 occurred at FRC_NetworkCommunications <secondsSinceReboot> 593.367



The Event List tab displays a list of events (warnings and errors) recorded by the Driver Station. The events and detail displayed are determined by the currently active filter (images shows “All Events, All Info” filter active).

### 10.6.5 Filters

Three filters are currently available in the Log Viewer:

1. Default: This filter filters out many of the errors and warnings produced by the Driver Station. This filter is useful for identifying errors thrown by the code on the Robot.
2. All Events and Time: This filter shows all events and the time they occurred
3. All Events, All Info: This filter shows all events and all recorded info. At this time the primary difference between this filter and “All Events and Time” is that this option shows the “unique” designator for the first occurrence of a particular message.

### 10.6.6 Identifying Logs from Matches

3:19:30.893 PM	FMS Connected: Practice - 1, Field Time: 13/02/06 15:19:37
----------------	--

A common task when working with the Driver Station Logs is to identify which logs came from competition matches. Logs which were taken during a match can now be identified using the FMS Connected event which will display the match type (Practice, Qualification or Elimination), match number, and the current time according to the FMS server. In this example, you can see that the FMS server time and the time of the Driver Station computer are fairly close, approximately 7 seconds apart.

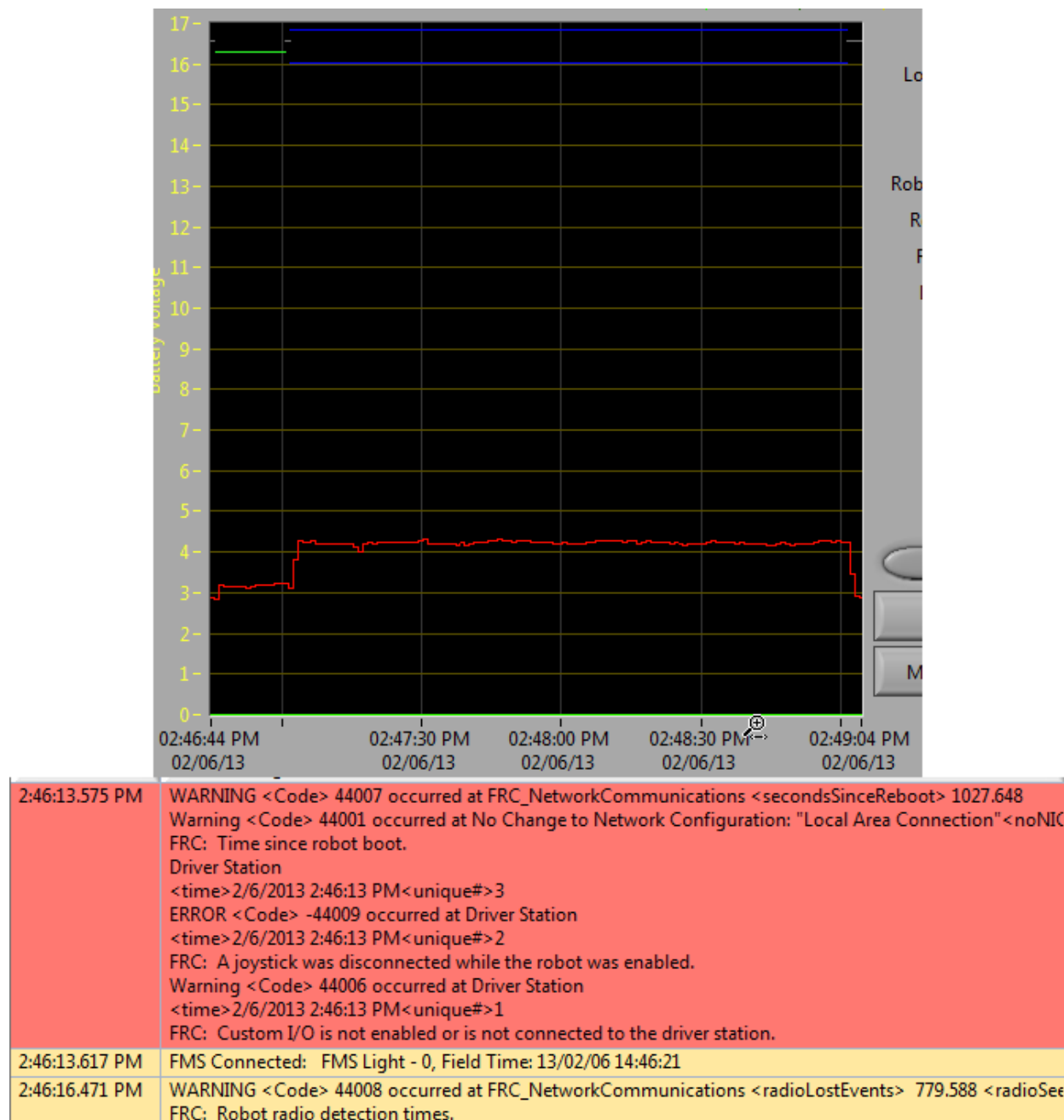
### 10.6.7 Identifying Common Connection Failures with the Log Viewer

When diagnosing robot issues, there is no substitute for thorough knowledge of the system and a methodical debugging approach. If you need assistance diagnosing a connection problem at your events it is strongly recommended to seek assistance from your FTA and/or CSA. The goal of this section is to familiarize teams with how some common failures can manifest themselves in the DS Log files. Please note that depending on a variety of conditions a particular failure show slightly differently in a log file.

Note that all log files shown in this section have been scaled to match length using the Match Length button and then scrolling to the beginning of the autonomous mode. Also, many of the logs do not contain battery voltage information, the platform used for log capture was not properly wired for reporting the battery voltage.

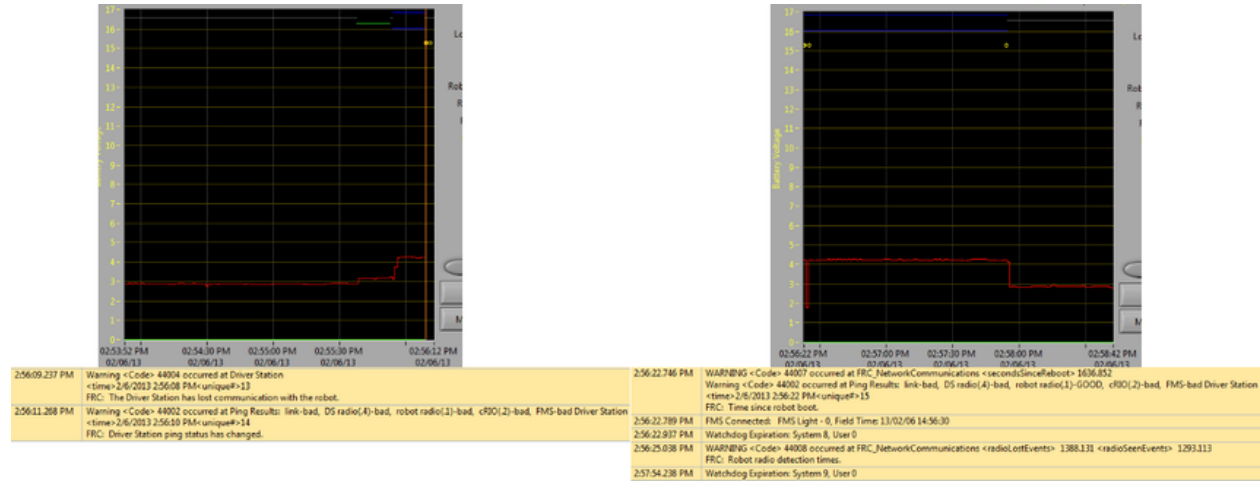


## “Normal” Log



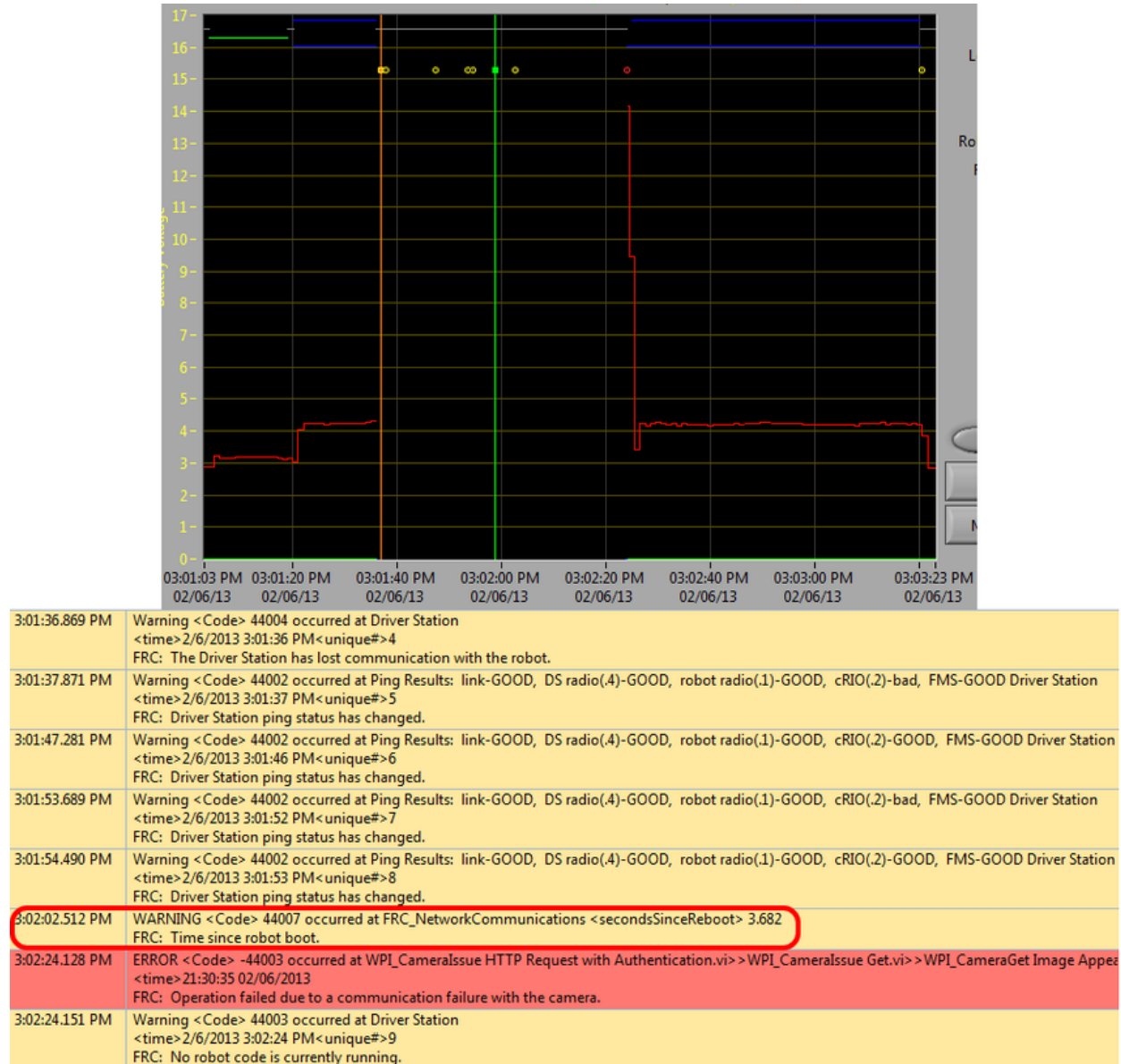
This is an example of a normal match log. The errors and warnings contained in the first box are from when the DS first started and can be ignored. This is confirmed by observing that these events occurred prior to the “FMS Connected:” event. The last event shown can also be ignored, it is also from the robot first connecting to the DS (it occurs 3 seconds after connecting to FMS) and occurs roughly 30 seconds before the match started.

## Disconnected from FMS



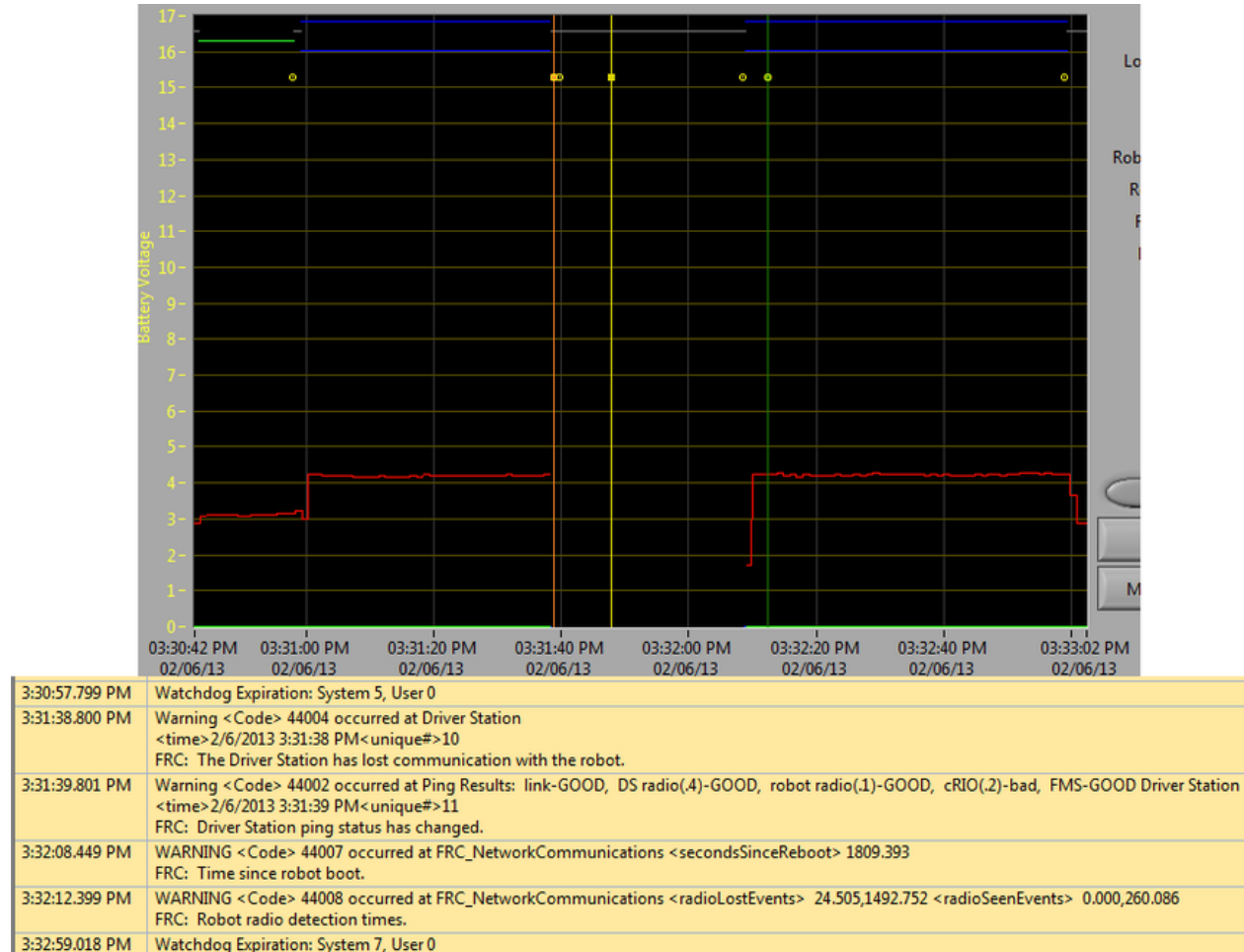
When the DS disconnects from FMS, and therefore the robot, during the match it may segment the log into pieces. The key indicators to this failure are the last event of the first log, indicating that the connection to FMS is now “bad” and the second event from the 2nd log which is a new FMS connected message followed by the DS immediately transitioning into Teleop Enabled. The most common cause of this type of failure is an ethernet cable with no latching tab or a damaged ethernet port on the DS computer.

## roboRIO Reboot



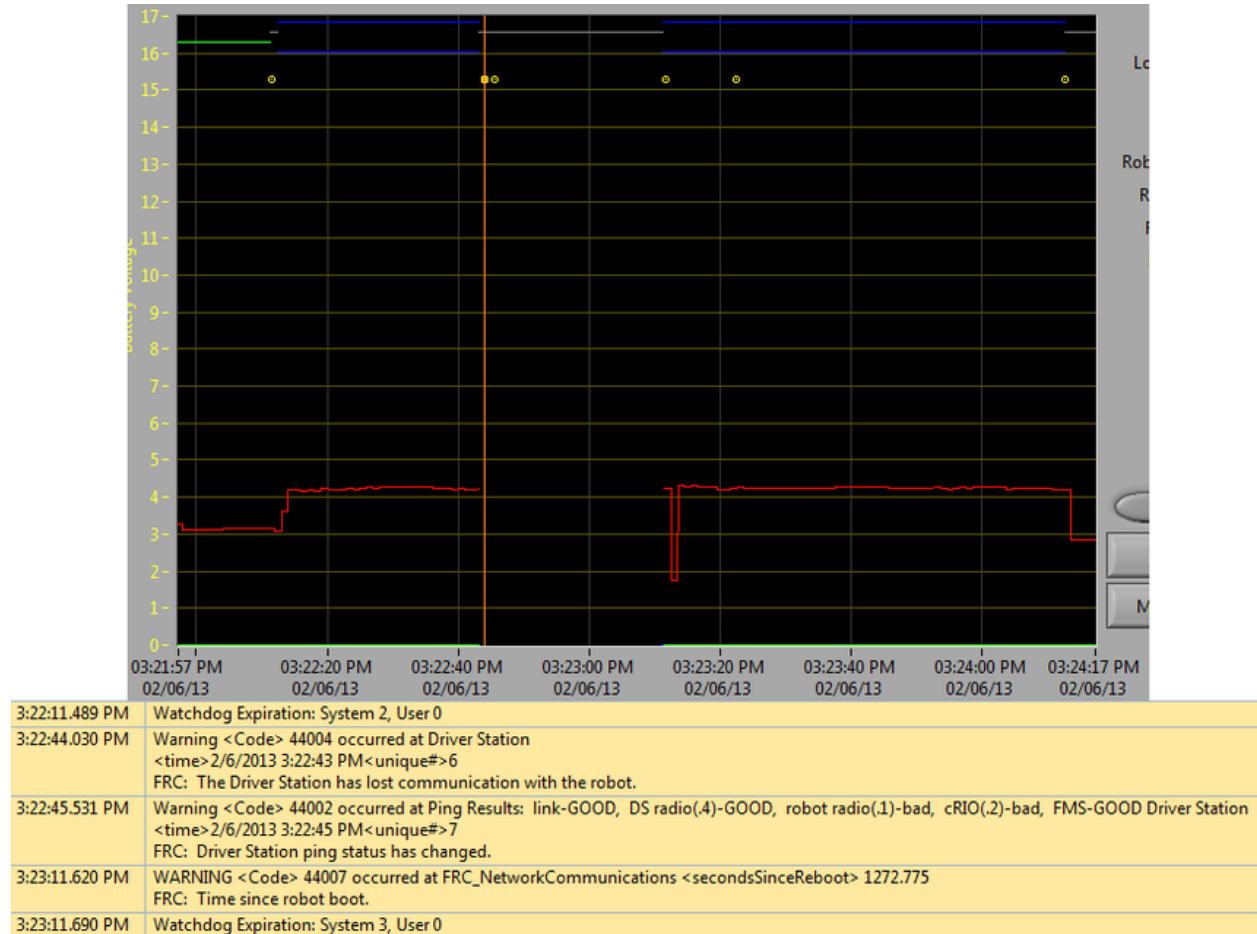
The “Time since robot boot” message is the primary indicator in a connection failure caused by the roboRIO rebooting. In this log the DS loses connection with the roboRIO at 3:01:36 as indicated by the first event. The second event indicates that the ping initiated after the connection failed was successful to all devices other than the roboRIO. At 3:01:47 the roboRIO begins responding to pings again, one additional ping fails at 3:01:52. At 3:02:02 the Driver Station connects to the roboRIO and the roboRIO reports that it has been up for 3.682 seconds. This is a clear indicator that the roboRIO has rebooted. The code continues to load and at 3:02:24 the code reports an error communicating with the camera. A warning is also reported indicating that no robot code is running right before the code finishes starting up.

## Ethernet cable issue on robot



An issue with the ethernet cable on the robot is primarily indicated by the ping to the roboRIO going to bad and Radio Lost and Radio Seen events when the roboRIO reconnects. The “Time since robot boot” message when the roboRIO reconnects will also indicate that the roboRIO has not rebooted. In this example, the robot Ethernet cable was disconnected at 3:31:38. The ping status indicates that the D-Link radio is still connected. When the robot reconnects at 3:32:08 the “Tim since robot boot” is 1809 seconds indicating that the roboRIO clearly did not reboot. At 3:32:12 the robot indicates that it lost the radio 24.505 seconds ago and it returned 0.000 seconds ago. These points are plotted as vertical lines on the graph, yellow for radio lost and green for radio seen. Note that the times are slightly offset from the actual events as shown via the disconnection and connection, but help to provide additional information about what is occurring.

## Radio reboot



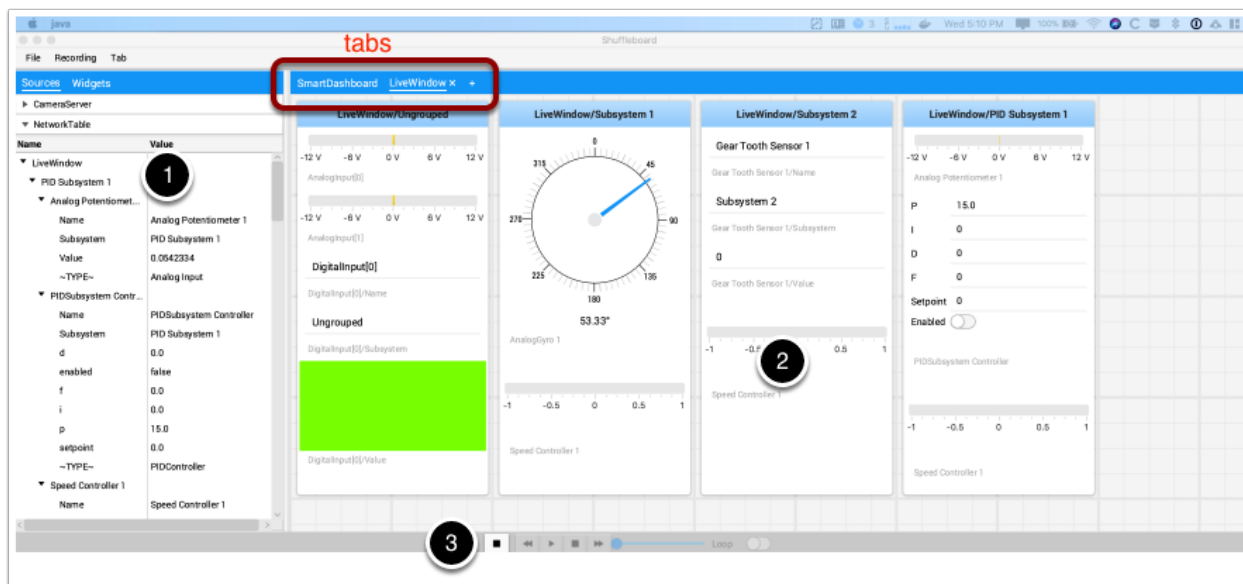
A reboot of the robot radio is typically characterized by a loss of connection to the radio for ~40-45 seconds. In this example, the radio briefly lost power at 3:22:44, causing it to start rebooting. The event at 3:22:45 indicates that the ping to the radio failed. At 3:23:11, the DS regains communication with the roboRIO and the roboRIO indicates it has been up for 1272.775 seconds, ruling out a roboRIO reboot. Note that the network switch on the radio comes back up very quickly so a momentary power loss may not result in a “radio lost”/“radio seen” event pair. A longer disturbance may result in radio events being logged by the DS. In that case, the distinguishing factor which points towards a radio reboot is the ping status of the radio from the DS. If the radio resets, the radio will be unreachable. If the issue is a cabling or connection issue on the robot, the radio ping should remain “GOOD”.

## 11.1 Shuffleboard - Getting Started

### 11.1.1 Tour of Shuffleboard

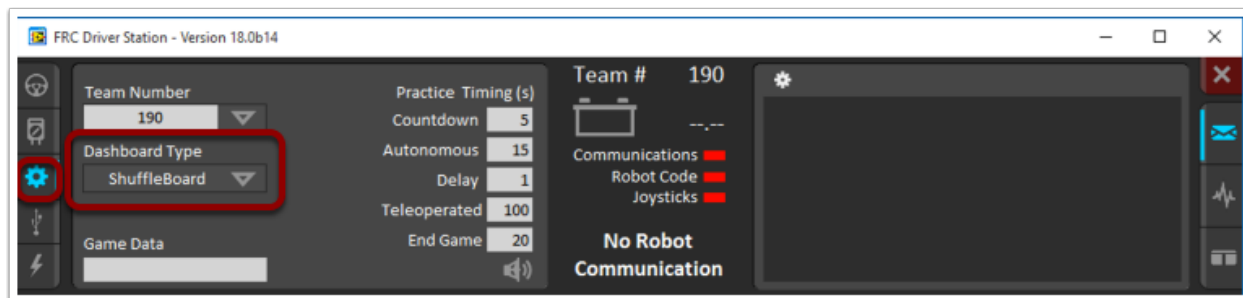
Shuffleboard is a dashboard for FRC based on newer technologies such as JavaFX that are available to Java programs. It is designed to be used for creating dashboards for C++ and Java programs. If you've used SmartDashboard in the past then you are already familiar with many of the features of Shuffleboard since they fundamentally work the same way. But Shuffleboard has many features that aren't in SmartDashboard. Here are some of the highlights:

- Graphics is based on **JavaFX**, the Java graphics standard. Each of the components has an associated style sheet so it becomes possible to have different “skins” or “themes” for Shuffleboard. We supply default light and dark themes.
- Shuffleboard supports **multiple sheets for the display of your data**. In fact you can create a new sheet (shown as a tab in the Shuffleboard window) and indicate if and which data should be autopopulated on it. By default there is a Test tab and a SmartDashboard tab that are autopopulated as data arrives. Other tabs might be for robot debugging vs. driving.
- Graphical **display elements (widgets) are laid out on a grid** to keep the interface clean and easy to read. You can change the grid size to have more or less resolution in your layouts and visual cues are provided to help you change your layout using drag and drop. Or you can choose to turn off the grid lines although the grid layout is preserved.
- Layouts are saved and the previous layout is instantiated by default when you run shuffleboard again.
- There is a **record and playback** feature that lets you review the data sent by your robot program after it finishes. That way you can carefully review the actions of the robot if something goes wrong.
- **Graph widgets are available for numeric data** and you can drag data onto a graph to see multiple points at the same time and on the same scale.
- You can extend Shuffleboard by writing your own widgets that are specific to your team's requirements. Documentation on extending it are on the [Shuffleboard Github Wiki](#).



1. **Sources area:** Here are data sources from which you can choose values from NetworkTables or other sources to display by dragging a value into one of the tabs
2. **Tab panes:** This is where your data is displayed from the robot or other sources. In this example it is Test-mode subsystems that are shown here in the LiveWindow tab. This area can show any number of tabbed windows, and each window has its own set of properties like grid size and auto-populate.
3. **Record/playback controls:** set of media-like controls where you can playback the current session to see historical data

## Starting Shuffleboard



You can start Shuffleboard in one of four ways:

1. You can automatically start it when the Driver Station starts by setting the “Dashboard Type” to Shuffleboard in the settings tab as shown in the picture above.
2. You can run it by double-clicking the Shuffleboard icon on the Windows Desktop.
3. You can run it by double-clicking on the shuffleboard.XXX file (where XXX is vbs on Windows and .py on Linux or macOS) in ~/WPILib/YYYY/tools/ (where YYYY is the year and ~ is C:\Users\Public on Windows). This is useful on a development system that does not have the Driver Station installed such as a macOS or Linux system.

4. You can start it from the command line by typing the command: `shuffleboard` on Windows or `python shuffleboard.py` on macOS or Linux from `~/WPILib/YYYY/tools` directory (where YYYY is the year and ~ is `C:\Users\Public` on Windows). This is often easiest on a development system that doesn't have the Driver Station installed.

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**Note:** The `.vbs` (Windows) and `.py` (macOS/Linux) scripts help launch the tools using the correct JDK.

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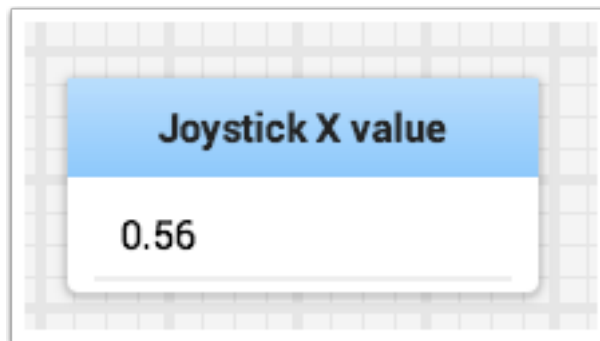
## Getting robot data onto the dashboard

The easiest way to get data displayed on the dashboard is simply to use methods in the SmartDashboard class. For example to write a number to Shuffleboard write:

Java

```
SmartDashboard.putNumber("Joystick X value", joystick1.getX());
```

to see a field displayed with the label "Joystick X value" and a value of the X value of the joystick. Each time this line of code is executed, a new joystick value will be sent to Shuffleboard. Remember: you must write the joystick value whenever you want to see an updated value. Executing this line once at the start of the program will only display the value once at the time the line of code was executed.

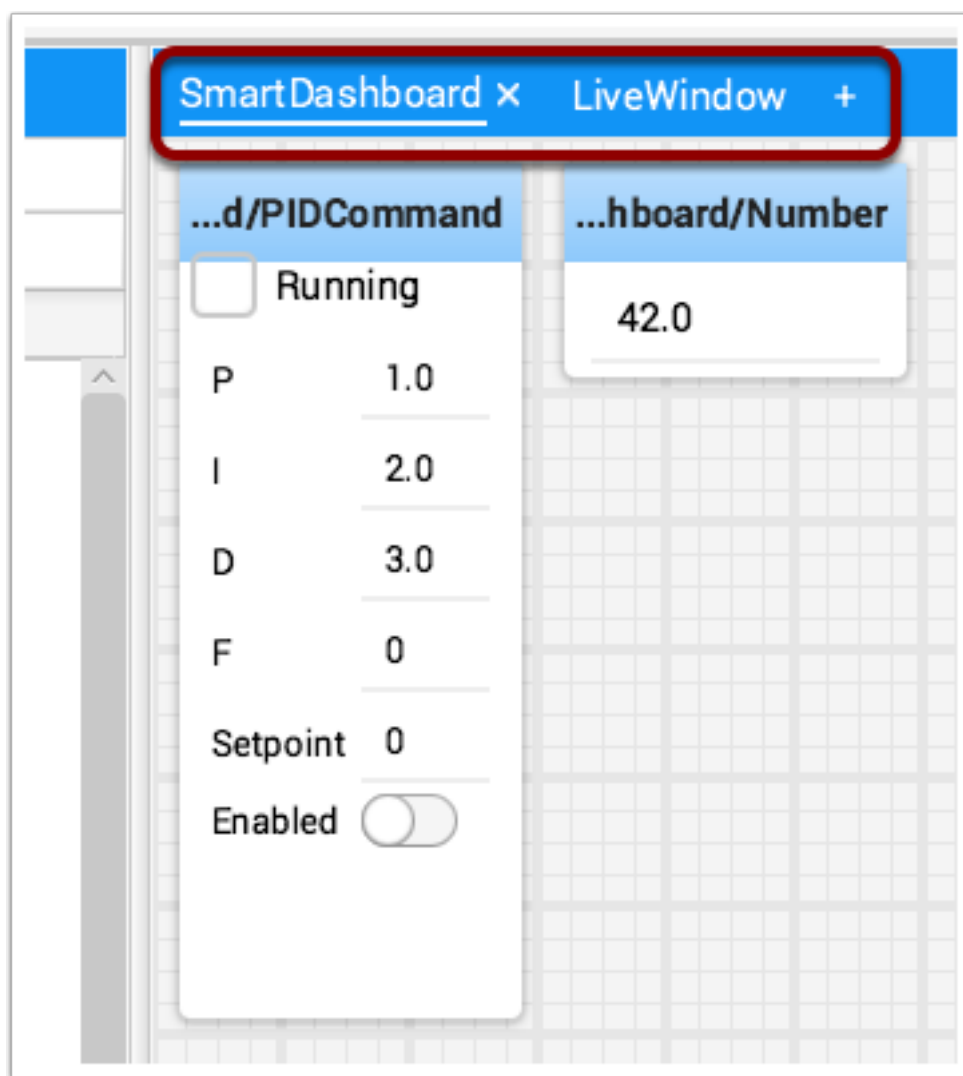


### 11.1.2 Displaying data from your robot

Your robot can display data in regular operating modes like Teleop and Autonomous modes but you can also display the status and operate all the robot subsystems when the robot is switched to Test mode. By default you'll see two tabs when you start Shuffleboard, one for Teleop/Autonomous and another for Test mode. The currently selected tab is underlined as can be seen in the picture below.

Often debugging or monitoring the status of a robot involves writing a number of values to the console and watching them stream by. With Shuffleboard you can put values to a GUI that is automatically constructed based on your program. As values are updated, the corresponding GUI element changes value - there is no need to try to catch numbers streaming by on the screen.

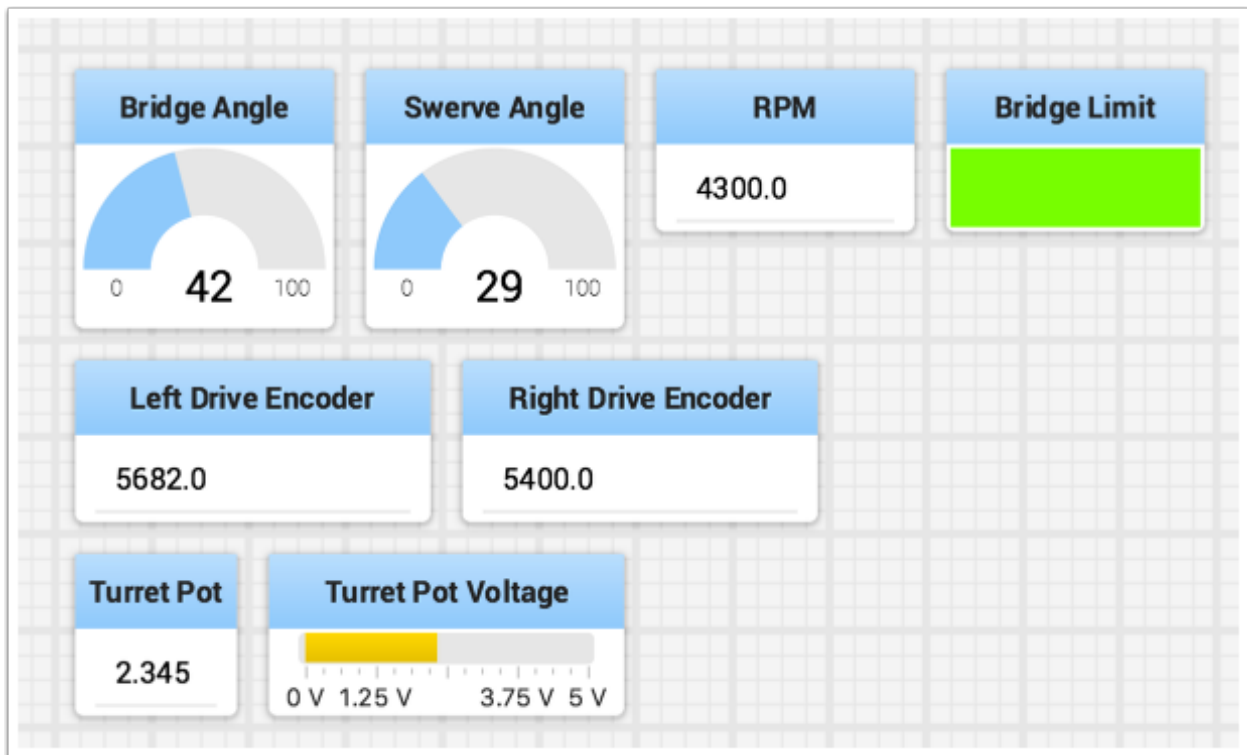




## Displaying values in normal operating mode (autonomous or teleop)

Java

```
protected void execute() {
    SmartDashboard.putBoolean("Bridge Limit", bridgeTipper.atBridge());
    SmartDashboard.putNumber("Bridge Angle", bridgeTipper.getPosition());
    SmartDashboard.putNumber("Swerve Angle", drivetrain.getSwerveAngle());
    SmartDashboard.putNumber("Left Drive Encoder", drivetrain.getLeftEncoder());
    SmartDashboard.putNumber("Right Drive Encoder", drivetrain.getRightEncoder());
    SmartDashboard.putNumber("Turret Pot", turret.getCurrentAngle());
    SmartDashboard.putNumber("Turret Pot Voltage", turret.getAverageVoltage());
    SmartDashboard.putNumber("RPM", shooter.getRPM());
}
```



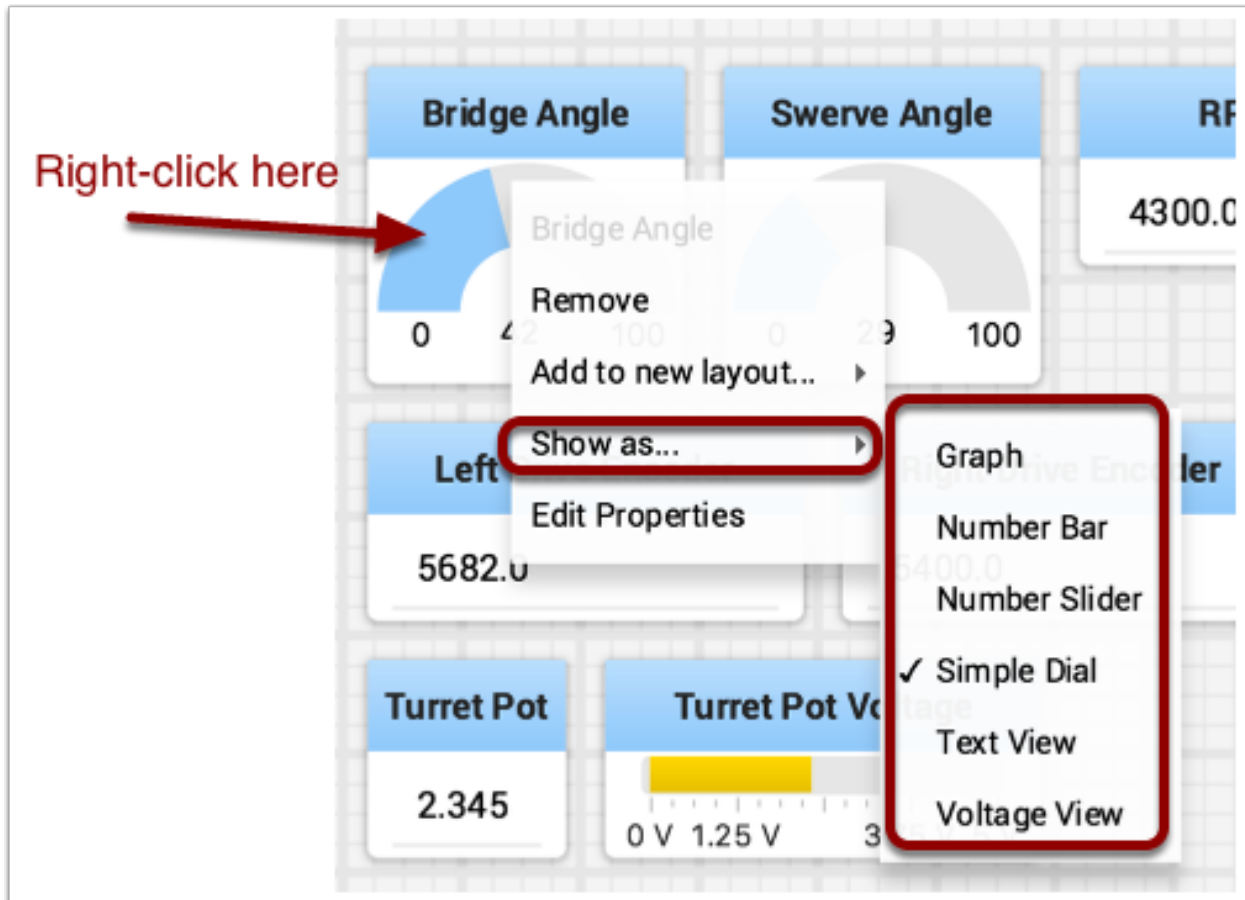
You can write Boolean, Numeric, or String values to Shuffleboard by simply calling the correct method for the type and including the name and the value of the data, no additional code is required.

- Numeric types such as char, int, long, float or double call `SmartDashboard.putNumber("dashboard-name", value)`.
- String types call `SmartDashboard.putString("dashboard-name", value)`
- Boolean types call `SmartDashboard.putBoolean("dashboard-name", value)`

## Changing the display type of data

Depending on the data type of the values being sent to Shuffleboard you can often change the display format. In the previous example you can see that number values were displayed

as either decimal numbers, a dial to better represent angles, and as a voltage view for the turret potentiometer. To set the display type right-click on the tile and select “Show as...”. You can choose display types from the list in the popup menu.

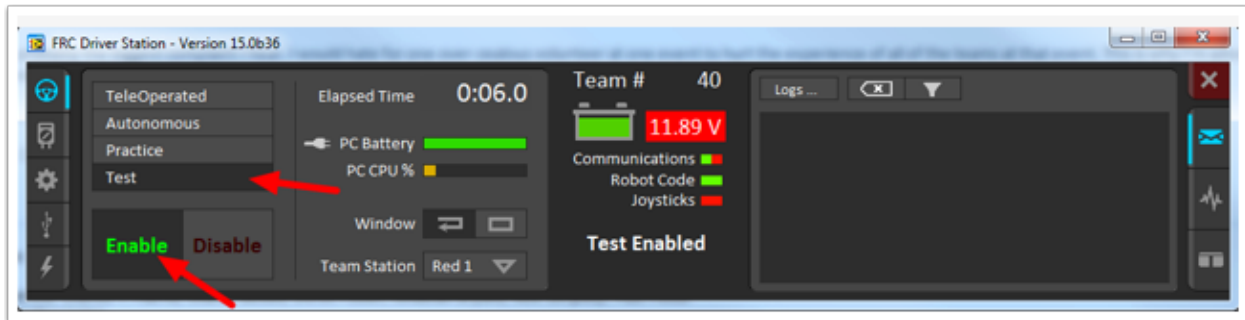


### Displaying data in Test mode

You may add code to your program to display values for your sensors and actuators while the robot is in Test mode. This can be selected from the Driver Station whenever the robot is not on the field. The code to display these values is automatically generated by RobotBuilder or manually added to your program and is described in the next article. Test mode is designed to verify the correct operation of the sensors and actuators on a robot. In addition it can be used for obtaining setpoints from sensors such as potentiometers and for tuning PID loops in your code.

### Setting test mode

Enable Test Mode in the Driver Station by clicking on the “Test” button and setting “Enable” on the robot. When doing this, Shuffleboard will display the status of any actuators and sensors used by your program organized by subsystem.



### Getting data from the Sources view

Normally network table data automatically appears on one of the tabs and you just rearrange and use that data. Sometimes you might want to recover a value that was accidentally deleted from the tab or display a value that is not part of the SmartDashboard/ NetworkTable key. For these cases the values can be dragged onto a pane from NetworkTable view under Sources on the left side of the window. Choose the value that you want to display and just drag it to the pane and it will be automatically created with the default type of widget for the data type.

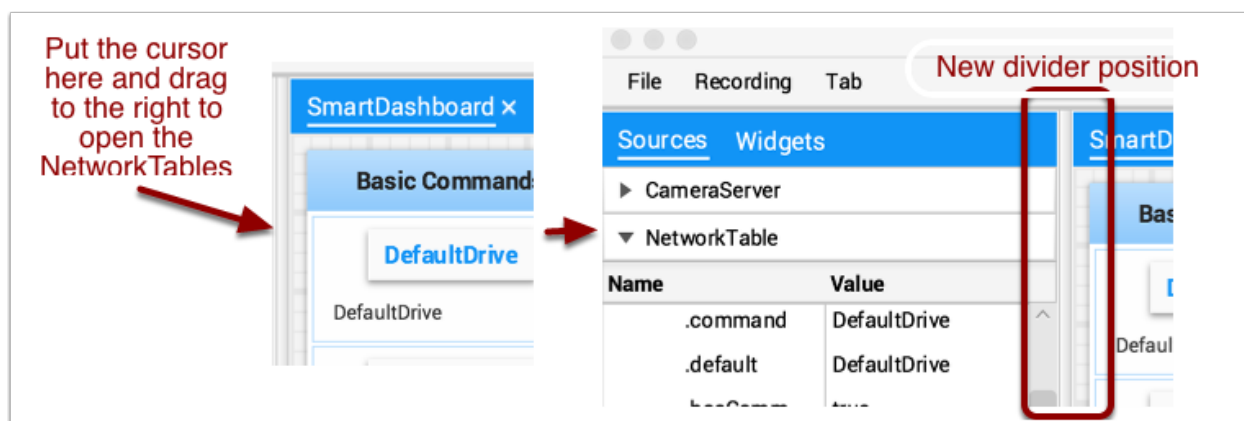
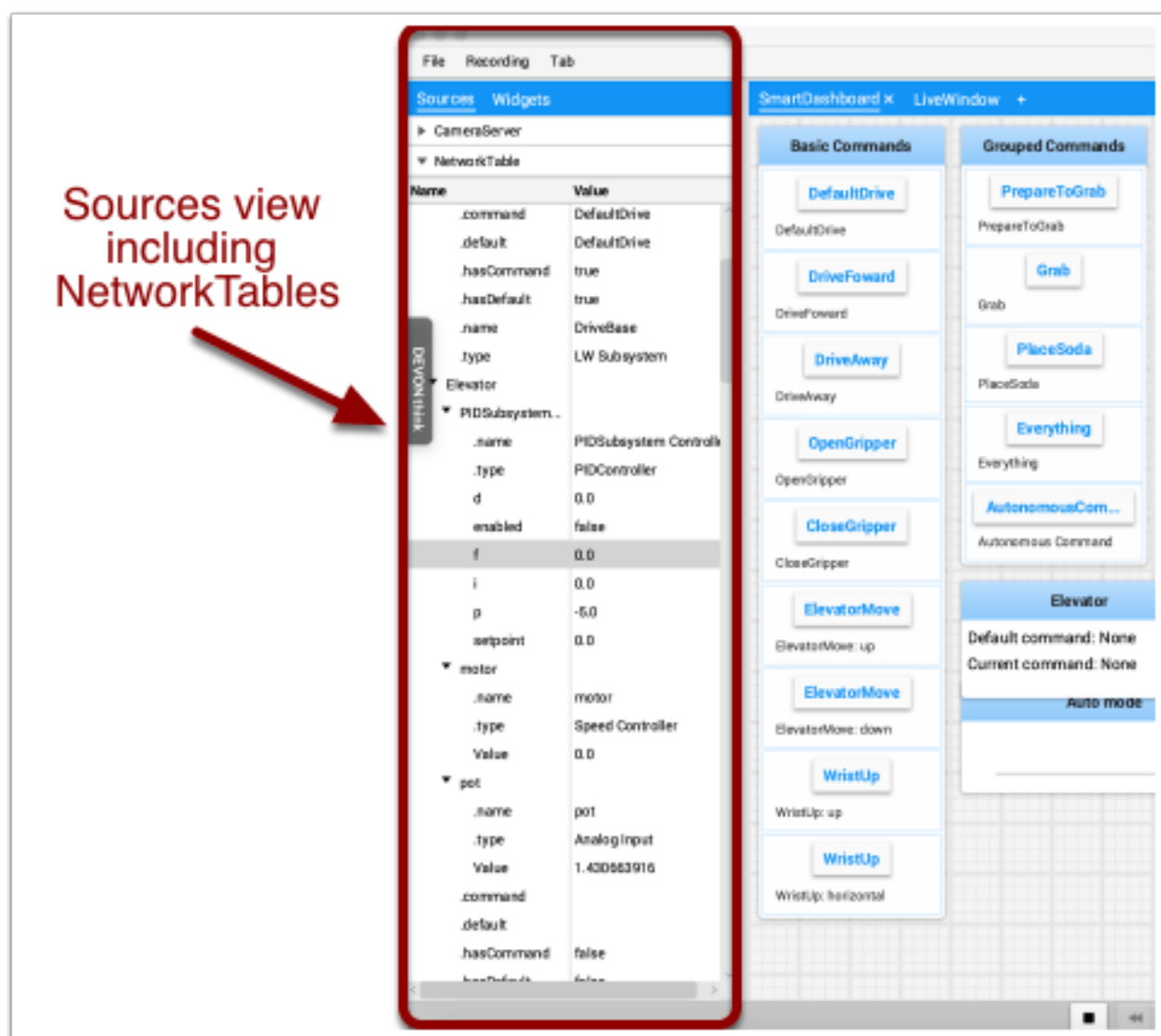
**Note:** Sometimes the Sources view is not visible on the left - it is possible to drag the divider between the tabbed panes and the Sources so the sources is not visible. If this happens move the cursor over the left edge and look for a divider resizing cursor, then left click and drag out the view. In the two images below you can see where to click and drag, and when finished the divider is as shown in the second image.

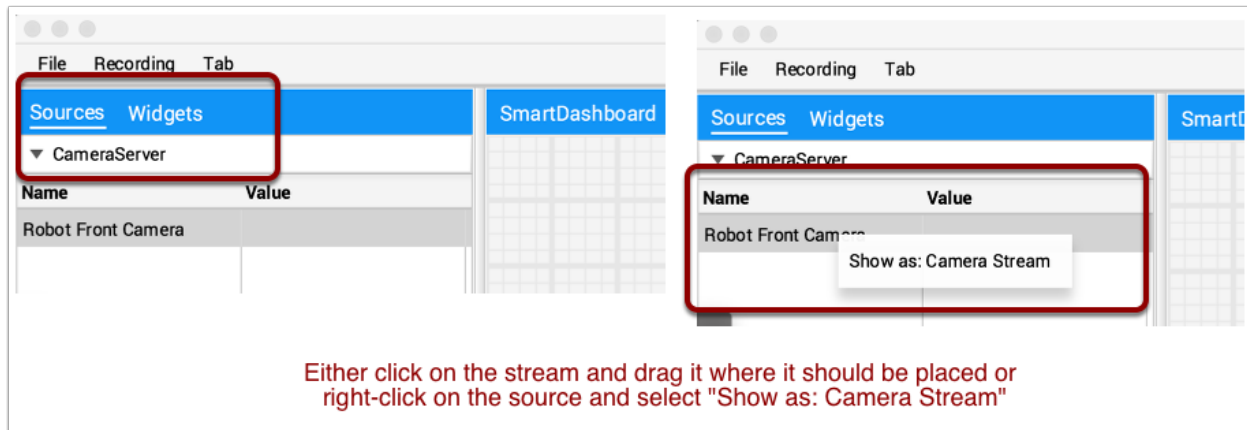
### 11.1.3 Displaying Camera Streams

Camera streams from the robot can be viewed on a tab in Shuffleboard. This is useful for viewing what the robot is seeing to give a less obstructed view for operators or helping visualize the output from a vision algorithm running on the driver station computer or a coprocessor on the robot. Any stream that is running using the CameraServer API can be viewed in a camera stream widget.

#### Adding a Camera Stream

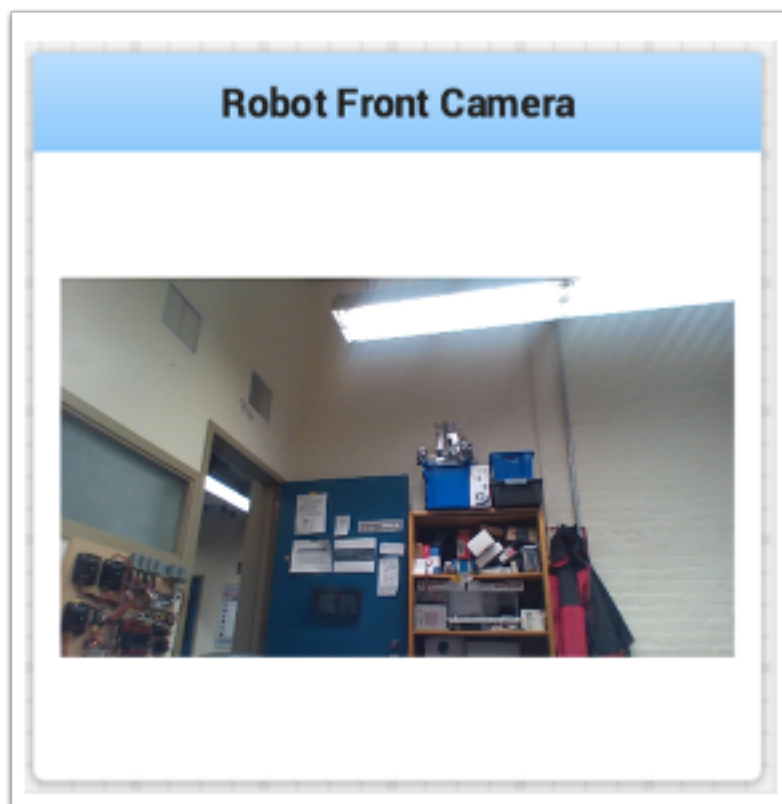
To add a camera to your dashboard select “Sources” and view the “CameraServer” source in the left side panel in the Shuffleboard window as shown in the example below. A list of camera streams will be shown, in this case there is only one camera called “Robot Front Camera”. Drag that to the tab where it should be displayed. Alternatively the stream can also be placed on the dashboard by right-clicking on the stream in the Sources list and selecting “Show as: Camera Stream”.





Once the camera stream is added it will be displayed in the window. It can be resized and moved where you would like it.

**Note:** Be aware that sending too much data from too high a resolution or too high a frame rate will cause high CPU usage on both the roboRIO and the laptop.

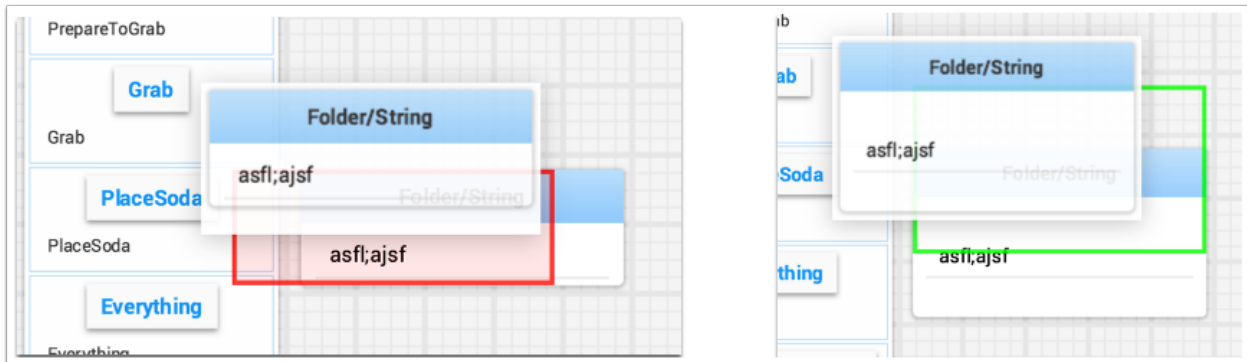


#### 11.1.4 Working with widgets

The visual displays that you manipulate on the screen in Shuffleboard are called widgets. Widgets are generally automatically displayed from values that the robot program publishes with NetworkTables.

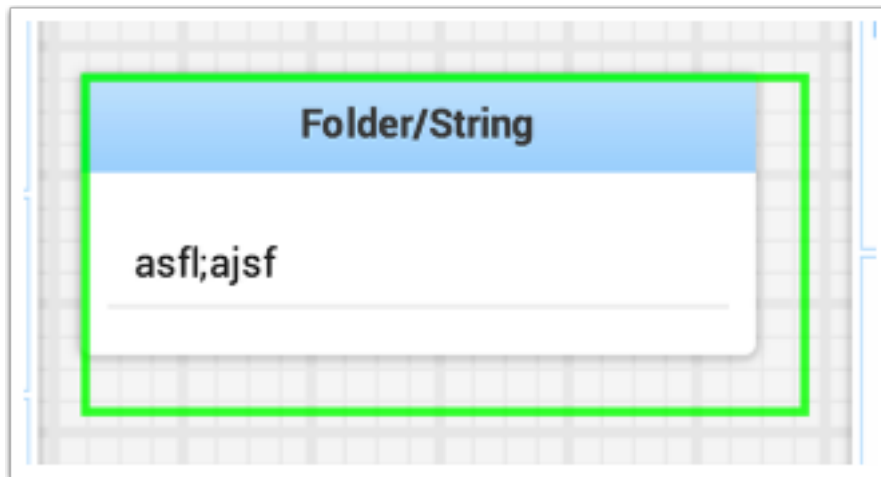
## Moving widgets

Widgets can be moved simply with drag and drop. Just move the cursor over the widget, left-click and drag it to the new position. When dragging you can only place widgets on grid squares and the size of the grid will effect the resolution of your display. When dragging a red or green outline will be displayed. Green generally means that there is enough room at the current location to drop the widget and red generally means that it will overlap or be too big to drop. In the example below a widget is being moved to a location where it doesn't fit.



## Resizing widgets

Widgets can be resized by clicking and dragging the edge or corner of the widget image. The cursor will change to a resize-cursor when it is in the right position to resize the widget. As with moving widgets, a green or red outline will be drawn indicating that the widget can be resized or not. The example below shows a widget being resized to a larger area with the green outline indicating that there is no overlap with surrounding widgets.



## Changing the display type of widgets

Shuffleboard is very rich in display types depending on the data published from the robot. It will automatically choose a default display type, but you might want to change it depending on the application. To see what the possible displays are for any widget, right-click on the

widget and select the “Show as...” and from the popup menu, choose the desired type. In the example below are two data values, one a number and the other a boolean. You can see the different types of display options that are available to each. The boolean value has only two possible values (true/false) it can be shown as a boolean box (the red/green color), or text, or a toggle button or toggle switch. The. number value can be displayed as a graph, number bar, number slider, dial, text, or a voltage view depending on the context of the value.

### **Changing the title of widgets**

You can change the title of widgets by double-clicking in their title bar and editing the title to the new value. If a widget is contained in a layout, then right-click on the widget and select the properties. From there you can change the widget title that is displayed.

### **Changing widget properties**

You can change the appearance of a widget such as the range of values represented, colors or some other visual element. In cases where this is possible right-click on the widget and select “Edit properties” from the popup menu. In this boolean value widget shown below, the widget title, true color and false color can all be edited.

## **11.1.5 Working with Lists**

Lists are sets of tiles that are be logically grouped together in a vertical layout. When tiles are added to a list, it becomes visually obvious that the tiles are related in function. In addition tiles in lists take up less screen space than the same tiles directly on the desktop because tiles in a list don’t display the dark window title, but instead display a smaller textual label documenting the contents of the list.

### **Creating a list**

A list can be created by: 1. Right-clicking on the first tile that should go into the list. 2. Select the “Add to new layout...” option from the popup menu. 3. A new list will be created called “List” and the tile will be at the top of it. Notice that tiles in lists do not have the window title at the top, but instead have the text that was in the window title.

### **Adding tiles to a list**

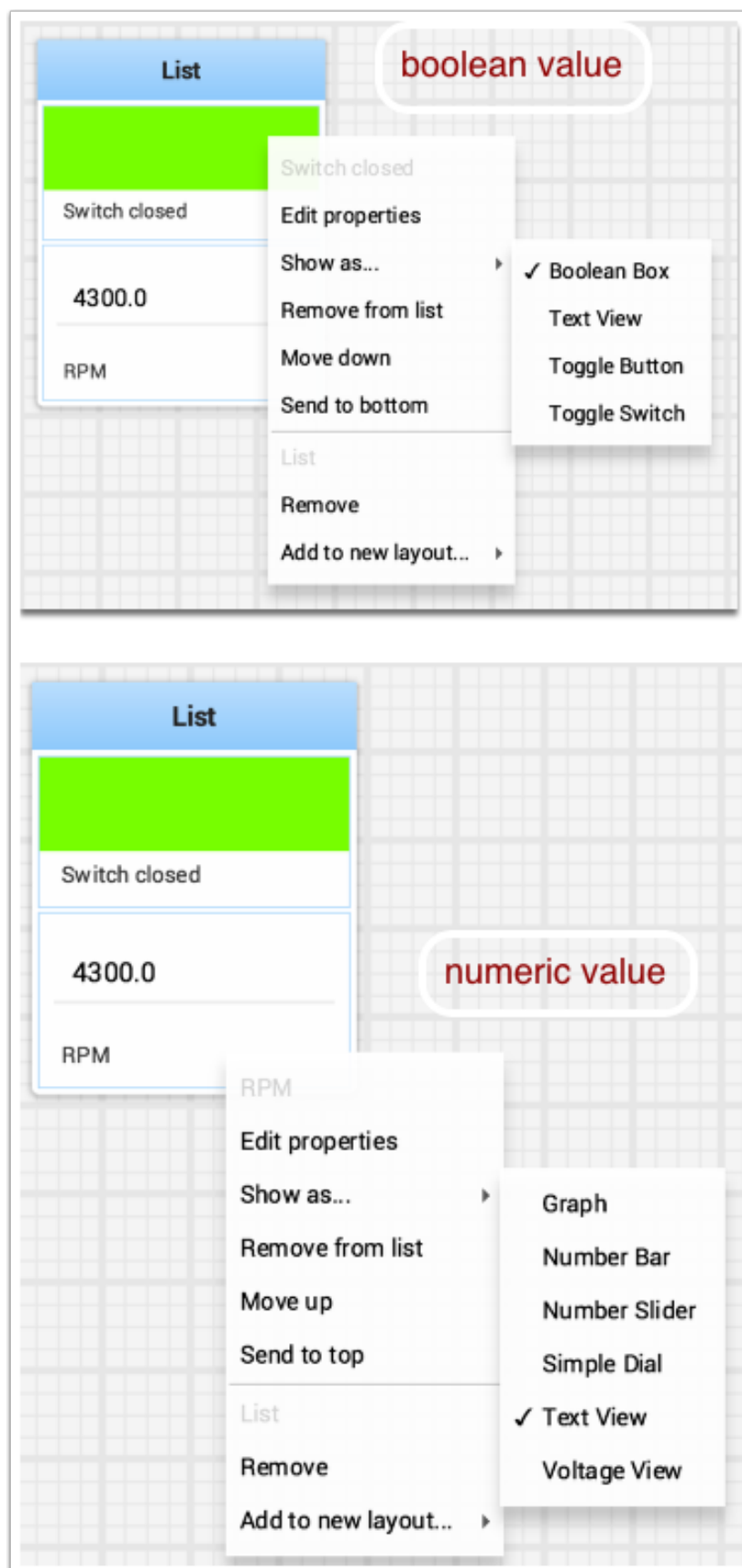
Add tiles to a list layout by: 1. identify the list and the tile to be added. 2. Drag the new tile onto the list. 3. The tile will be added to the list. If there is no room as the list is currently sized, the tile will be added off the end of the list and a vertical scrollbar will be added if it’s not already there.

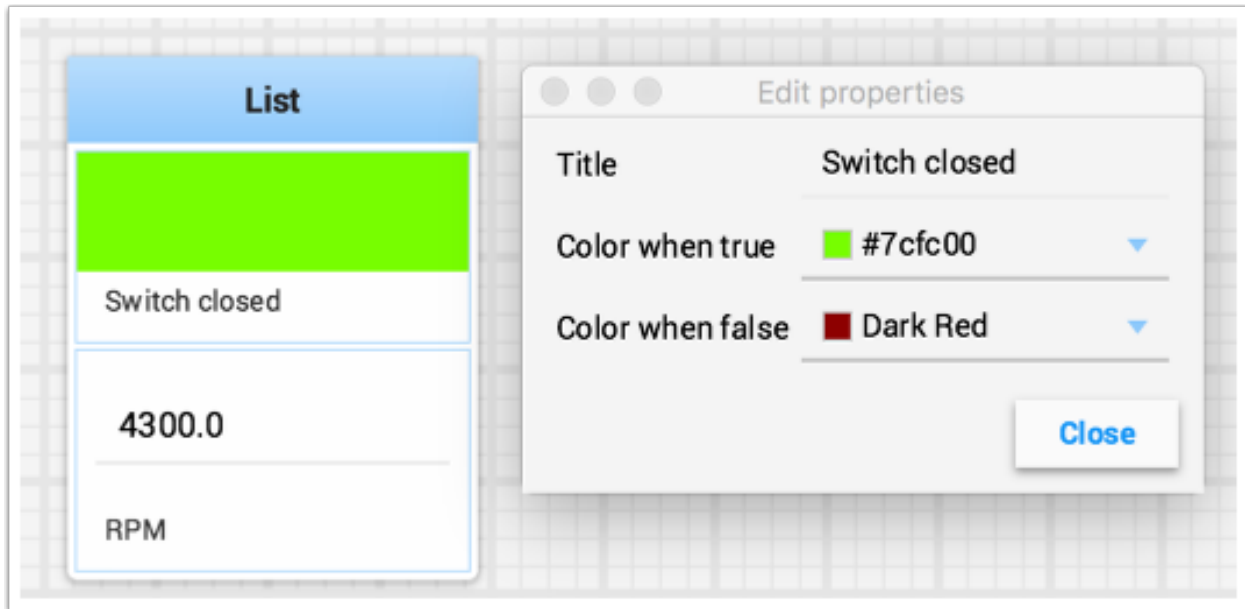
### **Rearranging tiles in a list**

Tiles in a list can be rearranged by right-clicking on the tile to be moved and selecting:

1. “Move up” to move the tile before the previous tile
2. “Move down” to move the tile after the next tile







3. “Send to top” to move the tile to the top of the list
4. “Send to bottom” to move the tile to the bottom of the list
5. “Remove from list” to delete the tile from the list.

### Renaming a list

You can rename a list by double-clicking on the list title and changing the name. Click outside the title to save the changes

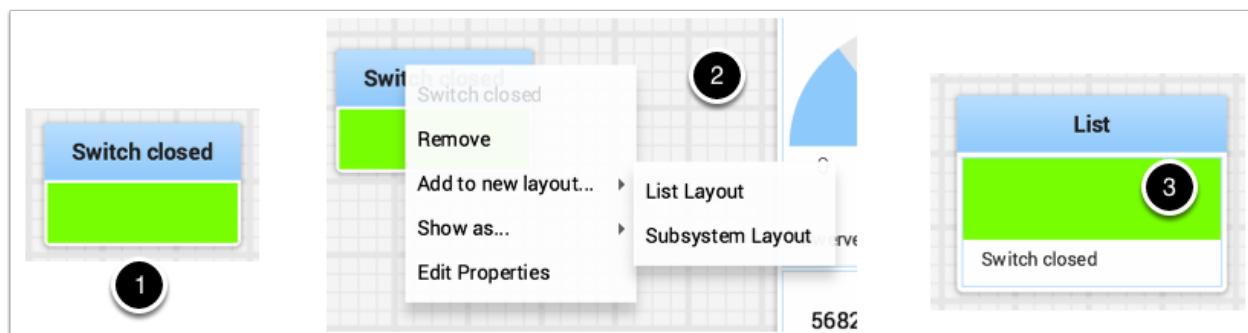
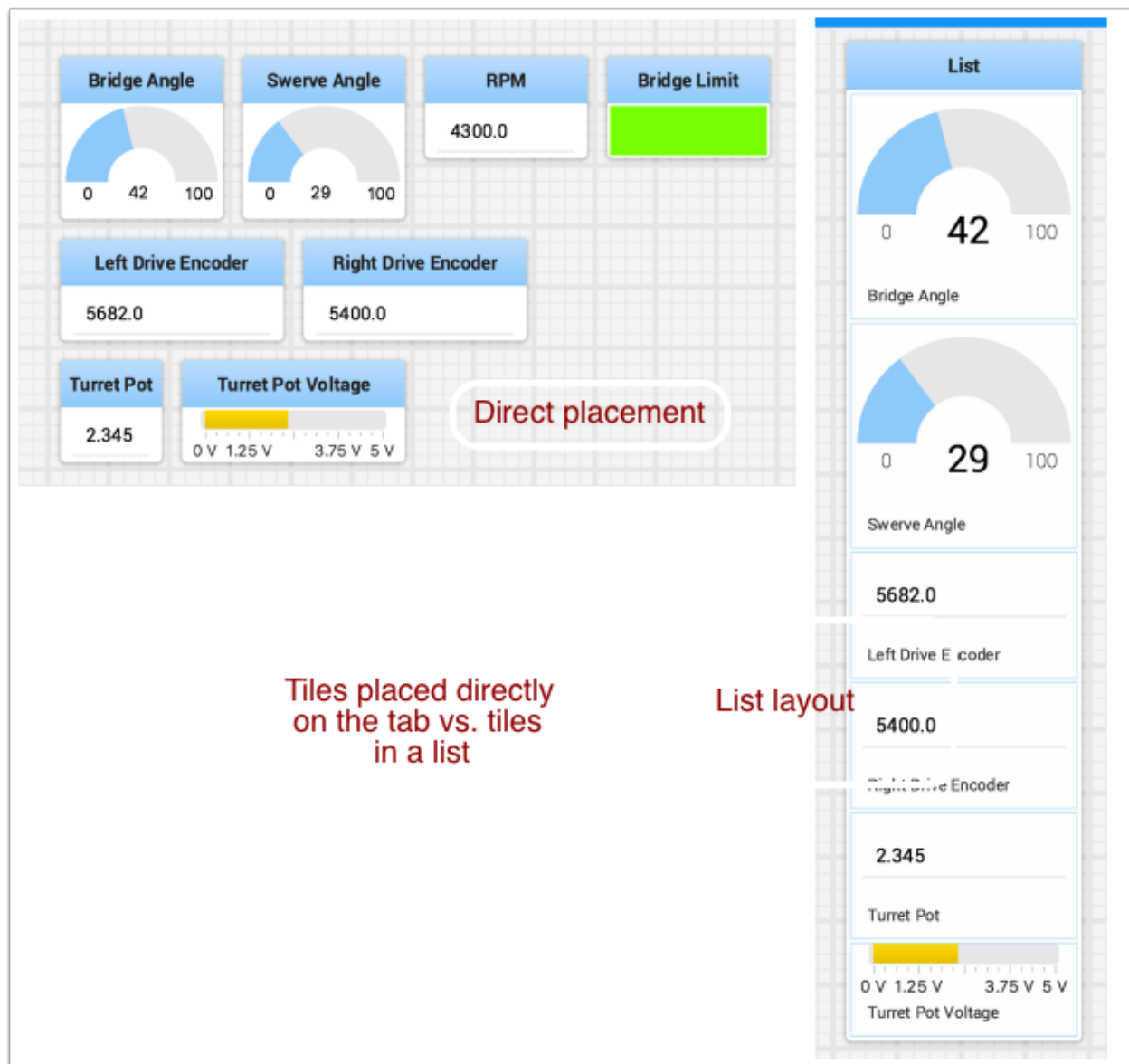
## 11.1.6 Creating and manipulating tabs

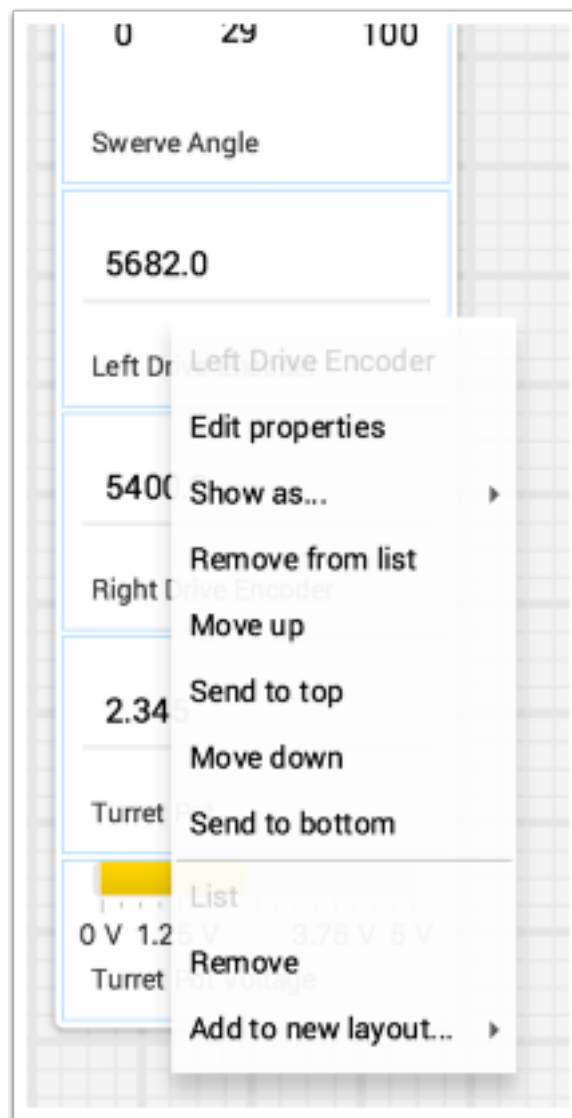
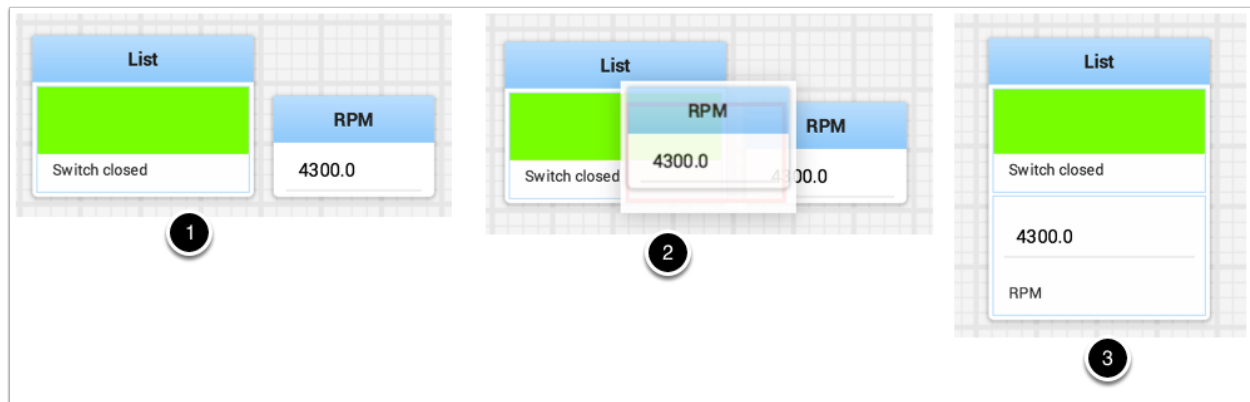
The tabbed layout the Shuffleboard uses help separate different “views” of your robot data and make the displays more useful. You might have a tab the has the display for helping debug the robot program and a different tab for use in competitions. There are a number of options that make tabs very powerful. You can control which data from NetworkTables or other sources appears in each of your tabs using the auto-populate options described later in this article.

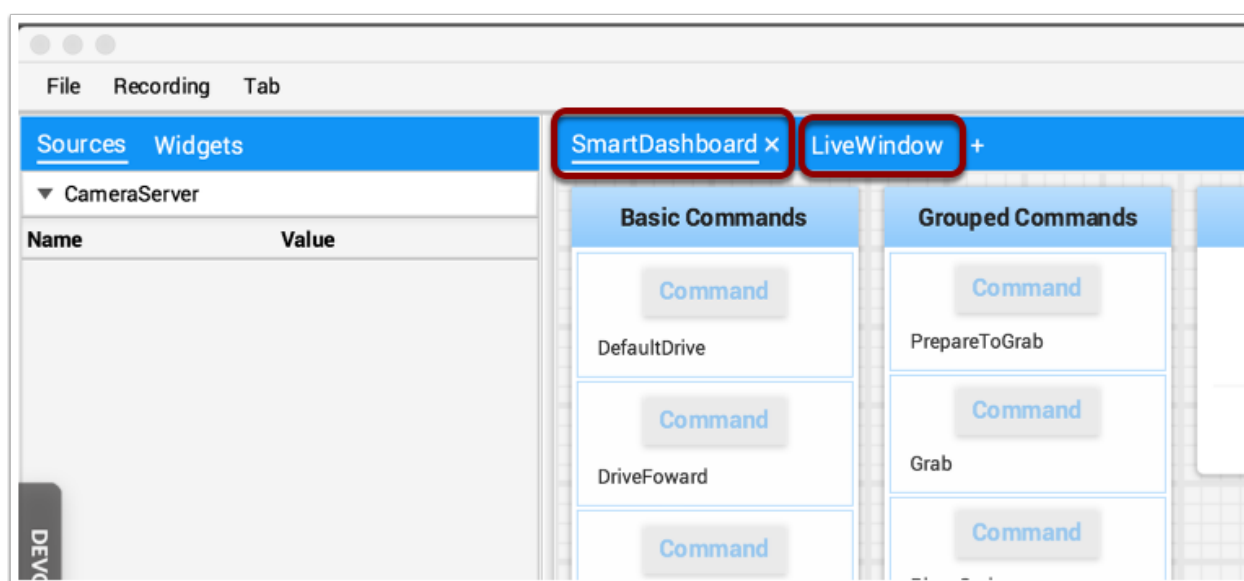
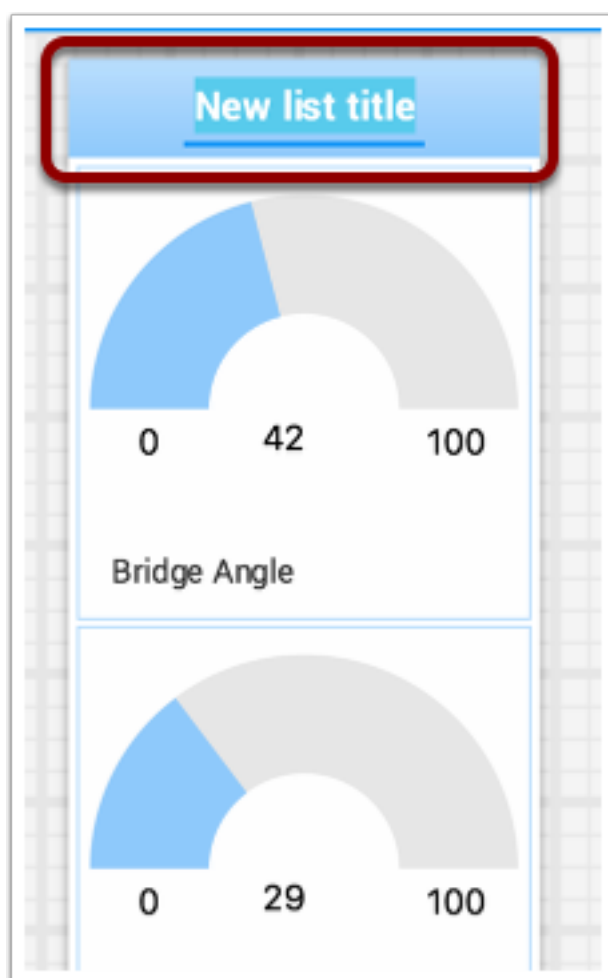
### Default tabs

When you open Shuffleboard for the first time there are two tabs, labeled SmartDashboard and LiveWindow. These correspond to the two views that SmartDashboard had depending on whether your robot is running in Autonomous/Teleop or Test mode. In shuffleboard both of these views are available any time.

On the SmartDashboard tab all the values that are written using the SmartDashboard.putType() set of methods. On the LiveWindow tab all the autogenerated debugging values are shown.





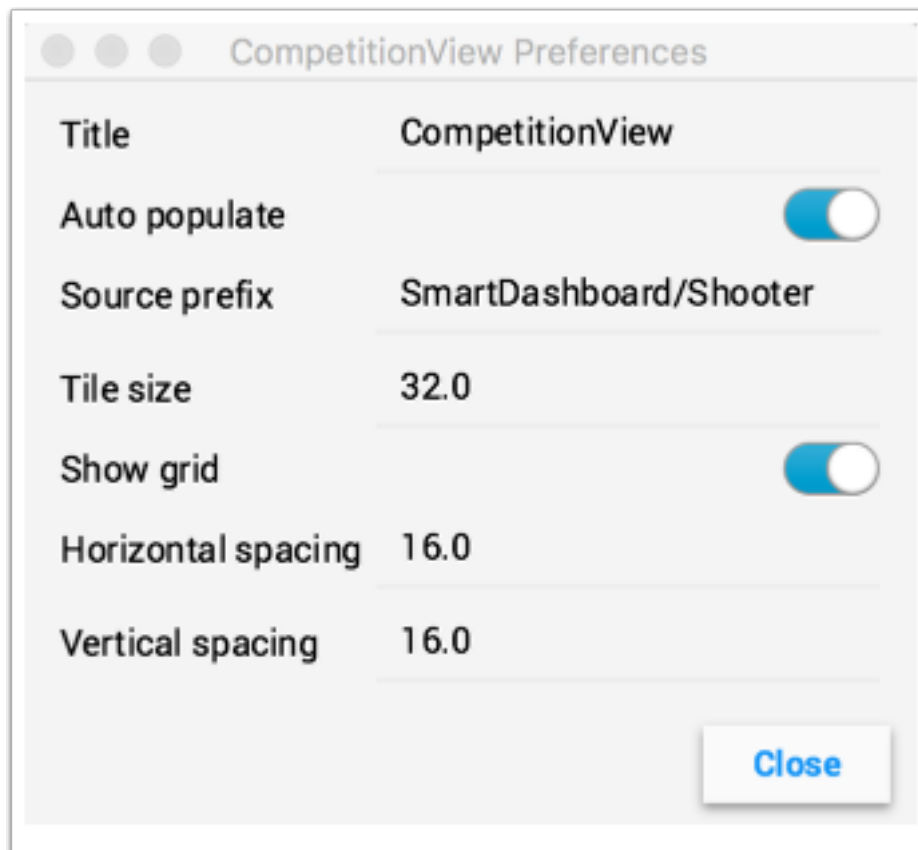


## Switching between tabs

You can switch between tabs clicking on the tab label at the top of the window. In the case above, simply click on SmartDashboard or LiveWindow to see the values that are associated with each tab.

## Adding tabs and deleting tabs

You can add additional tabs by clicking on the plus(+) symbol just to the right of the last tab. Once you create a new tab you can set the label by double-clicking on the label in the tab and editing it. You can also right-click on the tab or use the Tab menu to bring up the tab preferences and from that window you can change the name by editing the Title field.



## Setting the tab to auto-populate

One of the most powerful features with tabs is to have them automatically populate new values based on a source prefix that is supplied in the tab Preferences pane. In the above example the Preferences pane has a Source prefix of "SmartDashboard/Shooter" and Auto populate is turned on. Any values that are written using the SmartDashboard class that specifies a sub-key of Shooter will automatically appear on that tab. Note: keys that match more than one Source prefix will appear in both tabs. Because those keys also start with SmartDashboard/ and that's the Source prefix for the default SmartDashboard tab, those widgets will appear in both panes. To only have values appear in one pane, you can use NetworkTables to write labels and values and use a different path that is not under SmartDashboard. Alternatively

you could let everything appear in the SmartDashboard tab making it very cluttered, but have specific tabs for your needs that will be better filtered.

### Using the tab grid and spacing

Each tab can have it's own Tile size (number of pixels per large square). So some tabs might have coarser resolution for easier layout and others might have a fine grid. The Tile size in the Tab preferences overrides any global settings in the Shuffleboard preferences. In addition, you can specify the padding between the drawing in the widget and the edge of the of the widget. If you program user interfaces these parameters are usually referred to as horizontal and vertical gap (hgap, vgap).

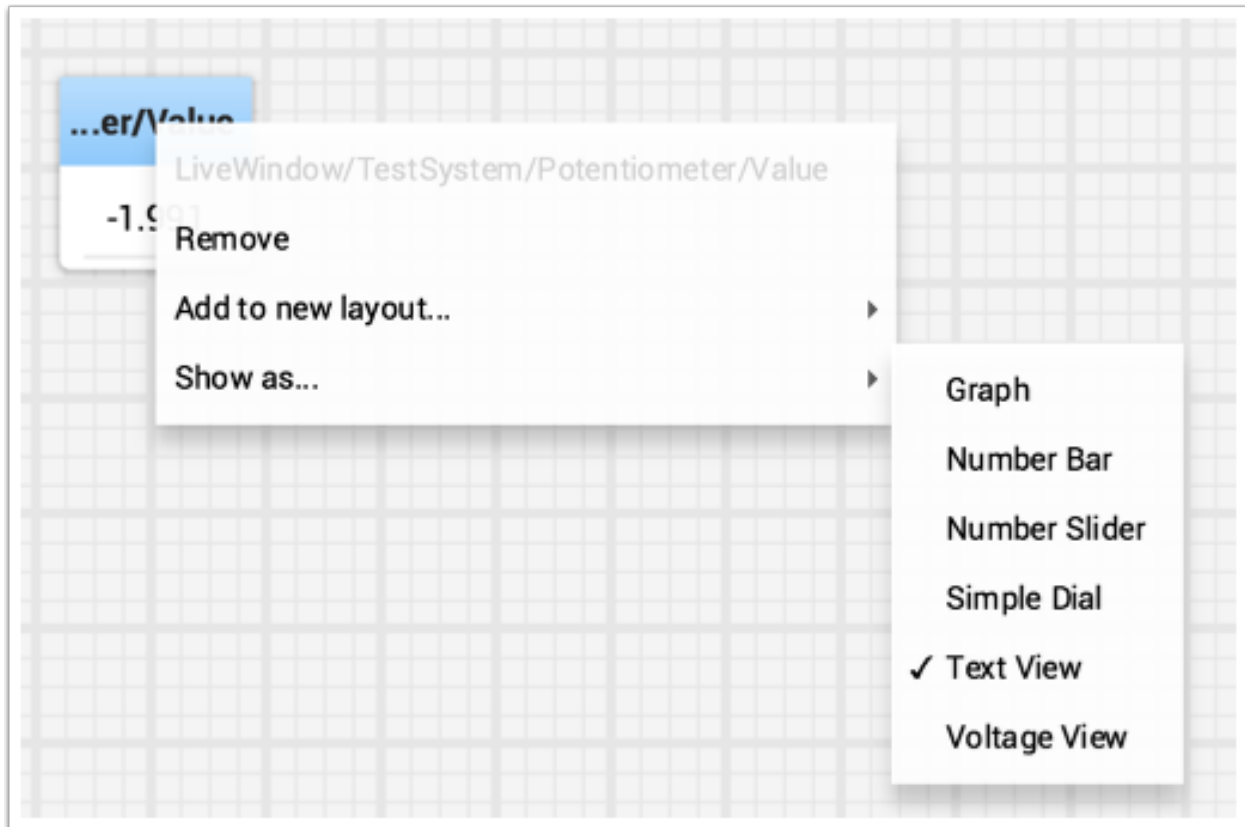
### Moving widgets between tabs

Currently there is no way to easily move widgets between tabs without deleting it from one tab and dragging the field from the sources hierarchy on the left into the new pane. We hope to have that capability in a subsequent update soon.

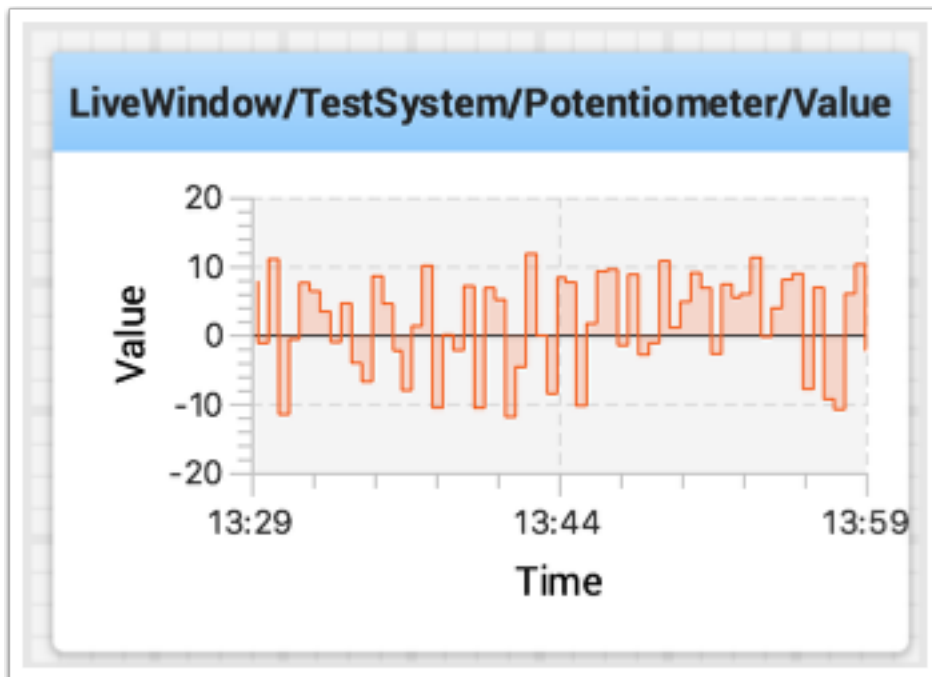
### 11.1.7 Working with Graphs

With Shuffleboard you can graph numeric values over time. Graphs are very useful to see how sensor or motor values are changing as your robot is operating. For example the sensor value can be graphed in a PID loop to see how it is responding during tuning.

To create a graph, choose a numeric value and right-click in the heading and select "Show as..." and then choose graph



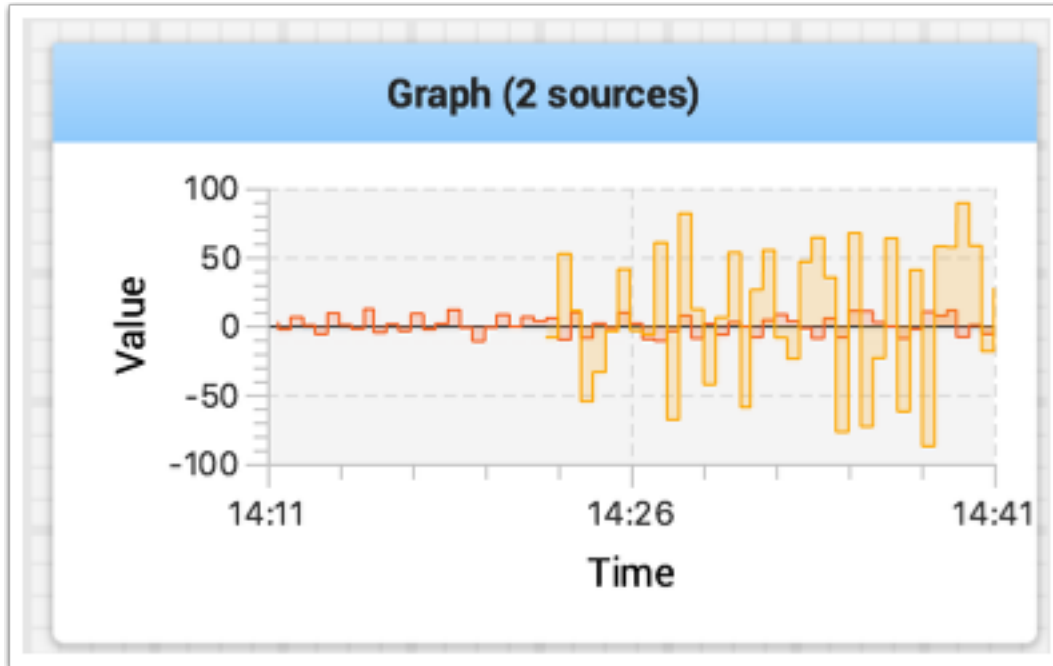
The graph widget shows line plots of the value that you selected. It will automatically set the scale and the default time interval that the graph will show will be 30 seconds. You can change that in the setting for the graph (see below).



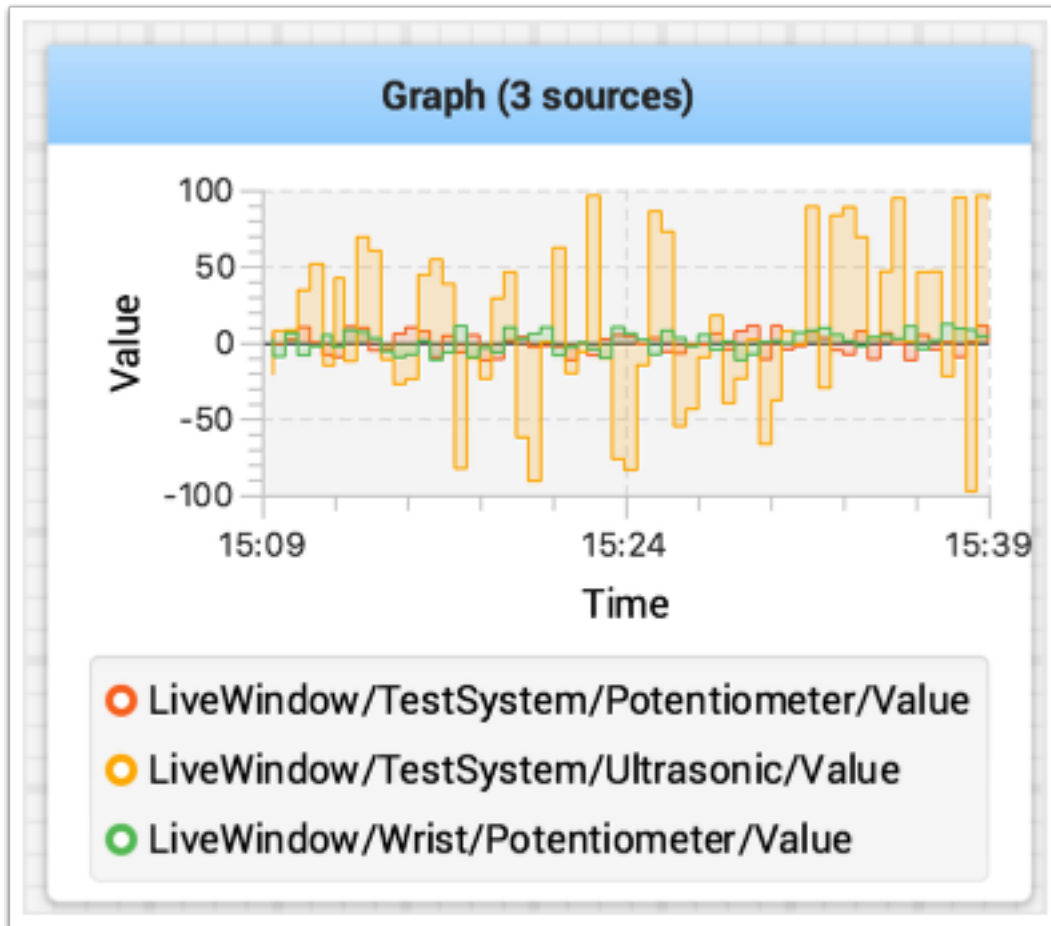


### Adding Additional Data Values

For related values it is often desirable to show multiple values on the same graph. To do that, simply drag additional values from the NetworkTable source view (left side of the Shuffleboard window) and drop it onto the graph and that value will be added as shown below. You can continue to drag additional values onto the graph.



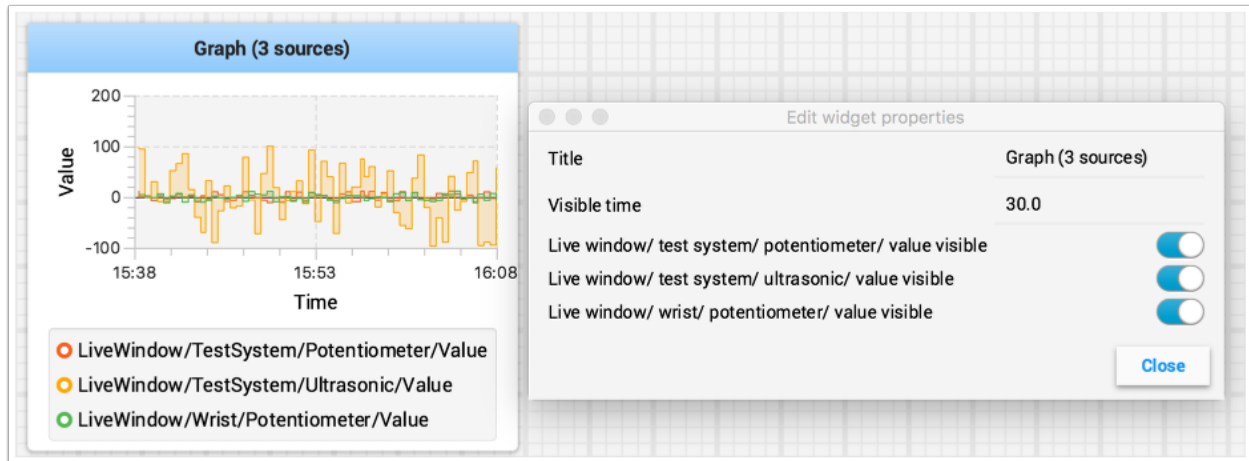
You can resize the graph vertically to view the legend if it is not displayed as shown in the image below. The legend shows all the sources that are used in the plot.



### Setting Graph Properties

You can set the number of seconds that are shown in the graph by changing the “Visible time” in the graph widget properties. To access the properties, right-click on the graph and select “Edit properties”.

In addition to setting the visible time the graph can selectively turn sources on and off by turning the switch on and off for each of the sources shown in the properties window (see below).

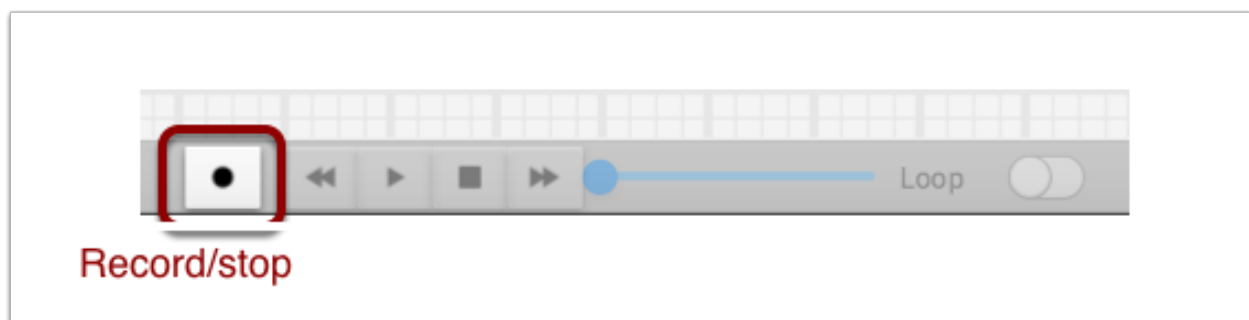


### 11.1.8 Recording and Playback

Shuffleboard can log all widget updates during a session. Later the log file can be “played back” to see what happened during a match or a practice run. This is especially useful if something doesn’t operate as intended during a match and you want to see what happened. Each recording is captured in a recording file.

#### Creating a Recording

When shuffleboard starts it begins recording to all the NetworkTable values are recorded and continues until stopped by hitting the record/stop button in the recorder controls as shown below. If a new recording is desired, such as when a new piece of code or mechanical system is being tested, stop the current recording if it is running, and click the record button. Click the button again to stop recording and close the recording file. If the button is round (as shown) then click it to start a recording. If the button is a square, then a recording is currently running so click it to stop the recording.

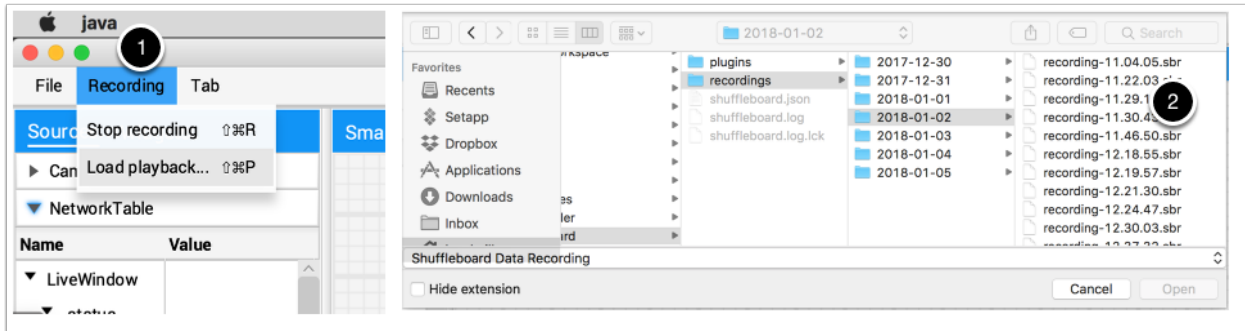


#### Playing a Recording

Previous recordings can be played back by:

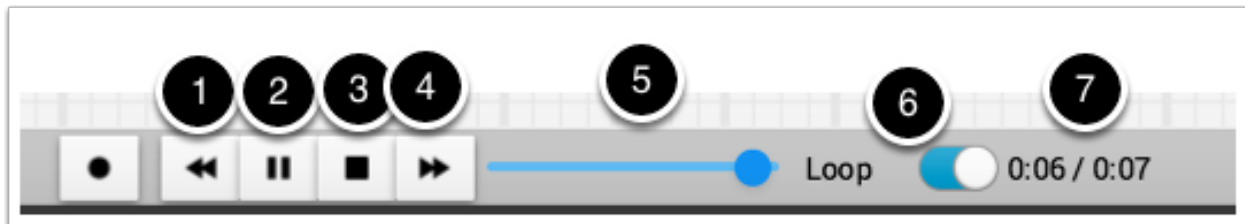
1. Selecting the “Recording” menu then click “Load playback”.

2. Choose a recording from the from the directory shown. Recordings are grouped by date and the file names are the time the recording was made to help identify the correct one. Select the correct recording from the list.



## Controlling the Playback

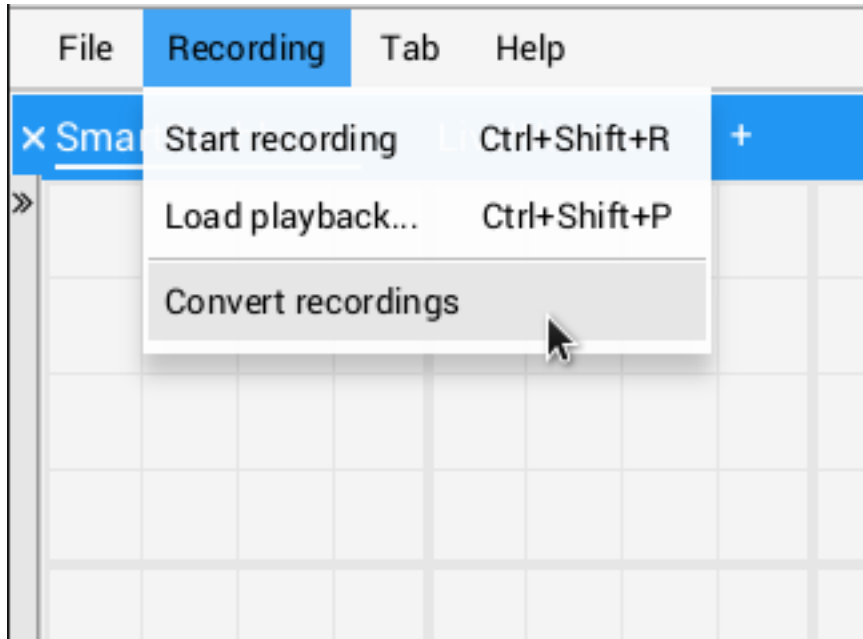
Selecting the recording file will begin playback of that file. While the recording is playing the recording controls will show the current time within the recording as well as the option to loop the recording while watching it. When the recording is being played back the “transport” controls will allow the playback to be controlled.



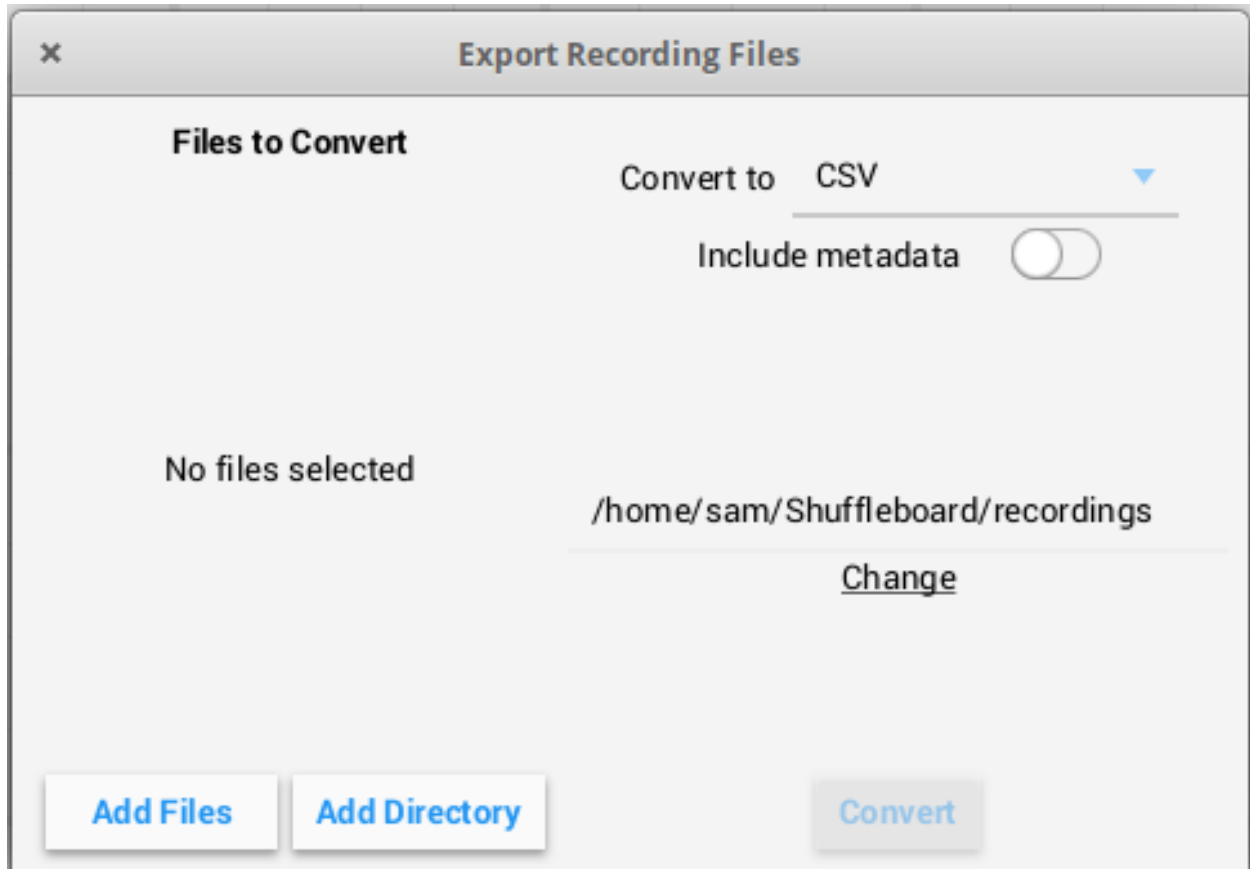
The controls work as follows:

1. The left double-arrow button backs up the playback to the last changed data point
2. The play/pause controls starts and stops the playback
3. The square stop button stops playback and resumes showing current robot values
4. The right double-arrow skips forward to the next changed data value
5. The scrubber is a slider that allow direct positioning to any point in time to view different parts of the recording
6. The loop switch turns on playback looping, that is, the playback will run over and over until stopped
7. The time shows the current point within the recording and the total time of the recording

## Converting to Different File Formats



Shuffleboard recordings are in a custom binary format for efficiency. To analyze recorded data without playing it back through the app, Shuffleboard supports data converters to convert the recordings to an arbitrary format. Only a simple CSV converter is shipped with the app, but teams can write custom converters and include them in Shuffleboard plugins.



Multiple recordings can be converted at once. Individual files can be selected with the “Add Files” button, or all recording files in a directory can be selected at once with the “Add Directory” button.

Converted recordings will be generated in the ~/Shuffleboard/recordings directory, but can be manually selected with the “Change” button.

Different converters can be selected with the dropdown in the top right. By default, only the CSV converter is available. Custom converters from plugins will appear as options in the dropdown.

### Additional Notes

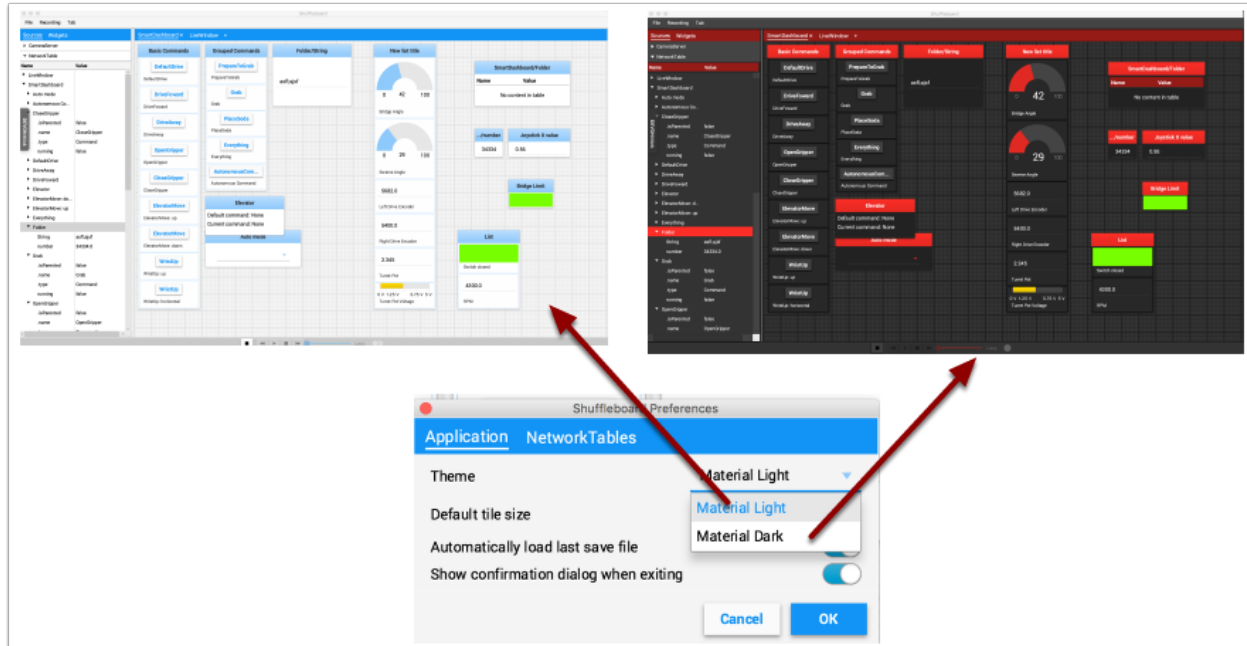
Graphs won’t display properly while scrubbing the timeline but if it is playing through where the graph history can be captured by the graph then they will display as in the original run.

### 11.1.9 Setting global preferences for Shuffleboard

There are a number of settings that set the way Shuffleboard looks and behaves. Those are on the Shuffleboard Preferences pane that can be accessed from the File menu.

### Setting the theme

Shuffleboard supports two themes, Material Dark and Material Light and the setting depends on your preferences. This uses css styles that apply to the entire application and can be changed any time.



### Setting the default tile size

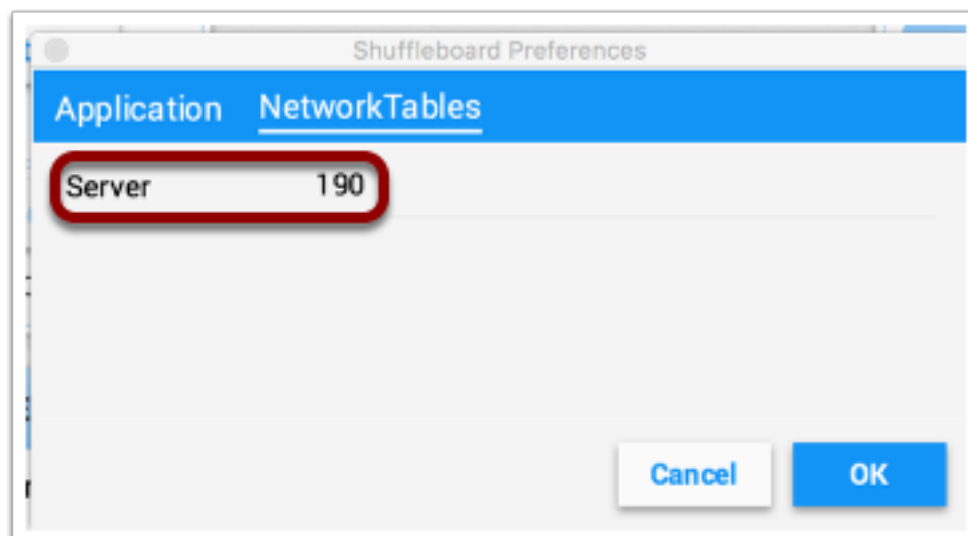
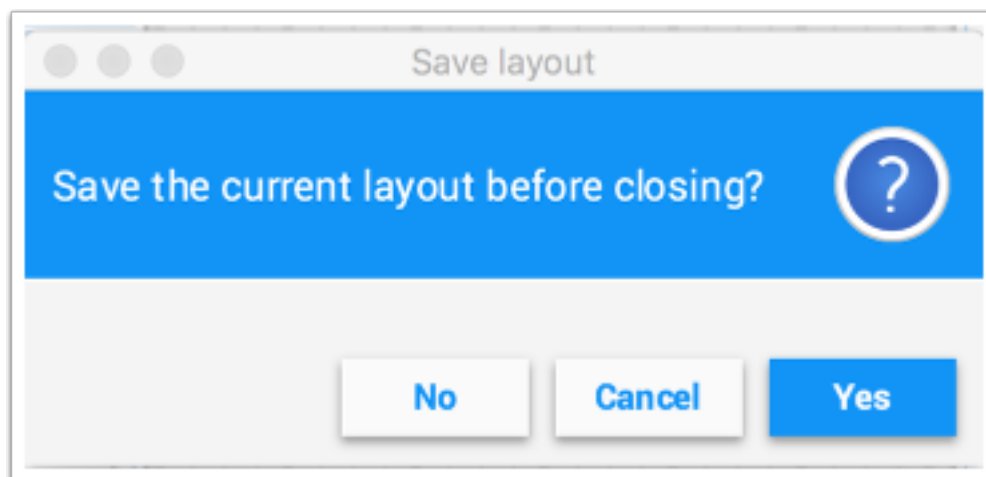
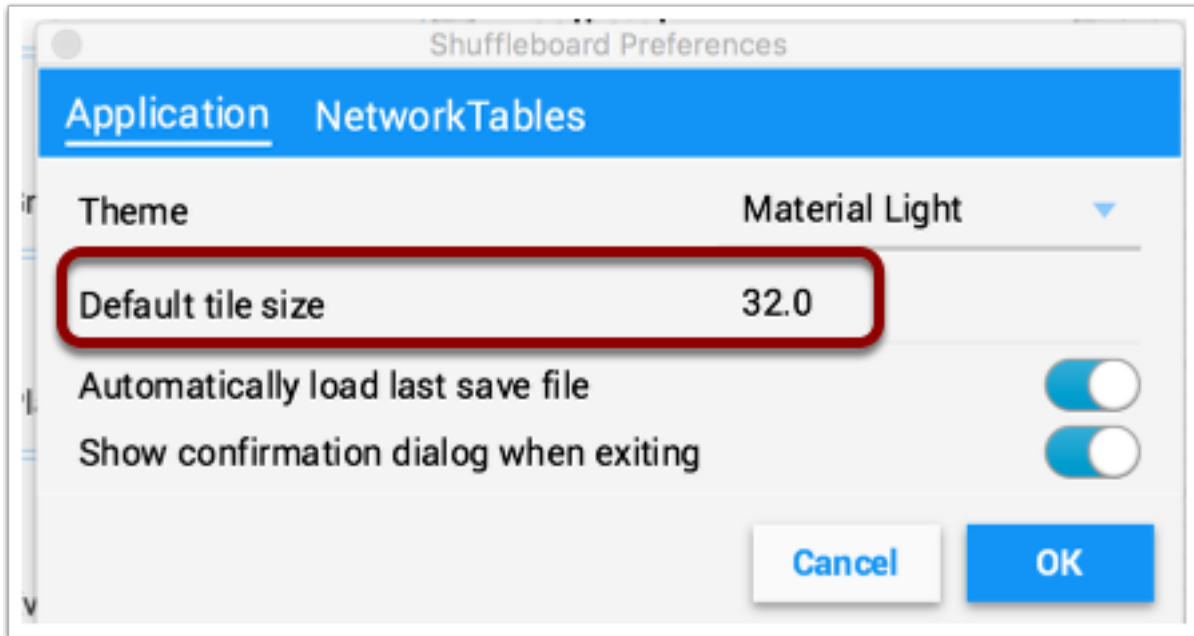
Shuffleboard positions tiles on a grid when you are adding or moving them yourself or when they are auto-populated. You can set the default tile size when for each tab or it can be set globally for all the tabs created after the default setting is changed. Finer resolution in the grid results in finer control over placement of tiles. This can be set in the Shuffleboard Preferences window as shown below.

### Working with the layout save files

Shuffleboard will default to saving your layout when you exit the application. You can also save it explicitly using the File / Save and File / Save as... menu options. The preferences window has options to cause the previous layout to be automatically applied when Shuffleboard starts. In addition, Shuffleboard will always display a “Save layout” window to remind you to save the layout. You can choose to turn off the automatic prompt on exit, but be sure to save the layout manually in this case so you don’t loose your changes.

### Setting the team number

In order for Shuffleboard to be able to find your NetworkTables server on your robot, specify your team number in the “NetworkTables” tab on the Preferences pane. If you’re running Shuffleboard with a running Driver Station, the Server field will be auto-populated with the





correct information. If you're running on a computer without the Driver Station, you can manually enter your team number or the robotRIO network address.

### 11.1.10 Shuffleboard FAQ, issues, and bugs

**Warning:** Shuffleboard as well as most of the other control system components were developed with Java 11 and will not work with Java 8. Be sure before reporting problems that your computer has Java 11 installed and is set as the default Java Environment.

#### Frequently Asked Questions

##### How do I report issues, bugs or feature requests with Shuffleboard?

Bugs, issues, and feature requests can be added on the Shuffleboard Github page by creating an issue. We will try to address them as they are entered into the system. Please try to look at existing issues before creating new ones to make sure you aren't duplicating something that has already been reported or work that is planned. You can find the issues on the [Shuffleboard GitHub page](#).

##### How can I add my own widgets or other extensions to Shuffleboard?

The [Shuffleboard wiki](#) has a large amount of documentation on extending the program with custom plugins. In the future we will be posting a sample plugin project that can be used for additional custom widgets, but for now the wiki documentation is complete.

##### How can I build Shuffleboard from the source code?

You can get the source code by downloading, cloning, or forking the repository on the GitHub site. To build and run Shuffleboard from the source, make sure that the current directory is the top level source code and use one of these commands:

Application	Command (for Windows systems run the gradlew.bat file)
Running Shuffleboard	<code>./gradlew :app:run</code>
Building the APIs and utility classes for plugin creation	<code>./gradlew :api:shadowJar</code>
Building the complete application jar file	<code>./gradlew :app:shadowJar</code>

## 11.2 Shuffleboard - Layouts with Code

### 11.2.1 Using tabs

Shuffleboard is a tabbed interface. Each tab organizes widgets in a logical grouping. By default, Shuffleboard has tabs for the legacy SmartDashboard and LiveWindow - but new tabs can now be created in Shuffleboard directly from a robot program for better organization.

Creating a new tab

Java

```
ShuffleboardTab tab = Shuffleboard.getTab("Tab Title");
```

C++

```
ShuffleboardTab& tab = Shuffleboard::GetTab("Tab Title");
```

Creating a new tab is as simple as calling a single method on the Shuffleboard class, which will create a new tab on Shuffleboard and return a handle for adding your data to the tab. Calling `getTab` multiple times with the same tab title will return the same handle each time.

## Selecting a tab

Java

```
Shuffleboard.selectTab("Tab Title");
```

C++

```
Shuffleboard::SelectTab("Tab Title");
```

This method lets a tab be selected by title. This is case-sensitive (so “Tab Title” and “Tab title” are two individual tabs), and only works if a tab with that title exists at the time the method is called, so calling `selectTab("Example")` will only have an effect if a tab named “Example” has previously been defined.

This method can be used to select any tab in Shuffleboard, not just ones created by the robot program.

## Caveats

Tabs created from a robot program differ in a few important ways from normal tabs created from the dashboard:

- Not saved in the Shuffleboard save file
- No support for autopopulation
- Users are expected to specify the tab contents in their robot program
- Have a special color to differentiate from normal tabs

### 11.2.2 Sending data

Unlike SmartDashboard, data cannot be sent directly to Shuffleboard without first specifying what tab the data should be placed in.

### Sending simple data

Sending simple data (numbers, strings, booleans, and arrays of these) is done by calling `add` on a tab. This method will set the value if not already present, but will not overwrite an existing value.

Java

```
Shuffleboard.getTab("Numbers")
    .add("Pi", 3.14);
```

C++

```
Shuffleboard::GetTab("Numbers")
    .Add("Pi", 3.14);
```

If data needs to be updated (for example, the output of some calculation done on the robot), call `getEntry()` after defining the value, then update it when needed or in a periodic function

Java

```
class VisionCalculator {
    private ShuffleboardTab tab = Shuffleboard.getTab("Vision");
    private NetworkTableEntry distanceEntry =
        tab.add("Distance to target", 0)
            .getEntry();

    public void calculate() {
        double distance = ...;
        distanceEntry.setDouble(distance);
    }
}
```

### Making choices persist between reboots

When configuring a robot from the dashboard, some settings may want to persist between robot or driverstation reboots instead of having drivers remember (or forget) to configure the settings before each match.

Simply using *`addPersistent`* instead of *`add`* will make the value saved on the roboRIO and loaded when the robot program starts.

---

**Note:** This does not apply to sendable data such as choosers or motor controllers.

---

Java

```
Shuffleboard.getTab("Drive")
    .addPersistent("Max Speed", 1.0);
```

### Sending sensors, motors, etc

Analogous to `SmartDashboard.putData`, any `Sendable` object (most sensors, speed controllers, and `SendableChoosers`) can be added to any tab

Java

```
Shuffleboard.getTab("Tab Title")
    .add("Sendable Title", mySendable);
```

### 11.2.3 Retrieving data

Unlike `SmartDashboard.getNumber` and friends, retrieving data from Shuffleboard is also done through the `NetworkTableEntries`, which we covered in the previous article.

Java

```
class DriveBase extends Subsystem {
    private ShuffleboardTab tab = Shuffleboard.getTab("Drive");
    private NetworkTableEntry maxSpeed =
        tab.add("Max Speed", 1)
            .getEntry();

    private DifferentialDrive robotDrive = ...;

    public void drive(double left, double right) {
        // Retrieve the maximum speed from the dashboard
        double max = maxSpeed.getDouble(1.0);
        robotDrive.tankDrive(left * max, right * max);
    }
}
```

This basic example has a glaring flaw: the maximum speed can be set on the dashboard to a value outside `[0, 1]` - which could cause the inputs to be saturated (always at maximum speed), or even reversed! Fortunately, there is a way to avoid this problem - covered in the next article.

### 11.2.4 Configuring widgets

Robot programs can specify exactly which widget to use to display a data point, as well as how that widget should be configured. As there are too many widgets to be listed here, consult the docs for details.

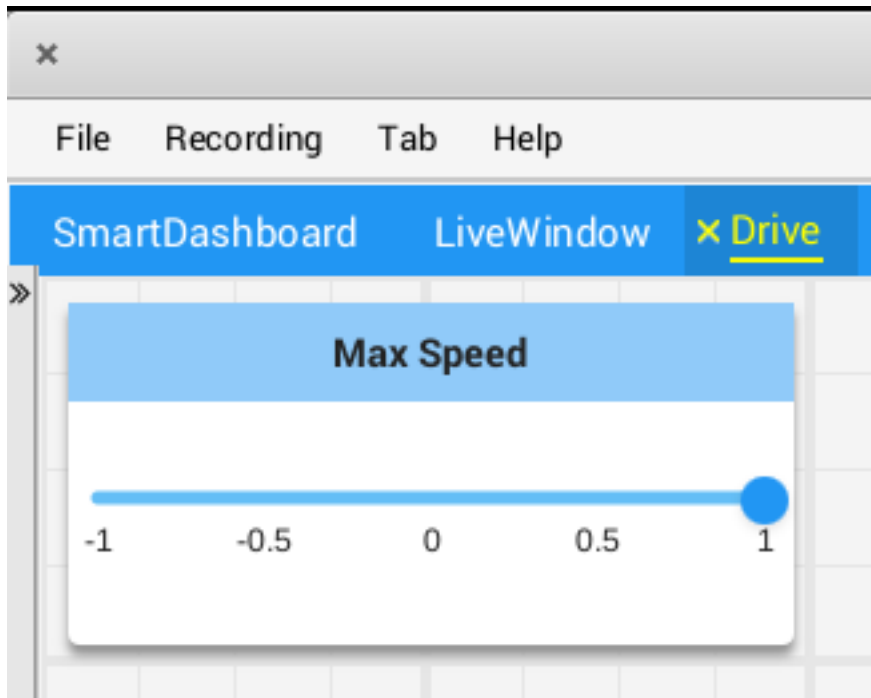
#### Specifying a widget

Call `withWidget` after `add` in the call chain:

Java

```
Shuffleboard.getTab("Drive")
    .add("Max Speed", 1)
    .withWidget(BuiltInWidgets.kNumberSlider) // specify the widget here
    .getEntry();
```

In this example, we configure the “Max Speed” widget to use a slider to modify the values instead of a basic text field.

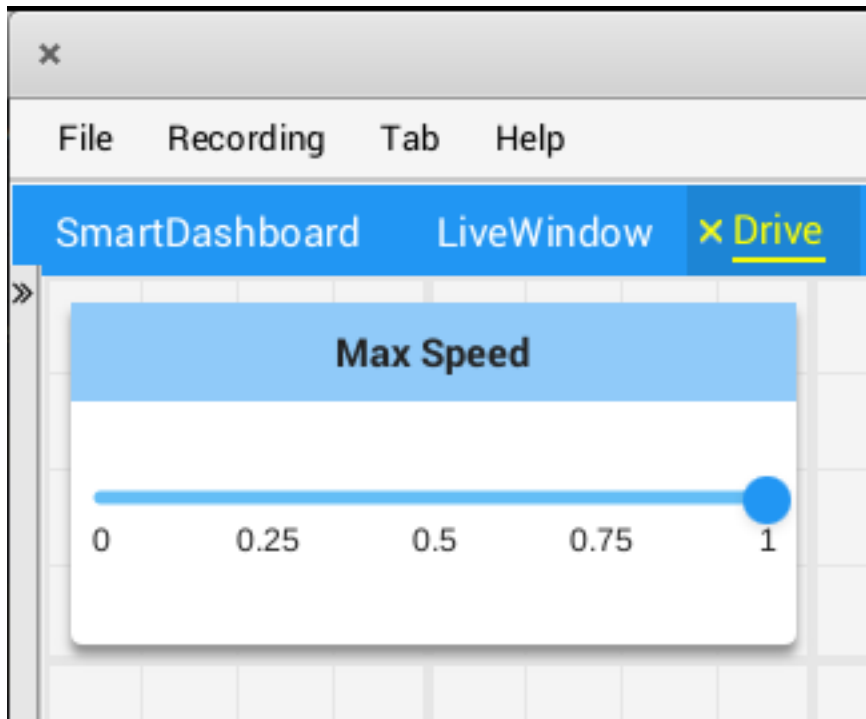


### Setting widget properties

Since the maximum speed only makes sense to be a value from 0 to 1 (full stop to full speed), a slider from -1 to 1 can cause problems if the value drops below zero. Fortunately, we can modify that using the `withProperties` method

Java

```
Shuffleboard.getTab("Drive")
    .add("Max Speed", 1)
    .withWidget(BuiltInWidgets.kNumberSlider)
    .withProperties(Map.of("min", 0, "max", 1)) // specify widget properties here
    .getEntry();
```



## Notes

Widgets can be specified by name; however, names are case- and whitespace-sensitive (“Number Slider” is different from “Number slider” and “NumberSlider”). For this reason, it is recommended to use the built in widgets class to specify the widget instead of by raw name. However, a custom widget can only be specified by name or by creating a custom `WidgetType` for that widget.

Widget property names are neither case-sensitive nor whitespace-sensitive (“Max” and “max” are the same). Consult the documentation on the widget in the `BuiltInWidgets` class for details on the properties of that widget.

## 11.2.5 Organizing Widgets

### Setting Widget Size and Position

Call `withSize` and `withPosition` to set the size and position of the widget in the tab.

`withSize` sets the number of columns wide and rows high the widget should be. For example, calling `withSize(1, 1)` makes the widget occupy a single cell in the grid. Note that some widgets have a minimum size that may be greater than the specified size, in which case the widget will use the smallest supported size.

`withPosition` sets the row and column of the top-left corner of the widget. Rows and columns are both 0-indexed, so the topmost row is number 0 and the leftmost column is also number 0. If the position of any widget in a tab is specified, every widget should also have its position set to avoid overlapping widgets.

**Note:** In order for the size to be applied position must also be specified. Be sure to call `withPosition` when using `withSize`.

---

Java

```
Shuffleboard.getTab("Pre-round")
    .add("Auto Mode", autoModeChooser)
    .withSize(2, 1) // make the widget 2x1
    .withPosition(0, 0); // place it in the top-left corner
```

C++

```
frc::Shuffleboard::GetTab("Pre-round")
    .Add("Auto Mode", autoModeChooser)
    .WithSize(2, 1)
    .WithPosition(0,0);
```

### Adding Widgets to Layouts

If there are many widgets in a tab with related data, it can be useful to place them into smaller subgroups instead of loose in the tab. Much like how the handle to a tab is retrieved with `Shuffleboard.getTab`, a layout inside a tab (or even in another layout) can be retrieved with `ShuffleboardTab.getLayout`.

Java

```
ShuffleboardLayout elevatorCommands = Shuffleboard.getTab("Commands")
    .getLayout("Elevator", BuiltInLayouts.kList)
    .withSize(2, 2)
    .withPosition(0, 0)
    .withProperties(Map.of("Label position", "HIDDEN")); // hide labels for commands

elevatorCommands.add(new ElevatorDownCommand());
elevatorCommands.add(new ElevatorUpCommand());
// Similarly for the claw commands
```

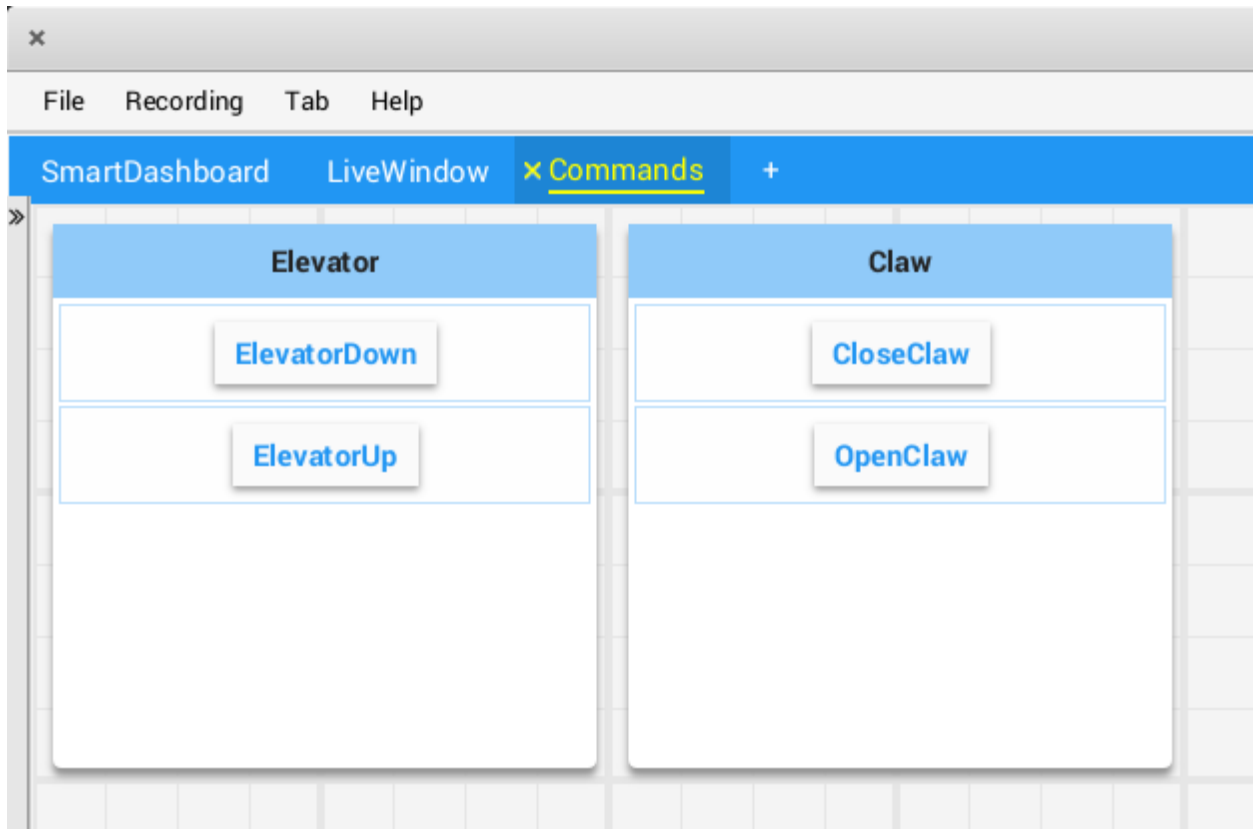
C++

```
wpi::StringMap<std::shared_ptr<nt::Value>> properties{
    std::make_pair("Label position", nt::Value::MakeString("HIDDEN"))
};

frc::ShuffleboardLayout& elevatorCommands = frc::Shuffleboard::GetTab("Commands")
    .GetLayout("Elevator", frc::BuiltInLayouts::kList)
    .WithSize(2, 2)
    .WithPosition(0, 0)
    .WithProperties(properties);

ElevatorDownCommand* elevatorDown = new ElevatorDownCommand();
ElevatorUpCommand* elevatorUp = new ElevatorUpCommand();

elevatorCommands.Add("Elevator Down", elevatorDown);
elevatorCommands.Add("Elevator Up", elevatorUp);
```



## 11.3 Shuffleboard - Advanced Usage

### 11.3.1 Commands and Subsystems

When using the command-based framework Shuffleboard makes it easier to understand what the robot is doing by displaying the state of various commands and subsystems in real-time.

#### Displaying Subsystems

To see the status of a subsystem while the robot is operating in either autonomous or teloperated modes, that is what its default command is and what command is currently using that subsystem, send a subsystem instance to Shuffleboard:

Java

```
SmartDashboard.putData(subsystem-reference);
```

C++

```
SmartDashboard::PutData(subsystem-pointer);
```

Shuffleboard will display the subsystem name, the default command associated with this subsystem, and the currently running command. In this example the default command for the

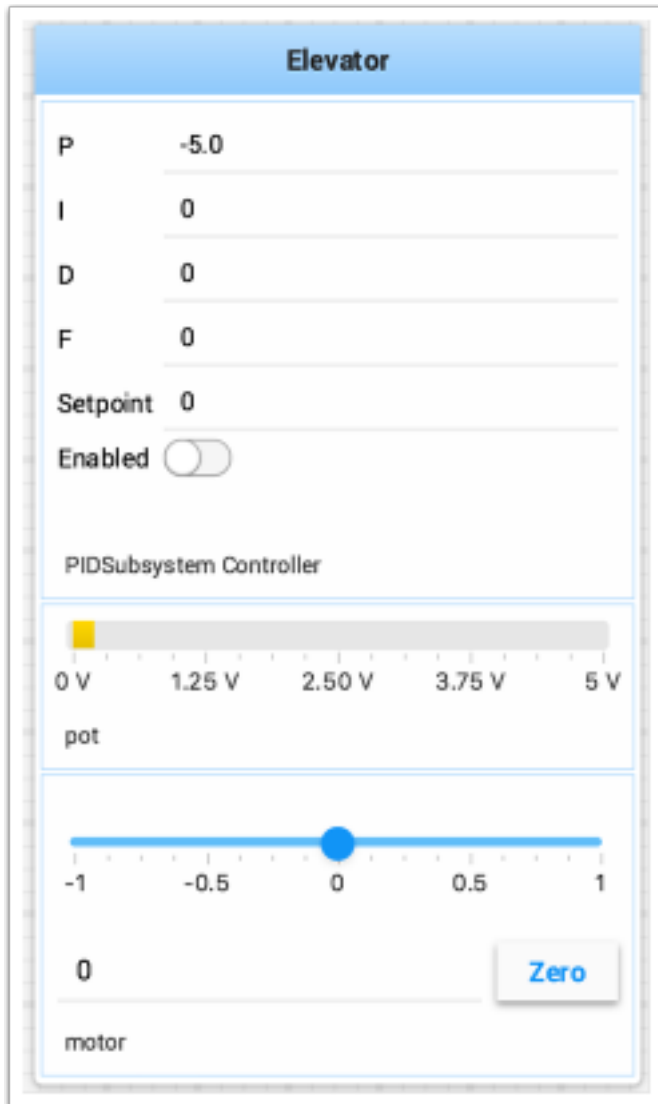


Elevator subsystem is called `AutonomousCommand` and it is also the current command that is using the Elevator subsystem.



### Subsystems in Test Mode

In Test mode (Test/Enabled in the driver station) subsystems may be displayed in the LiveWindow tab with the sensors and actuators of the subsystem. This is ideal for verifying of sensors are working by seeing the values that they are returning. In addition, actuators can be operated. For example, motors can be operated using sliders to set their commanded speed and direction. For PIDSubsystems the P, I, D, and F constants are displayed along with the setpoint and an enable control. This is useful for tuning PIDSubsystems by adjusting the constants, putting in a setpoint, and enabling the embedded PIDController. Then the mechanism's response can be observed. This cycle (change parameters, enable, and observe) can be repeated until a reasonable set of parameters is found.



More information on tuning PIDSubsystems can be found [here](#). Using RobotBuilder will automatically generate the code to get the subsystem displayed in Test mode. The code that is necessary to have subsystems displayed is shown below where subsystem-name is a string containing the name of the subsystem:

```
setName(subsystem-name);
```

### Displaying Commands

Using commands and subsystems makes very modular robot programs that can easily be tested and modified. Part of this is because commands can be written completely independently of other commands and can therefor be easily run from Shuffleboard. To write a command to Shuffleboard use the SmartDashboard.putData method as shown here:

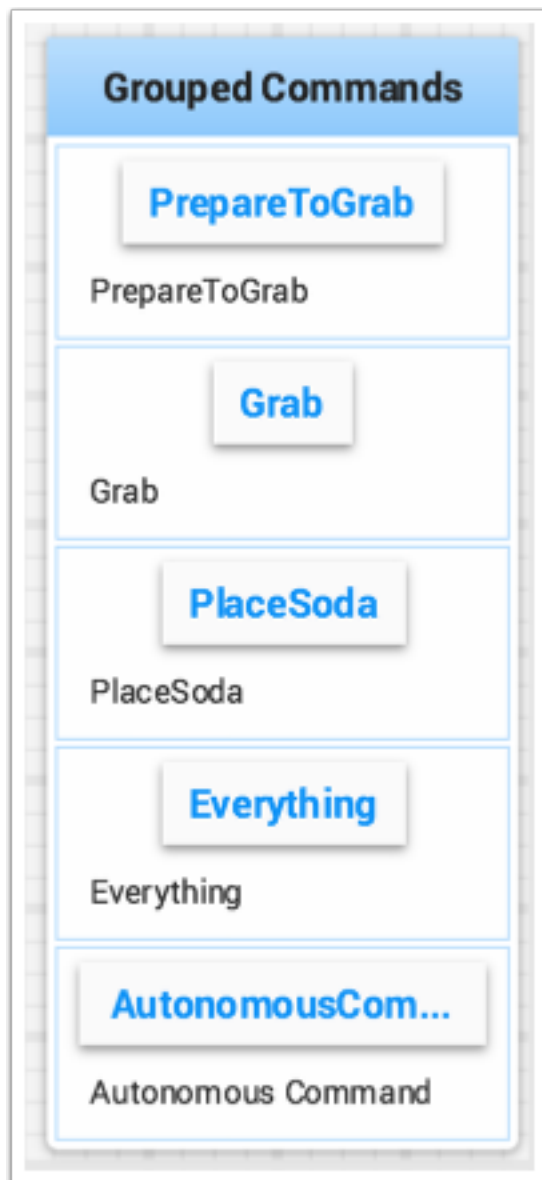
Java

```
SmartDashboard.putData("ElevatorMove: up", new ElevatorMove(2.7));
```

C++

```
SmartDashboard::PutData("ElevatorMove: up", new ElevatorMove(2.7));
```

Shuffleboard will display the command name and a button to execute the command. In this way individual commands and command groups can easily be tested without needing special test code in a robot program. In the image below there are a number of commands contained in a Shuffleboard list. Pressing the button once runs the command and pressing it again stops the command. To use this feature the robot must be enabled in teleop mode.



### 11.3.2 Testing and Tuning PID Loops

One challenge in using sensors to control mechanisms is to have a good algorithm to drive the motors to the proper position or speed. The most commonly used control algorithm is called PID control. There is a [good set of videos](#) (look for the robot controls playlist) that explain

the control algorithms described here. The PID algorithm converts sensor values into motor speeds by:

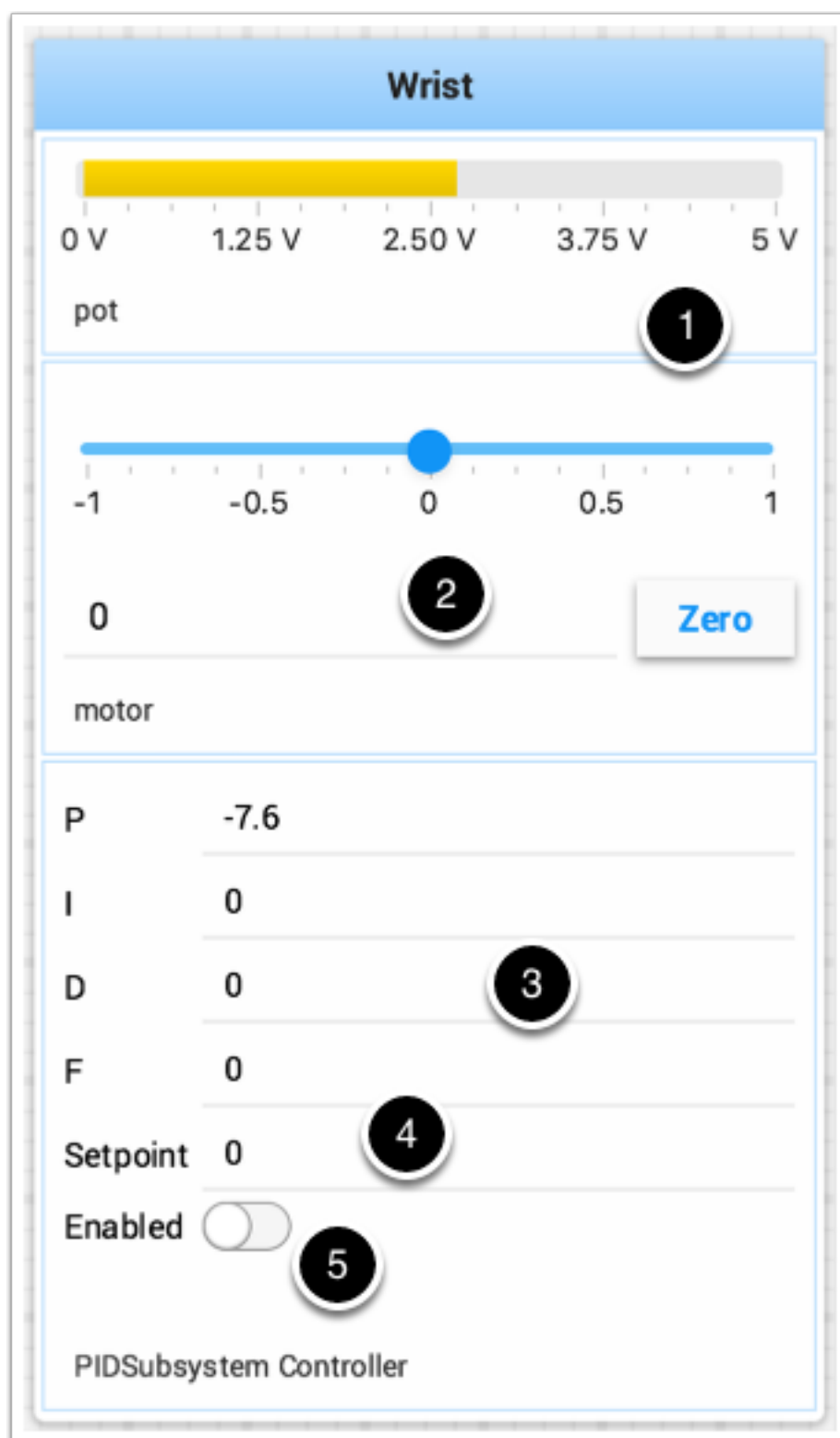
1. Reading sensor values to determine how far the robot or mechanism from the desired setpoint. The setpoint is the sensor value that corresponds to the expected goal. For example, a robot arm with a wrist joint should be able to move to a specified angle very quickly and stop at that angle as indicated by a sensor. A potentiometer is a sensor that can measure rotational angle. By connecting it to an analog input, the program can get a voltage measurement that is directly proportional to the angle.
2. Compute an error (the difference between the sensor value and the desired value). The sign of the error value indicates which side of the setpoint the wrist is on. For example negative values might indicate that the measured wrist angle is larger than the desired wrist angle. The magnitude of the error is how far the measured wrist angle is from the actual wrist angle. If the error is zero, then the measured angle exactly matches the desired angle. The error can be used as an input to the PID algorithm to compute a motor speed.
3. The resultant motor speed is then used to drive the motor in the correct direction and a speed that hopefully will reach the setpoint as quickly as possible without overshooting (moving past the setpoint).

WPILib has a `PIDController` class that implements the PID algorithm and accepts constants that correspond to the  $K_p$ ,  $K_i$ , and  $K_d$  values. The PID algorithm has three components that contribute to computing the motor speed from the error.

1. P (proportional) - this is a term that when multiplied by a constant ( $K_p$ ) will generate a motor speed that will help move the motor in the correct direction and speed.
2. I (integral) - this term is the sum of successive errors. The longer the error exists the larger the integral contribution will be. It is simply a sum of all the errors over time. If the wrist isn't quite getting to the setpoint because of a large load it is trying to move, the integral term will continue to increase (sum of the errors) until it contributes enough to the motor speed to get it to move to the setpoint. The sum of the errors is multiplied by a constant ( $K_i$ ) to scale the integral term for the system.
3. D (differential) - this value is the rate of change of the errors. It is used to slow down the motor speed if it's moving too fast. It's computed by taking the difference between the current error value and the previous error value. It is also multiplied by a constant ( $K_d$ ) to scale it to match the rest of the system.

## **Tuning the PID Controller**

Tuning the PID controller consists of picking constants that will give good performance. Shuffleboard helps this process by displaying the details of a PID subsystem with a user interface for setting constant values and testing how well it operates. This is displayed while the robot is operating in test mode (done by setting "Test" in the driver station).



This is the test mode picture of a wrist subsystem that has a potentiometer as the sensor (pot) and a speed controller connected to the motor. It has a number of areas that correspond to the PIDSubsystem.

1. The analog input voltage value from the potentiometer. This is the sensor input value.

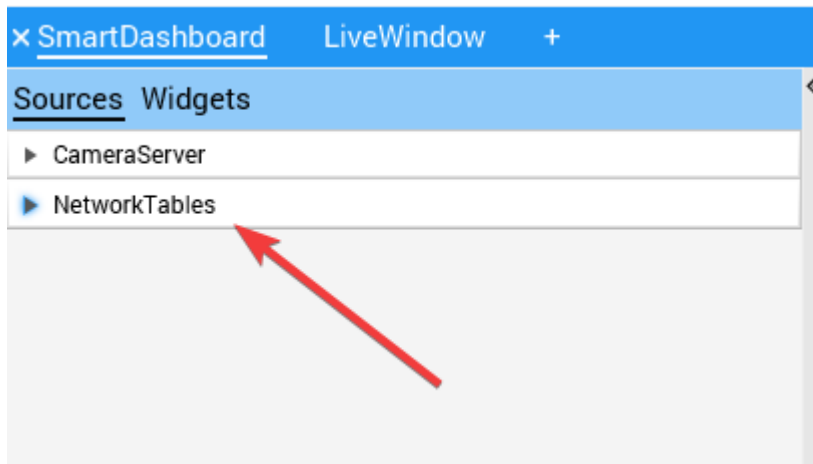
2. A slider that moves the wrist motor in either direction with 0 as stopped. The positive and negative values correspond to moving up or down.
3. The PID constants as described above (F is a feedforward value that is used for speed PID loops)
4. The setpoint value that corresponds to the pot value when the wrist has reached the desired value
5. Enables the PID controller - that is, starts it looping at regular intervals reading the pot value, computing the error, applying the P, I, and D terms and setting the motor value.

Try various values to get the desired motor performance. You can look at the video linked to at the beginning of this article or other sources on the internet to get the desired performance.

### 11.3.3 Viewing Hierarchies of Data

Dragging a key with other keys below it (deeper in the hierarchy) displays the hierarchy in a tree, similar to the NetworkTables sources on the left.

Select the data source:

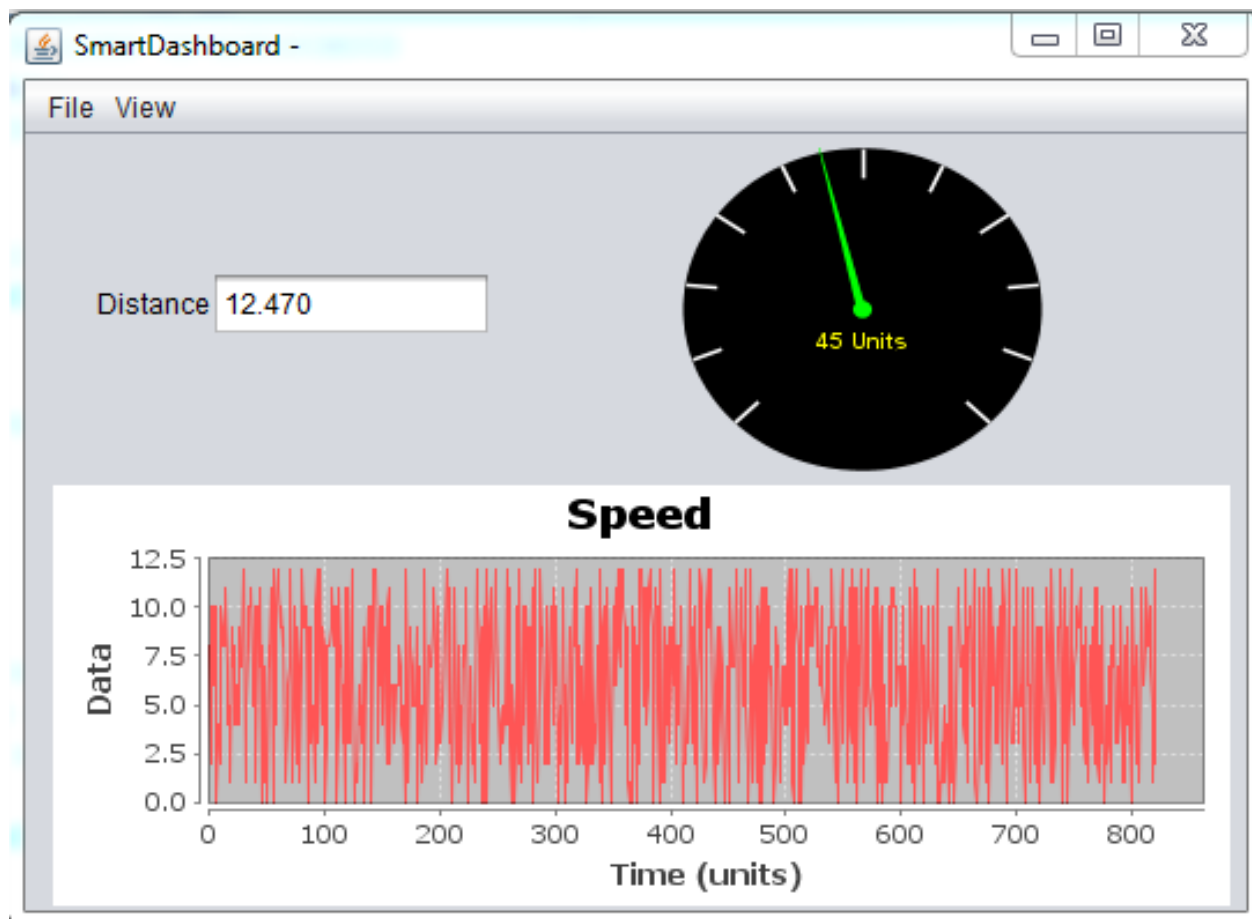


Click and drag the NetworkTables key into the preferred tab.

The screenshot shows the SmartDashboard LiveWindow interface. On the left, the 'Sources' tab is active, displaying a tree of data sources. A red box highlights the 'SmartDashboard' source, and a red arrow points from it to a preview window on the right. The preview window shows a 'SmartDashboard' widget with a table of data.

Name	Value
▼ FMSInfo	
EventName	
FMSControlData	0.0
GameSpecificMessage	
IsRedAlliance	true
MatchNumber	0.0
MatchType	0.0
ReplayNumber	0.0
StationNumber	1.0
▼ SmartDashboard	
▼ Auto choices	
active	Default Auto
default	Default Auto
options	[Default Auto, M...

## 12.1 SmartDashboard Introduction



The SmartDashboard is a Java program that will display robot data in real time. The SmartDashboard helps you with these things:

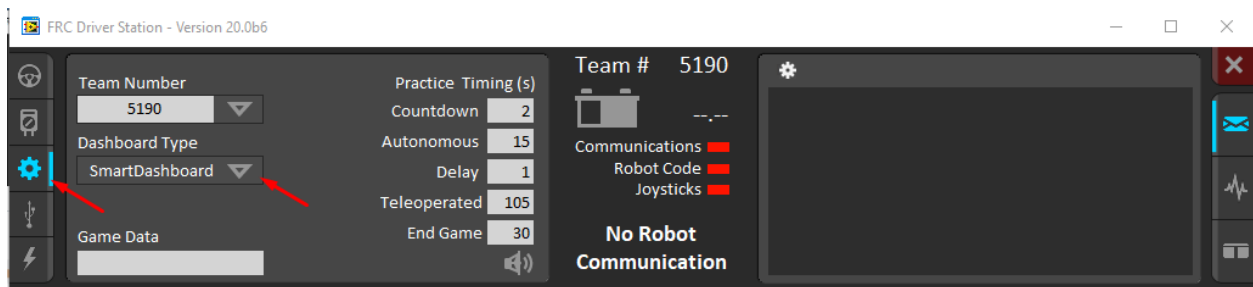
- Displays robot data of your choice while the program is running. It can be displayed as simple text fields or more elaborately in many other display types like graphs, dials, etc.



- Displays the state of the robot program such as the currently executing commands and the status of any subsystems
- Displays buttons that you can press to cause variables to be set on your robot
- Allows you to choose startup options on the dashboard that can be read by the robot program

The displayed data is automatically formatted in real-time as the data is sent from the robot, but you can change the format or the display widget types and then save the new screen layouts to be used again later. And with all these options, it is still extremely simple to use. To display some data on the dashboard, simply call one of the SmartDashboard methods with the data and its name and the value will automatically appear on the dashboard screen.

### 12.1.1 Installing the SmartDashboard



The SmartDashboard is packaged with the C++ and Java language updates and can be launched directly from the Driver Station by selecting the **SmartDashboard** button on the Setup tab.

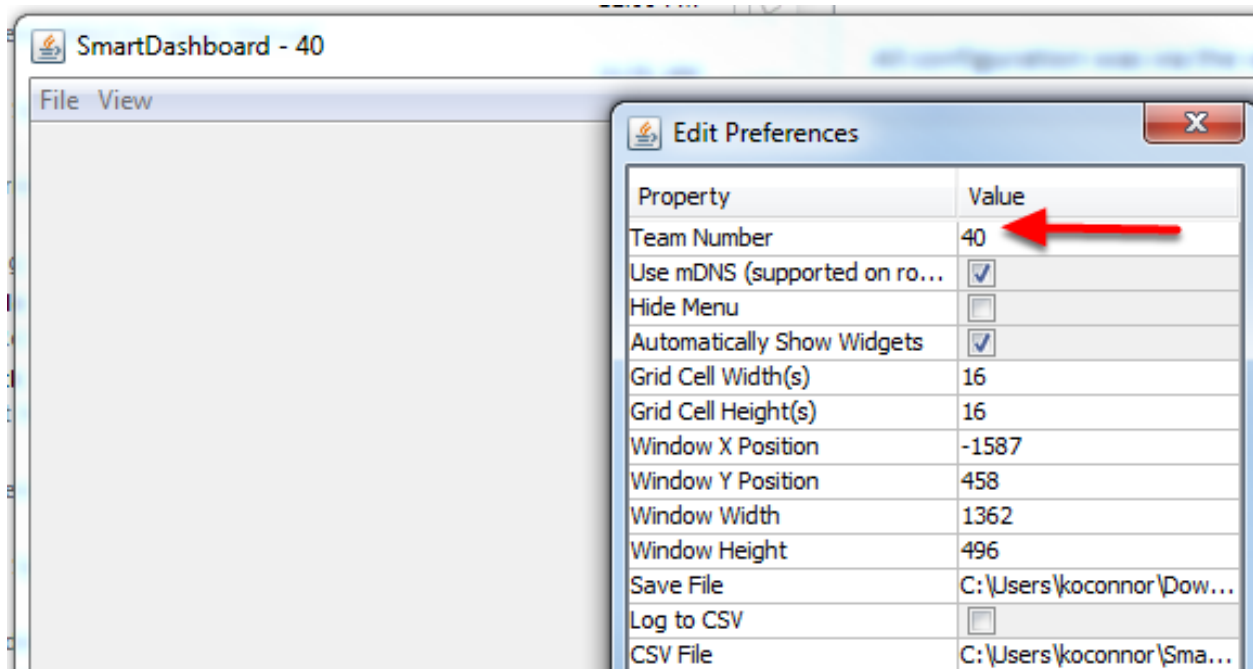
---

**Note:** If using the Classmate PC or other PC where the DS is run from a separate account from the C++/Java tools install (e.g. Driver and Developer) the buttons shown above may not work.

---

You can utilize the SmartDashboard in this type of setup in one of two ways. The first way is to set the type to **Default** and modify the DS INI file to launch the appropriate dashboard, details can be found in this article. The second option is to copy the C:\Users\Developer\wpilib\tools directory to C:\Users\Driver\wpilib\tools. When using this second method it is recommended to make sure that the Dashboard under both the Driver and Developer accounts point to the same save file (see Locating the Save File) below.

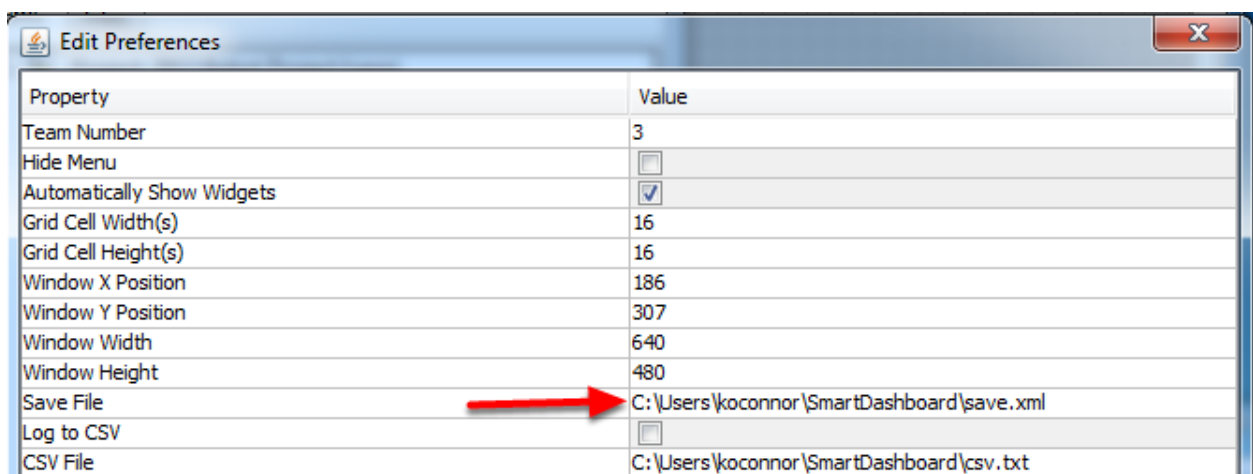
### 12.1.2 Configuring the Team Number



The first time you launch the SmartDashboard you should be prompted for your team number. To change the team number after this: click **File > Preferences** to open the Preferences dialog. Double-click the box to the right of **Team Number** and enter your FRC Team Number, then click outside the box to save.

**Note:** SmartDashboard will take a moment to configure itself for the team number, do not be alarmed.

### 12.1.3 Locating the Save File



Users may wish to customize the save location of the SmartDashboard. To do this click the box next to **Save File** then browse to the folder where you would like to save the configuration.

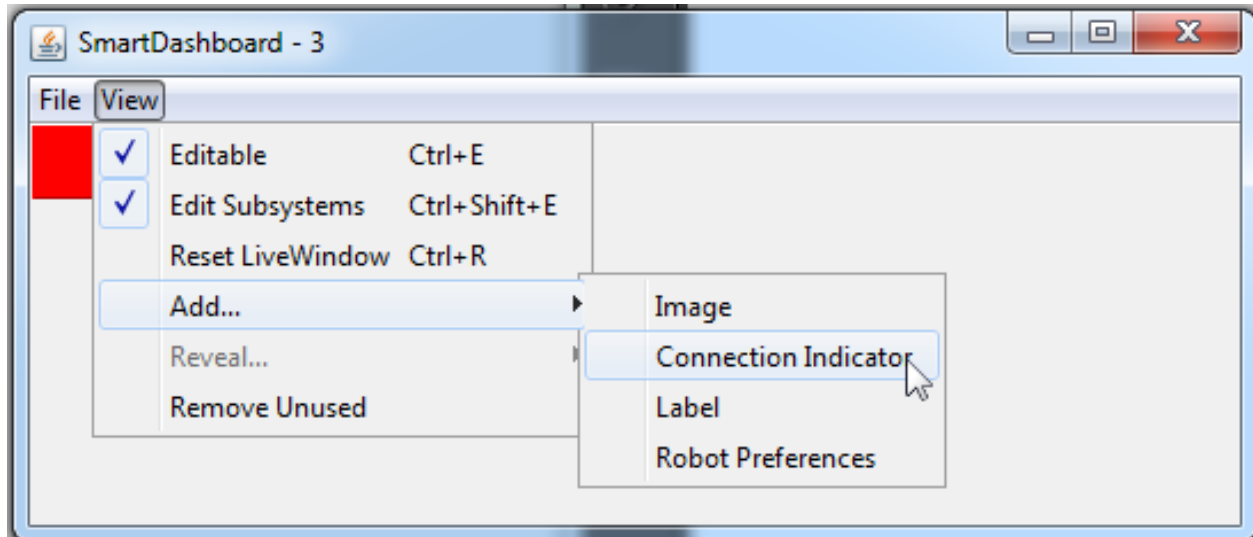
Files saved in the installation directories for the WPILib components will likely be overwritten on updates to the tools.

---

**Important:** It is recommended that this folder be inside the users home directory and not inside the sunspotfrcsdk or workbench directories.

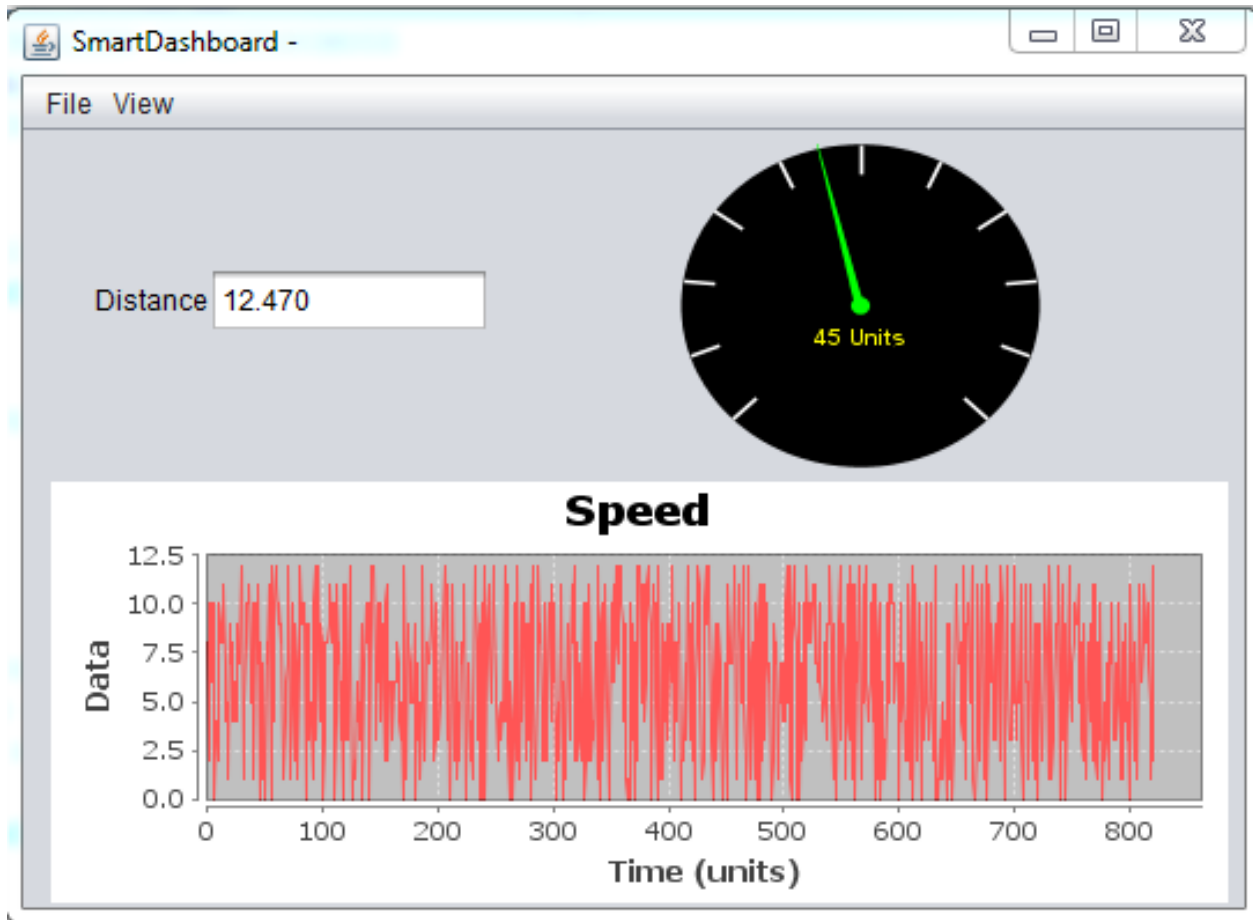
---

### 12.1.4 Adding a Connection Indicator



It is often helpful to see if the SmartDashboard is connected to the robot. To add a connection indicator, select **View > Add > Connection Indicator**. This indicator will be red when disconnected and green when connected. To move or resize this indicator, select **View > Editable** to toggle the SmartDashboard into editable mode, then drag the center of the indicator to move it or the edges to resize. Select the **Editable** item again to lock it in place.

### 12.1.5 Adding Widgets to the SmartDashboard



Widgets are automatically added to the SmartDashboard for each “key” sent by the robot code. For instructions on adding robot code to write to the SmartDashboard see [Displaying Expressions from Within the Robot Program](#).

## 12.2 Displaying Expressions from a Robot Program

**Note:** Often debugging or monitoring the status of a robot involves writing a number of values to the console and watching them stream by. With SmartDashboard you can put values to a GUI that is automatically constructed based on your program. As values are updated, the corresponding GUI element changes value - there is no need to try to catch numbers streaming by on the screen.

### 12.2.1 Writing Values to SmartDashboard

Java

```
protected void execute() {
    SmartDashboard.putBoolean("Bridge Limit", bridgeTipper.atBridge());
    SmartDashboard.putNumber("Bridge Angle", bridgeTipper.getPosition());
    SmartDashboard.putNumber("Swerve Angle", drivetrain.getSwerveAngle());
    SmartDashboard.putNumber("Left Drive Encoder", drivetrain.getLeftEncoder());
    SmartDashboard.putNumber("Right Drive Encoder", drivetrain.getRightEncoder());
    SmartDashboard.putNumber("Turret Pot", turret.getCurrentAngle());
    SmartDashboard.putNumber("Turret Pot Voltage", turret.getAverageVoltage());
    SmartDashboard.putNumber("RPM", shooter.getRPM());
}
```

C++

```
void Command::Execute() {
    frc::SmartDashboard::PutBoolean("Bridge Limit", BridgeTipper.AtBridge());
    frc::SmartDashboard::PutNumber("Bridge Angle", BridgeTipper.GetPosition());
    frc::SmartDashboard::PutNumber("Swerve Angle", Drivetrain.GetSwerveAngle());
    frc::SmartDashboard::PutNumber("Left Drive Encoder", Drivetrain.GetLeftEncoder());
    frc::SmartDashboard::PutNumber("Right Drive Encoder", Drivetrain.GetRightEncoder());
    frc::SmartDashboard::PutNumber("Turret Pot", Turret.GetCurrentAngle());
    frc::SmartDashboard::PutNumber("Turret Pot Voltage", Turret.GetAverageVoltage());
    frc::SmartDashboard::PutNumber("RPM", Shooter.GetRPM());
}
```

You can write Boolean, Numeric, or String values to the SmartDashboard by simply calling the correct method for the type and including the name and the value of the data, no additional code is required. Any time in your program that you write another value with the same name, it appears in the same UI element on the screen on the driver station or development computer. As you can imagine this is a great way of debugging and getting status of your robot as it is operating.

## 12.2.2 Creating Widgets on SmartDashboard

Widgets are populated on the SmartDashboard automatically, no user intervention is required. Note that the widgets are only populated when the value is first written, you may need to enable your robot in a particular mode or trigger a particular code routine for an item to appear. To alter the appearance of the widget, see the next two sections Changing the Display Properties of a Value and Changing the Display Widget Type for a Value.

## 12.2.3 Stale Data

SmartDashboard uses NetworkTables for communicating values between the robot and the driver station laptop. Network Tables acts as a distributed table of name and value pairs. If a name/value pair is added to either the client (laptop) or server (robot) it is replicated to the other. If a name/value pair is deleted from, say, the robot but the SmartDashboard or OutlineViewer are still running, then when the robot is restarted, the old values will still appear in the SmartDashboard and OutlineViewer because they never stopped running and continue to have those values in their tables. When the robot restarts, those old values will be replicated to the robot.

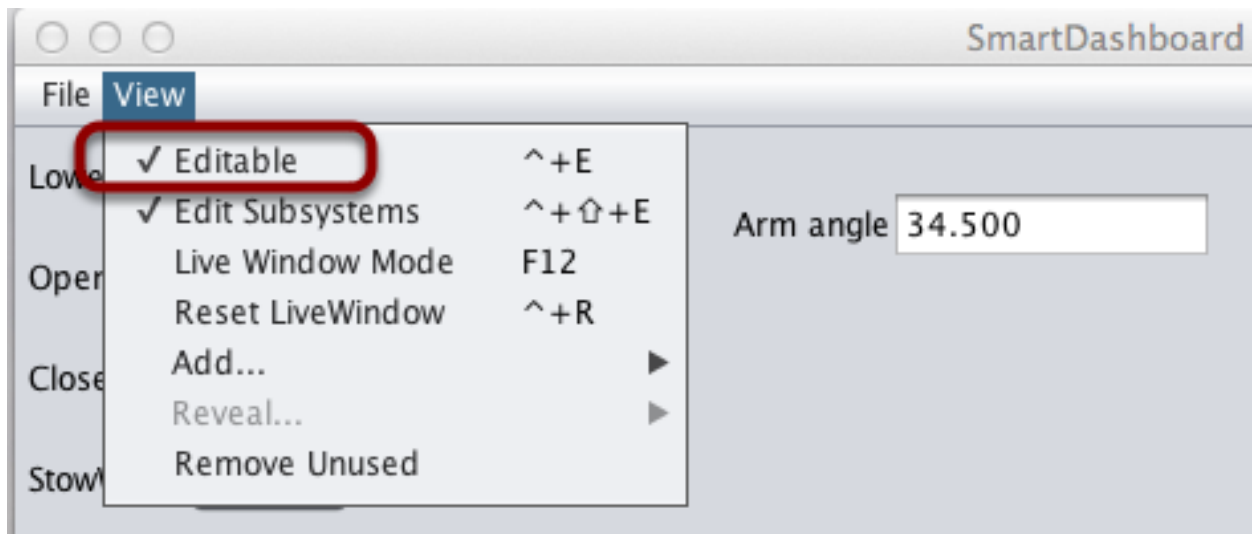
To ensure that the SmartDashboard and OutlineViewer are showing current values, it is necessary to restart the network table clients and robot at the same time. That way, old values that one is holding won't get replicated to the others.

This usually isn't a problem if the program isn't constantly changing, but if the program is in development and the set of keys being added to NetworkTables is constantly changing, then it might be necessary to do the restart of everything to accurately see what is current.

## 12.3 Changing the display properties of a value

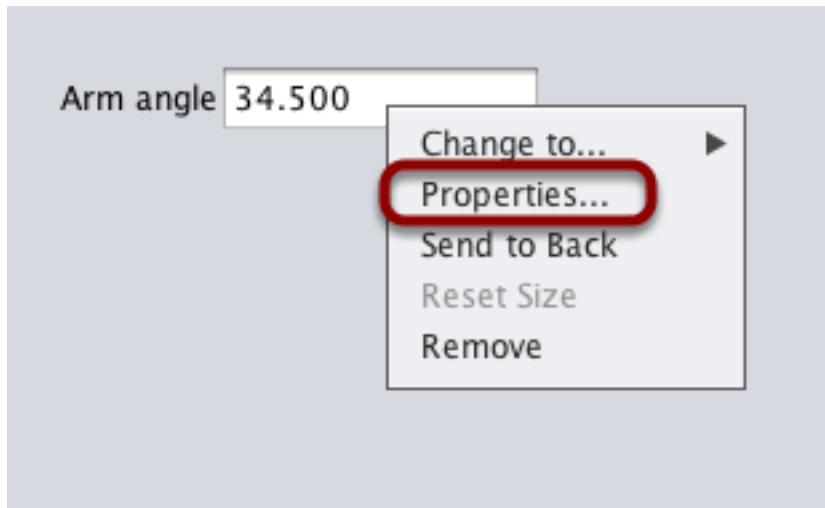
Each value displayed with SmartDashboard has a set of properties that effect the way it's displayed.

### 12.3.1 Setting the SmartDashboard display into editing mode



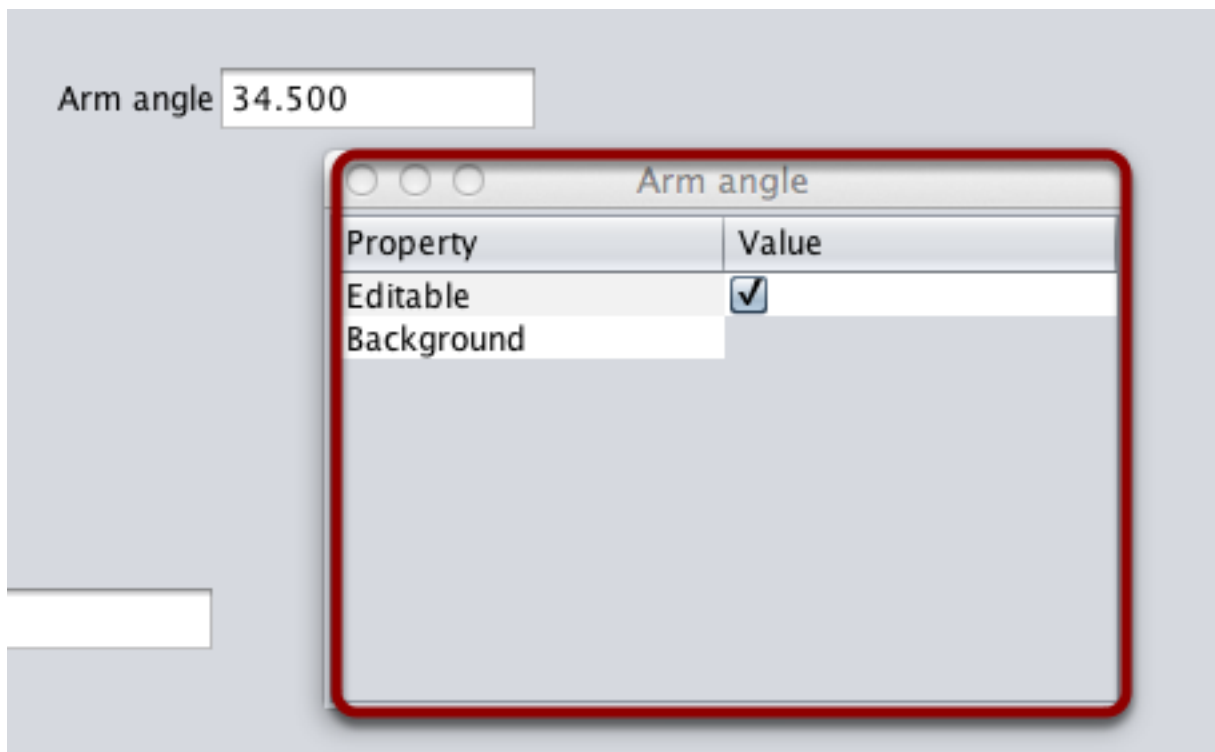
The SmartDashboard has two modes it can operate in, display mode and edit mode. In edit mode you can move around widgets on the screen and edit their properties. To put the SmartDashboard into edit mode, click the "View" menu, then select "Editable" to turn on edit mode.

### 12.3.2 Getting the properties editor of a widget



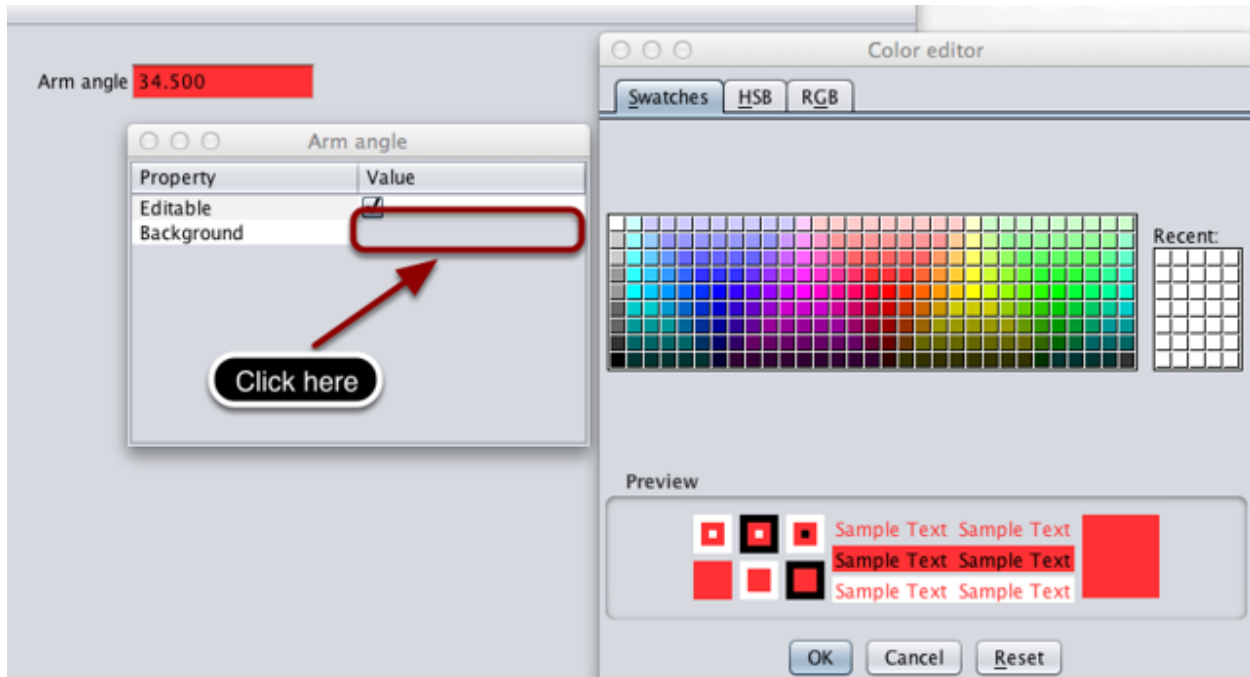
Once in edit mode, you can display and edit the properties for a widget. Right-click on the widget and select “Properties...”.

### 12.3.3 Editing the properties on a field



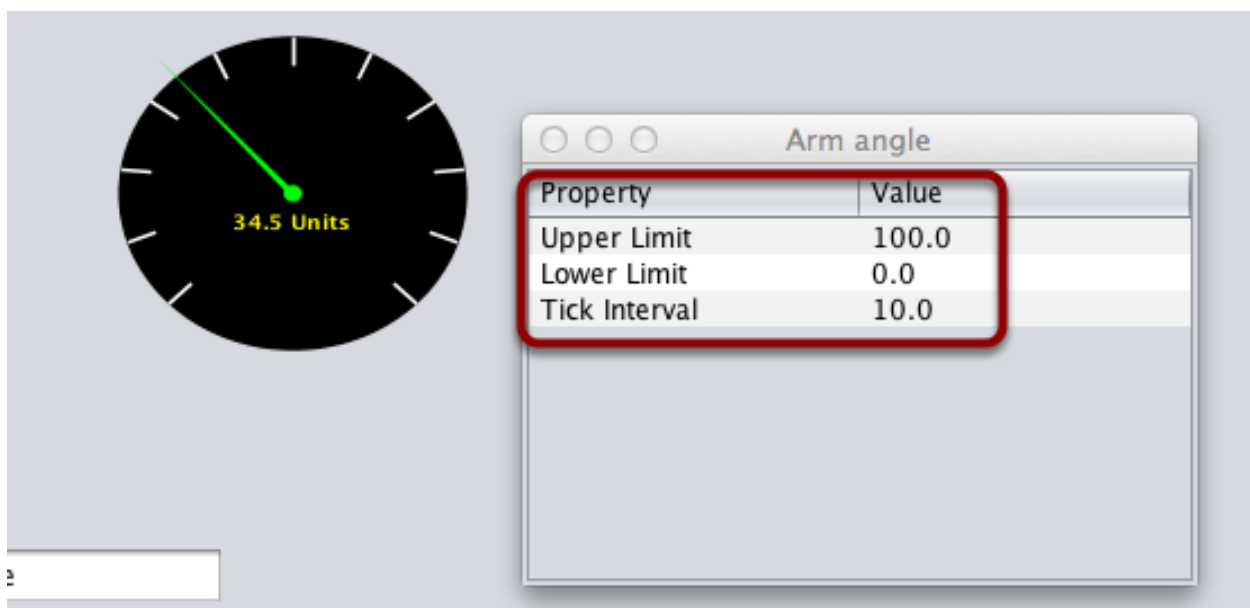
A dialog box will be shown in response to the “Properties...” menu item on the widgets right-click context menu.

### 12.3.4 Editing the widgets background color



To edit a property value, say, Background color, click the background color shown (in this case grey), and choose a color from the color editor that pops up. This will be used as the widgets background color.

### 12.3.5 Edit properties of other widgets



Different widget types have different sets of editable properties to change the appearance. In this example, the upper and lower limits of the dial and the tick interval are changeable parameters.



## 12.4 SmartDashboard: Test Mode and Live Window

### 12.4.1 Displaying LiveWindow Values

**Note:** LiveWindow will automatically add your sensors for you. There is no need to do it manually.

---

LiveWindow values may also be displayed by writing the code yourself and adding it to your robot program. LiveWindow will display values grouped in subsystems. This is a convenient method of displaying whether they are actual command based program subsystems or just a grouping that you decide to use in your program.

#### Adding the Necessary Code to your Program

1. First, get a reference (Java) or pointer (C++) to the LiveWindow object.

Java

```
LiveWindow lw = LiveWindow.getInstance();
```

C++

```
frc::LiveWindow lw = frc::LiveWindow::GetInstance();
```

2. Then for each sensor or actuator that is created, add it to the LiveWindow display by either calling AddActuator or AddSensor (addActuator or addSensor in Java). When the SmartDashboard is put into LiveWindow mode, it will display the sensors and actuators.

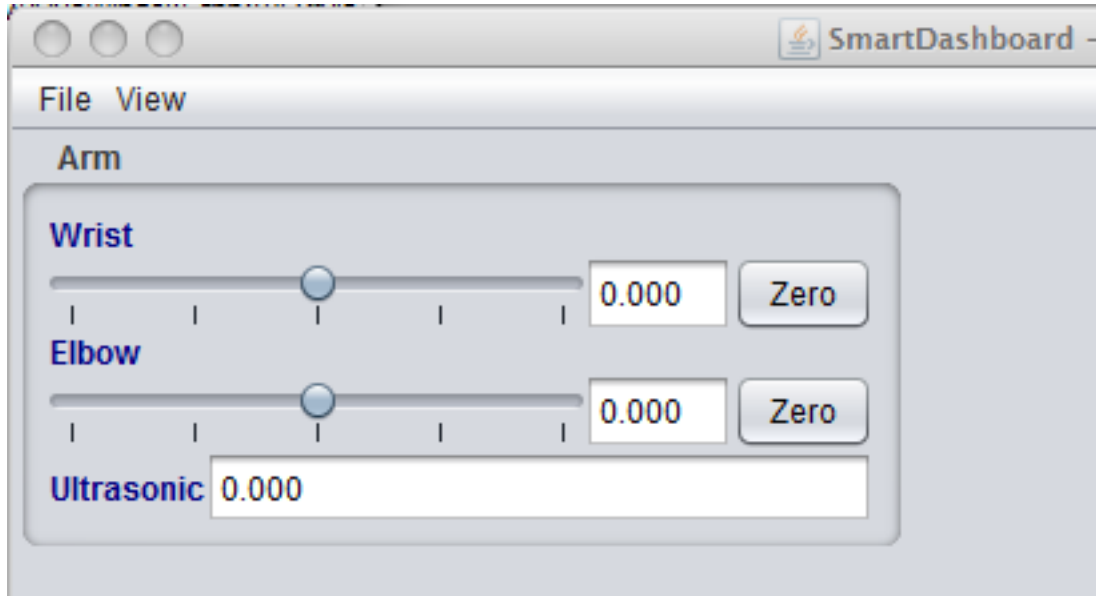
Java

```
Ultrasonic ultrasonic = new Ultrasonic(1, 2);  
lw.addSensor("Arm", "Ultrasonic", ultrasonic);  
  
Jaguar elbow = new Jaguar(1);  
lw.addActuator("Arm", "Elbow", elbow);  
  
Victor wrist = new Victor(2);  
lw.addActuator("Arm", "Wrist", wrist);
```

C++

```
frc::Ultrasonic ultrasonic{1, 2};  
lw->AddSensor("Arm", "Ultrasonic", ultrasonic);  
  
frc::Jaguar elbow{1};  
lw->AddActuator("Arm", "Elbow", elbow);  
  
frc::Victor wrist{2};  
lw->AddActuator("Arm", "Wrist", wrist);
```

## Viewing the Display in SmartDashboard

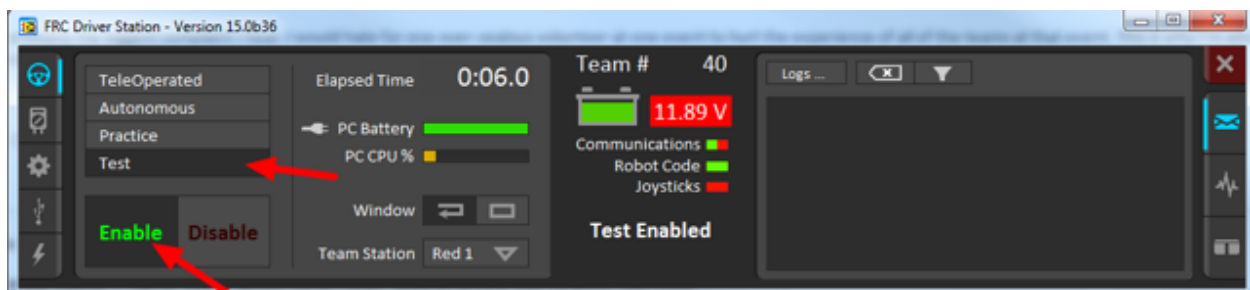


The sensors and actuators added to the LiveWindow will be displayed grouped by subsystem. The subsystem name is just an arbitrary grouping the helping to organize the display of the sensors. Actuators can be operated by operating the slider for the two motor controllers.

### 12.4.2 Enabling Test mode (LiveWindow)

You may add code to your program to display values for your sensors and actuators while the robot is in Test mode. This can be selected from the Driver Station whenever the robot is not on the field. The code to display these values is automatically generated by RobotBuilder and is described in the next article. Test mode is designed to verify the correct operation of the sensors and actuators on a robot. In addition it can be used for obtaining setpoints from sensors such as potentiometers and for tuning PID loops in your code.

## Setting Test mode with the Driver Station



Enable Test Mode in the Driver Station by clicking on the "Test" button and setting "Enable" on the robot. When doing this, the SmartDashboard display will switch to test mode (LiveWindow) and will display the status of any actuators and sensors used by your program.

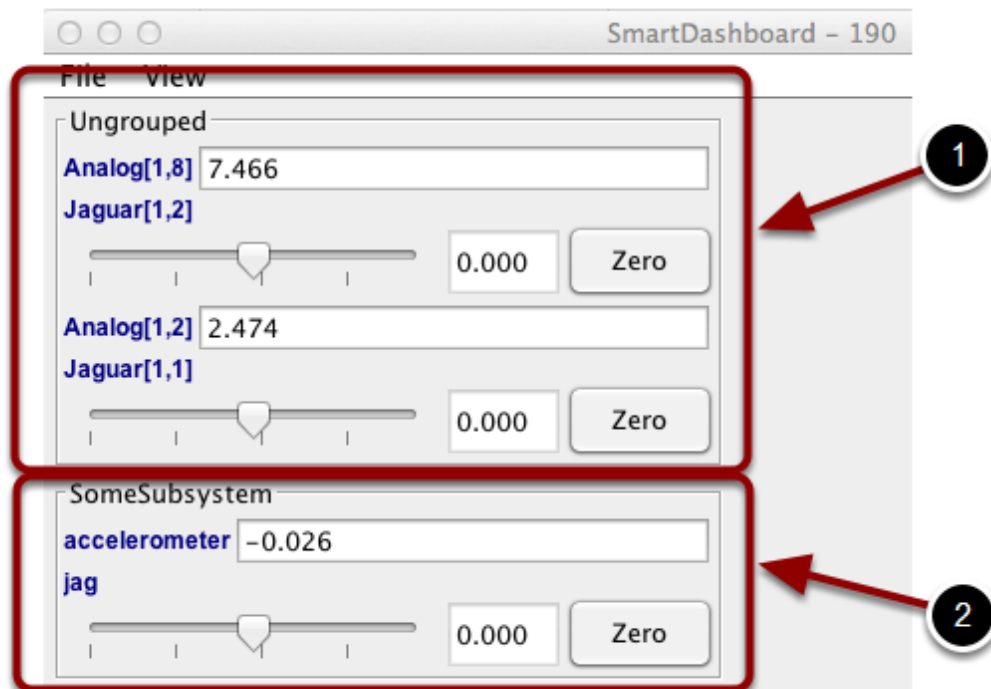
## Explicitly vs. implicit test mode display

```
RobotDrive drive = new RobotDrive(1, 2);
Jaguar jag;
Accelerometer accel = new Accelerometer(1, 2);

public void robotInit() {
    jag = new Jaguar(3);
    drive.setSafetyEnabled(false);
    LiveWindow.addActuator("SomeSubsystem", "jag", jag);
    LiveWindow.addSensor("SomeSubsystem", "accelerometer", accel);
    SmartDashboard.putData("TestPID", new PIDController(1, 1, 1, accel, jag));
    SmartDashboard.putNumber("X", 0.0);
}
```

All sensors and actuators will automatically be displayed on the SmartDashboard in test mode and will be named using the object type (such as Jaguar, Analog, Victor, etc.) with the module number and channel number with which the object was created. In addition, the program can explicitly add sensors and actuators to the test mode display, in which case programmer-defined subsystem and object names can be specified making the program clearer. This example illustrates explicitly defining those sensors and actuators in the highlighted code.

## Understanding what is displayed in Test mode



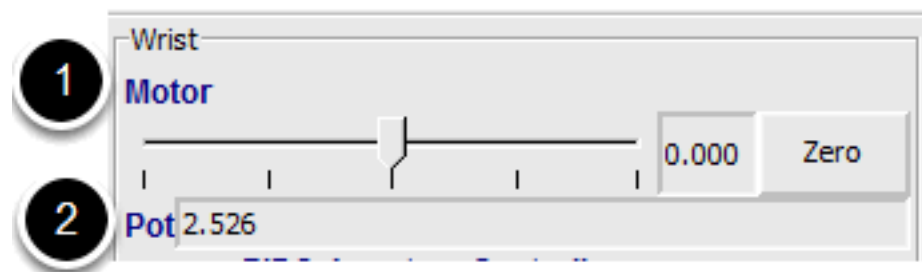
This is the output in the SmartDashboard display when the robot is placed into test mode. In the display shown above the objects listed as Ungrouped were implicitly created by WPILib when the corresponding objects were created. These objects are contained in a subsystem

group called “Ungrouped” **(1)** and are named with the device type (Analog, Jaguar in this case), and the module and channel numbers. The objects shown in the “SomeSubsystem” **(2)** group are explicitly created by the programmer from the code example in the previous section. These are named in the calls to `LiveWindow.addActuator()` and `LiveWindow.AddSensor()`. Explicitly created sensors and actuators will be grouped by the specified subsystem.

### 12.4.3 PID Tuning with SmartDashboard

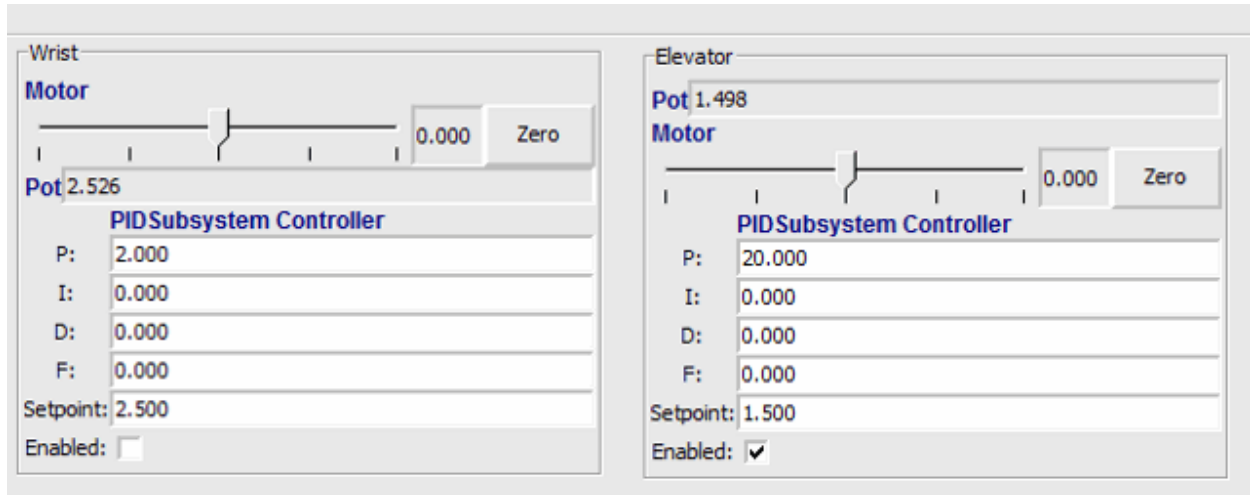
The PID (Proportional, Integral, Differential) is an algorithm for determining the motor speed based on sensor feedback to reach a setpoint as quickly as possible. For example, a robot with an elevator that moves to a predetermined position should move there as fast as possible then stop without excessive overshoot leading to oscillation. Getting the PID controller to behave this way is called “tuning”. The idea is to compute an error value that is the difference between the current value of the mechanism feedback element and the desired (setpoint) value. In the case of the arm, there might be a potentiometer connected to an analog channel that provides a voltage that is proportional to the position of the arm. The desired value is the voltage that is predetermined for the position the arm should move to, and the current value is the voltage for the actual position of the arm.

#### Finding the setpoint values with LiveWindow



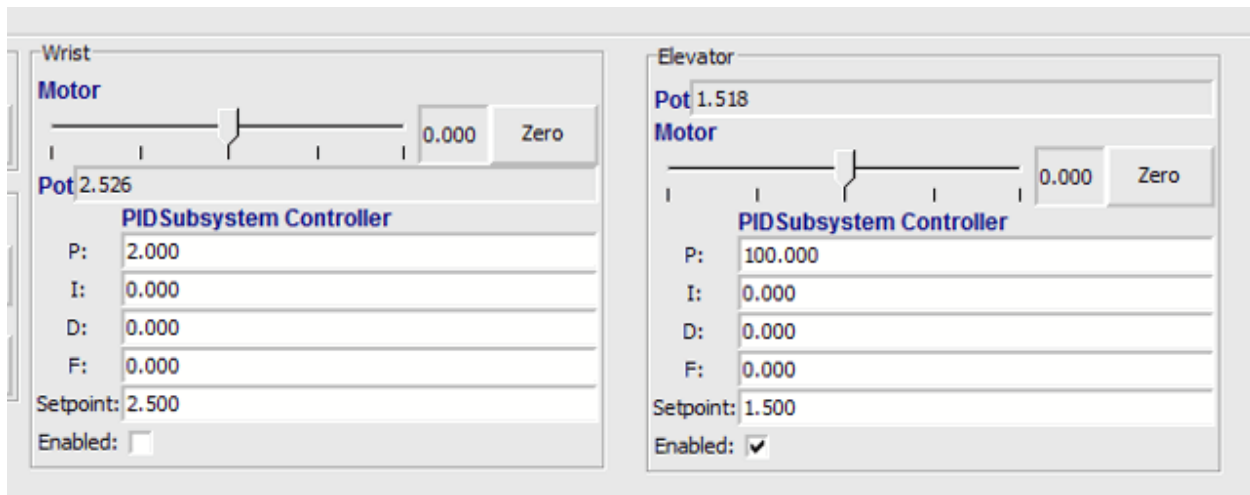
Create a PID Subsystem for each mechanism with feedback. The PID Subsystems contain the actuator (motor) and the feedback sensor (potentiometer in this case). You can use Test mode to display the subsystem sensors and actuators. Using the slider manually adjust the actuator to each desired position. Note the sensor values (2) for each of the desired positions. These will become the setpoints for the PID controller.

## Viewing the PIDController in LiveWindow



In Test mode, the PID Subsystems display their P, I, and D parameters that are set in the code. The P, I, and D values are the weights applied to the computed error (P), sum of errors over time (I), and the rate of change of errors (D). Each of those terms is multiplied by the weights and added together to form the motor value. Choosing the optimal P, I, and D values can be difficult and requires some amount of experimentation. The Test mode on the robot allows the values to be modified, and the mechanism response observed.

## Tuning the PIDController



Tuning the PID controller can be difficult and there are many articles that describe techniques that can be used. It is best to start with the P value first. To try different values fill in a low number for P, enter a setpoint determined earlier in this document, and note how fast the mechanism responds. If it responds too slowly, perhaps never reaching the setpoint, increase P. If it responds too quickly, perhaps oscillating, reduce the P value. Repeat this process until you get a response that is as fast as possible without oscillation. It's possible that having a P term is all that's needed to achieve adequate control of your mechanism. Further information is located in the [Tuning a PID Controller](#) document.

Once you have determined P, I, and D values they can be inserted into the program. You'll find them either in the properties for the PIDSubsystem in RobotBuilder or in the constructor for the PID Subsystem in your code.

The F (feedforward) term is used for controlling velocity with a PID controller.

You can find more information in [Operating the robot with feedback from sensors](#).



## 13.1 Introduction to PathWeaver

Autonomous is an important section of the match; it is exciting when robots do impressive things in autonomous. In order to score, the robot usually need to go somewhere. The faster the robot arrives at that location, the sooner it can score points! The traditional method for autonomous is driving in a straight line, turning to a certain angle, and driving in a straight line again. This approach works fine, but the robot spends a non-negligible amount of time stopping and starting again after each straight line and turn.

A more advanced approach to autonomous is called “path planning”. Instead of driving in a straight line and turning once the line is complete, the robot continuously moves, driving with a curve-like motion. This can reduce turning stoppage time.

WPILib contains a trajectory generation suite that can be used by teams to generate and follow trajectories. This series of articles will go over how to generate and visualize trajectories using PathWeaver. For a comprehensive tutorial on following trajectories, please visit the [end-to-end trajectory tutorial](#).

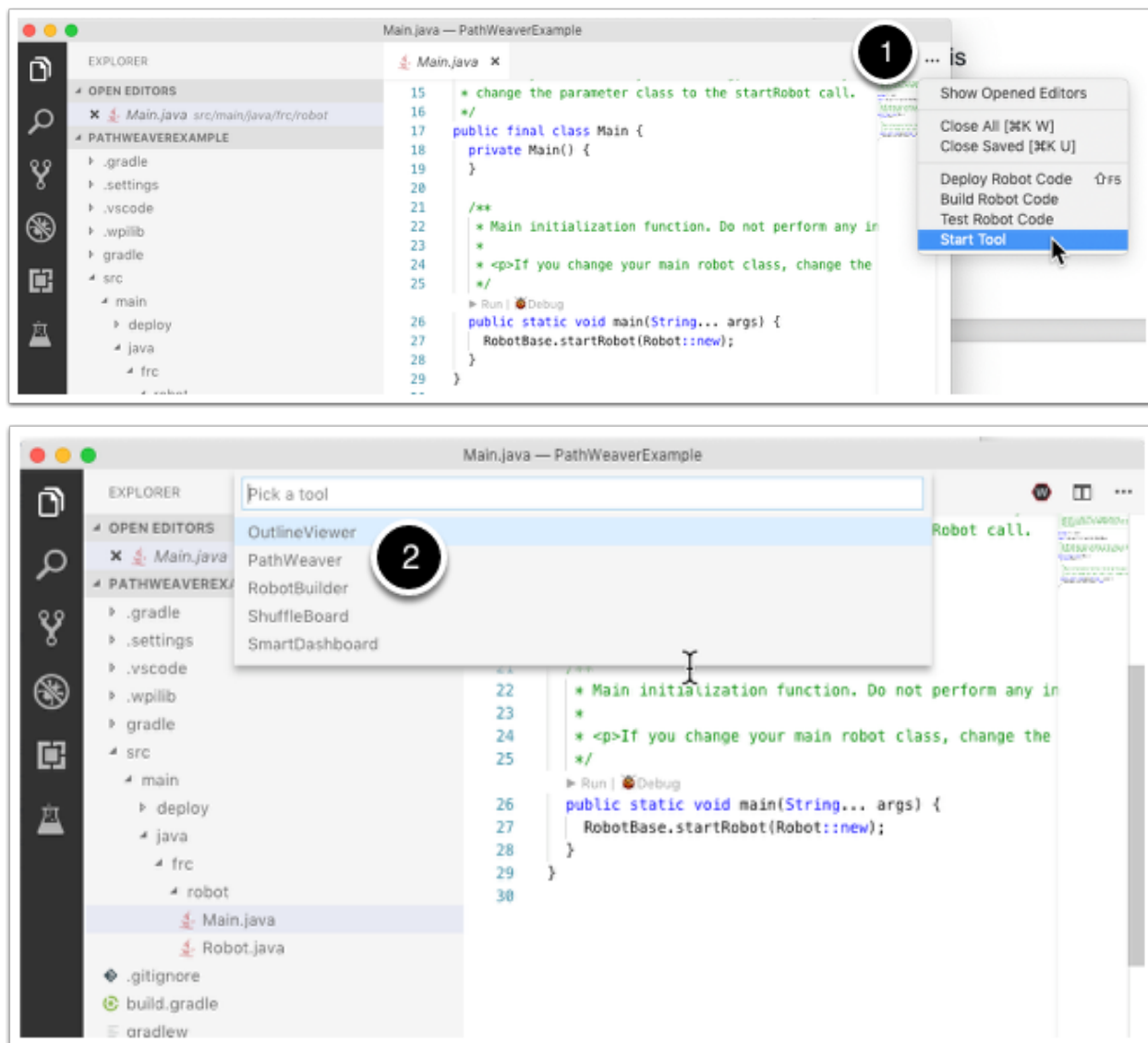
## 13.2 Creating a Pathweaver Project

PathWeaver is the tool used to draw the paths for a robot to follow. The paths for a single program are stored in a PathWeaver project.

### 13.2.1 Starting PathWeaver

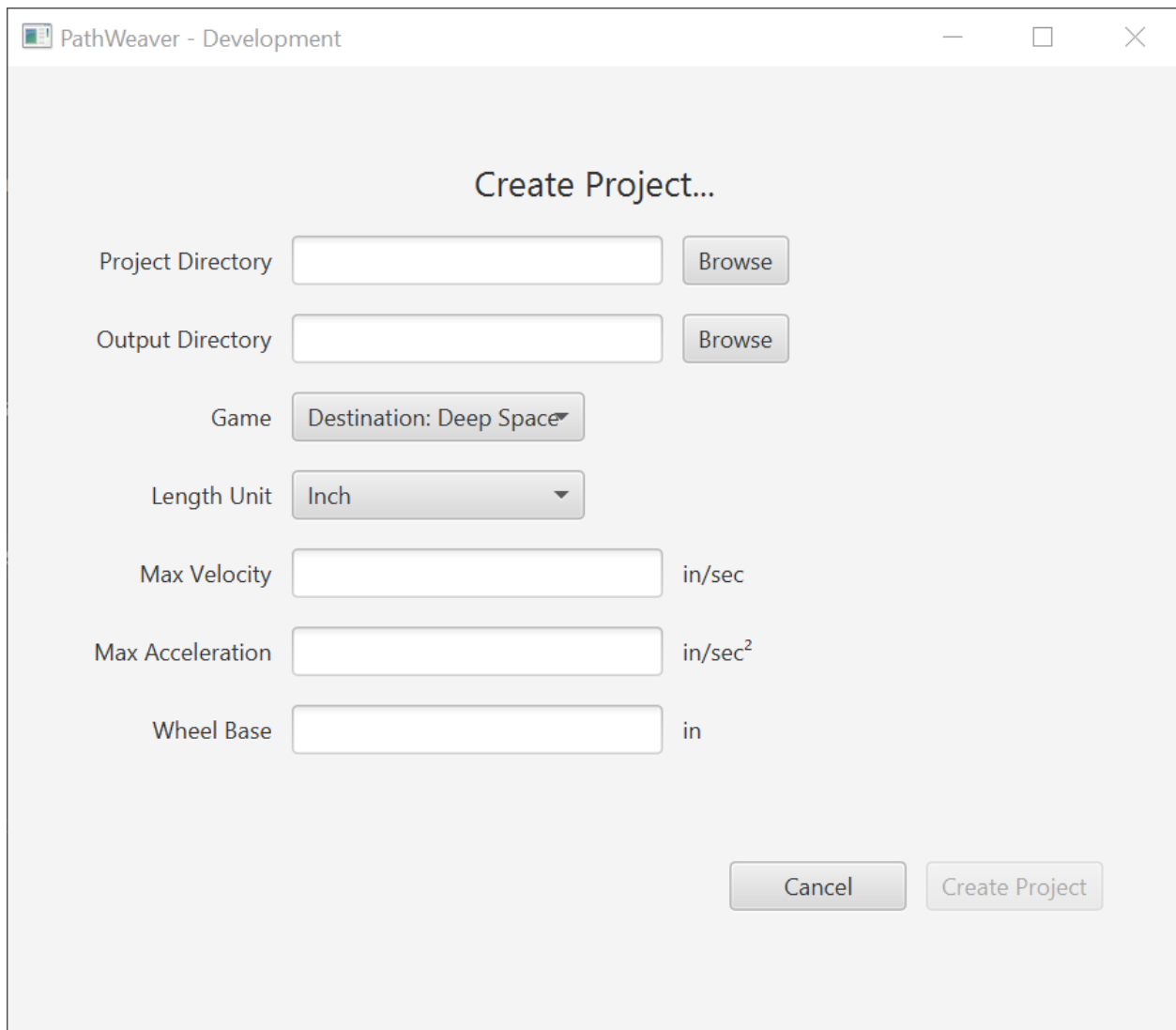
PathWeaver is started by clicking on the ellipsis icon in the top right of the corner of the Visual Studio Code interface. You must select a source file from the WPILib project to see the icon. Then click on “Start tool” and then click on “PathWeaver” as shown below.





### 13.2.2 Creating the Project

To create a PathWeaver project, click on “Create project” and then fill out the project creation form. Notice that hovering over any of the fields in the form will display more information about what is required.



PathWeaver - Development

### Create Project...

Project Directory

Output Directory

Game

Length Unit

Max Velocity  in/sec

Max Acceleration  in/sec<sup>2</sup>

Wheel Base  in

**Project Directory:** This is normally the top level project directory that contains the build.gradle and src files for your robot program. Choosing this directory is the expected way to use PathWeaver and will cause it to locate all the output files in the correct directories for automatic path deployment to your robot.

**Output directory:** The directory where the paths are stored for deployment to your robot. If you specified the top level project folder of our robot project in the previous step (as recommended) filling in the project directory is optional.

**Game:** The game (which FRC game is being used) will cause the correct field image overlay to be used. You can also create your own field images and the procedure will be described later in this series.

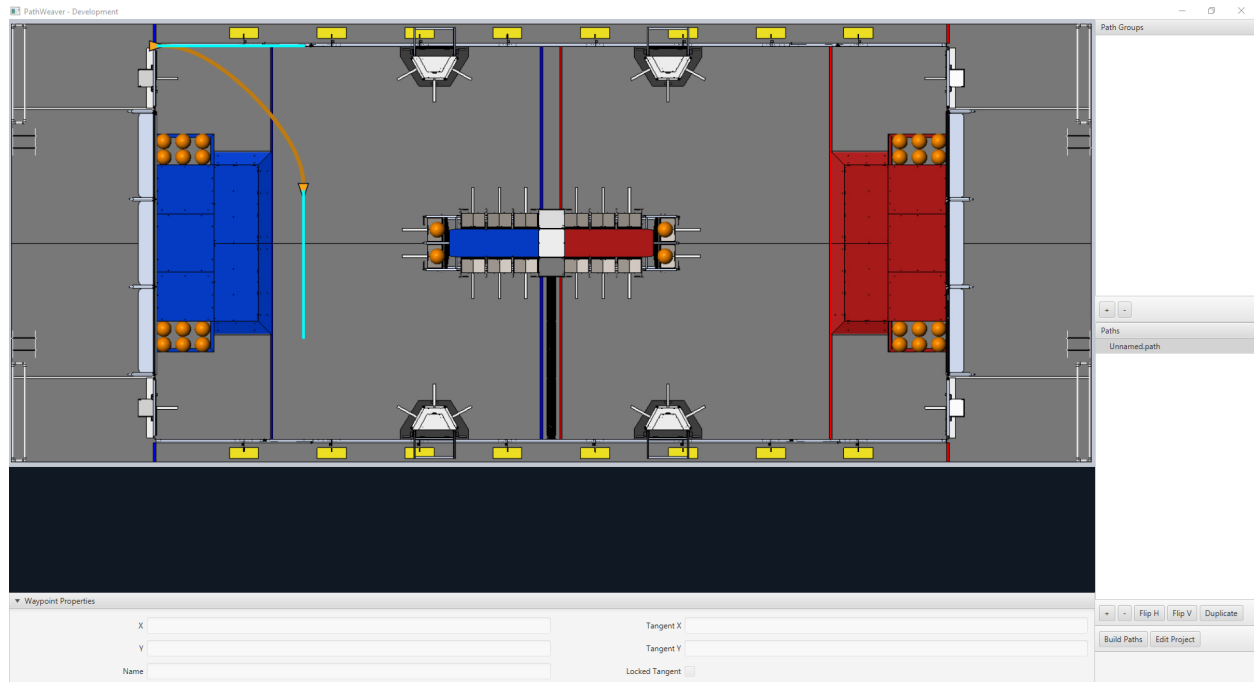
**Length Unit:** The units to be used in describing your robot and for the field measurements when visualizing trajectories using PathWeaver. It's best to use units of meters, as this is what is recommended when following WPILib trajectories.

**Max Velocity:** The max speed of the robot for trajectory tracking. This does not need to be the maximum attainable speed of the robot, but just the max speed that you want to run trajectories at.

**Max Acceleration:** The max acceleration of the robot for trajectory tracking. This does not need to be the maximum attainable acceleration of the robot, but just the max acceleration that you want to run trajectories at.

**Wheel Base:** The distance between the left and right wheels of your robot. This is used to ensure that no wheel on a differential drive will go over the specified max velocity around turns.

### 13.2.3 PathWeaver User Interface

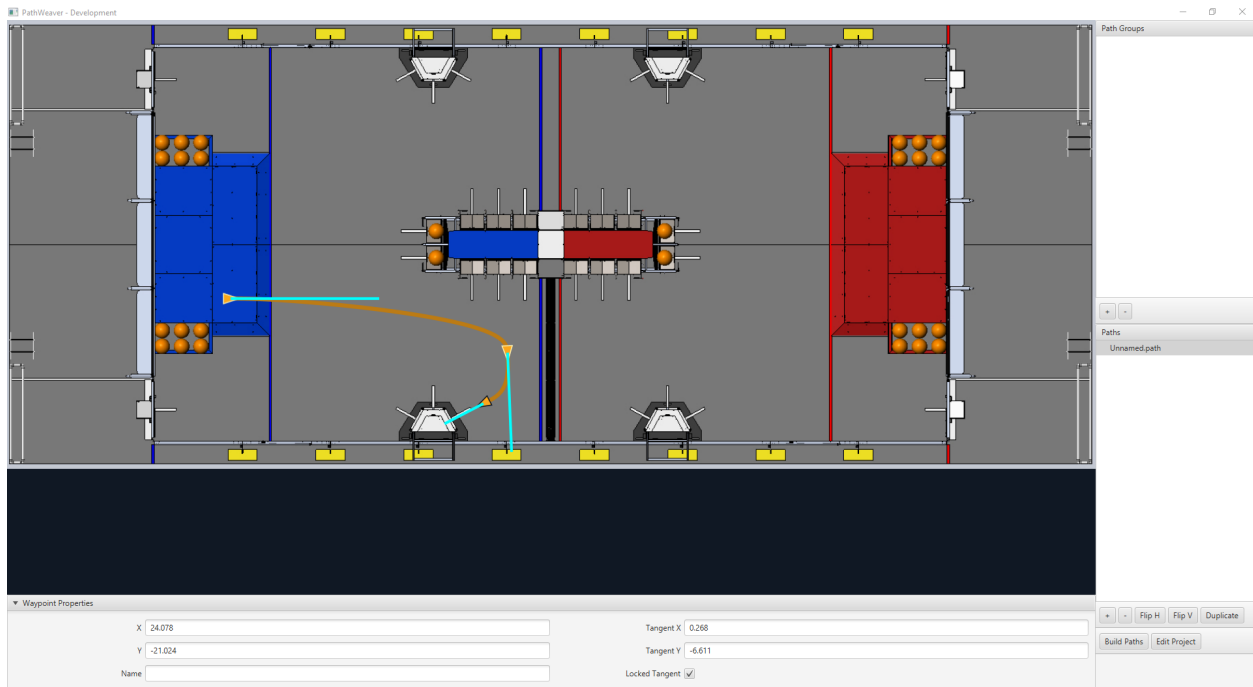


The PathWeaver user interface consists of the following:

1. The field area in the top left corner, which takes up most of the PathWeaver window. Trajectories are drawn on this part of the program.
2. The properties of the currently selected waypoint are displayed in the bottom pane. These properties include the X and Y, along with the tangents at each point.
3. A group of paths (or an “autonomous” mode) is displayed on the upper right side of the window. This is a convenient way of seeing all of the trajectories in a single auto mode.
4. The individual paths that a robot might follow are displayed in the lower right side of the window.
5. The “Build Paths” button will export the trajectories in a JSON format. These JSON files can be used from the robot code to follow the trajectory.
6. The “Edit Project” button allows you to edit the project properties.

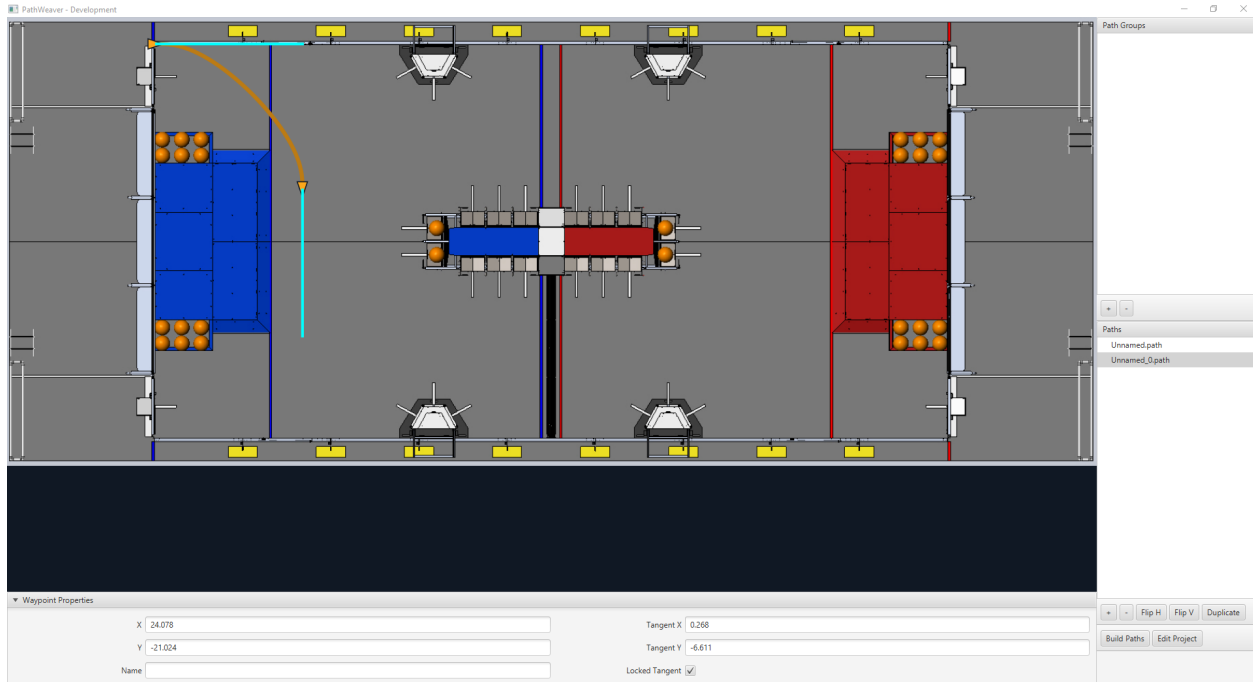
## 13.3 Visualizing PathWeaver Trajectories

PathWeaver's primary feature is to visualize trajectories. The following images depict a smooth trajectory that represents a trajectory that a robot might take during the autonomous period. Paths can have any number of waypoints that can allow more complex driving to be described. In this case there are 3 waypoints (including the start and stop) depicted with the triangle icons. Each waypoint consists of a X, Y position on the field as well as a robot heading described as the X and Y tangent lines.



### 13.3.1 Creating the Initial Trajectory

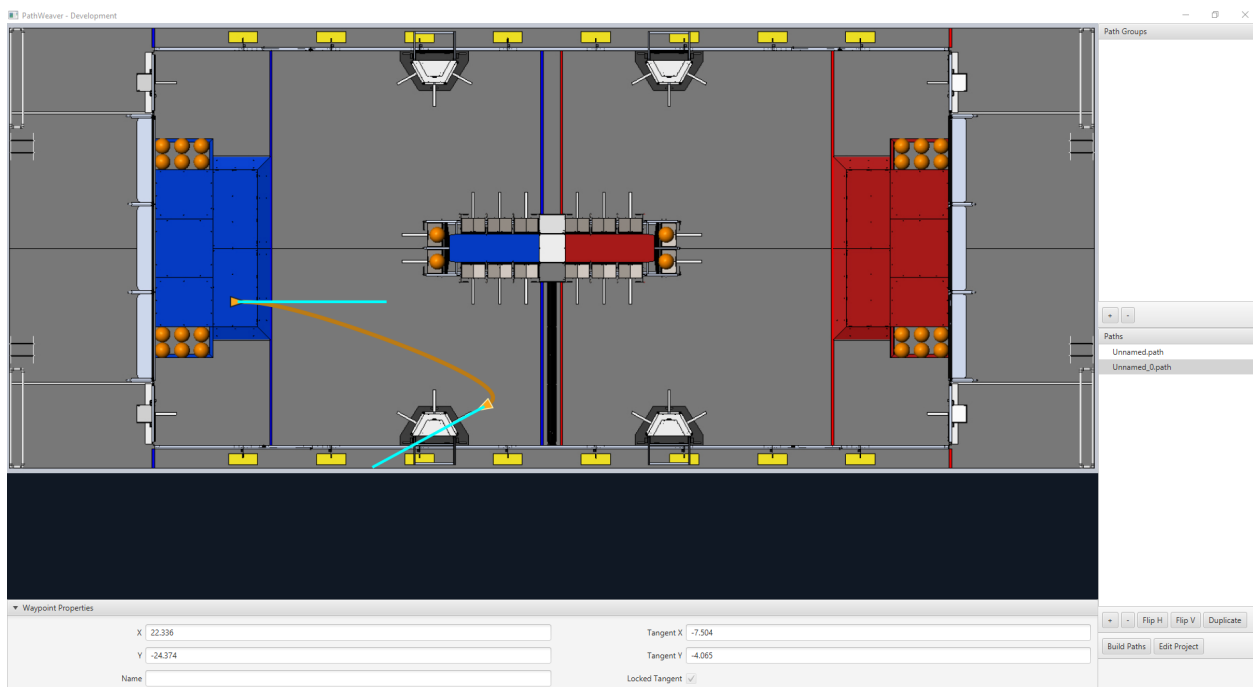
To start creating a trajectory, click the + (plus) button in the path window. A default trajectory will be created that probably does not have the proper start and end points that you desire. The path also shows the tangent vectors (teal lines) for the start and end points. Changing the angle of the tangent vectors changes the shape of the trajectory.



Drag the start and end points of the trajectory to the desired locations. Notice that in this case, the default trajectory does not start in a legal spot for the 2019 game. We can drag the initial waypoint to make the robot start on the HAB.

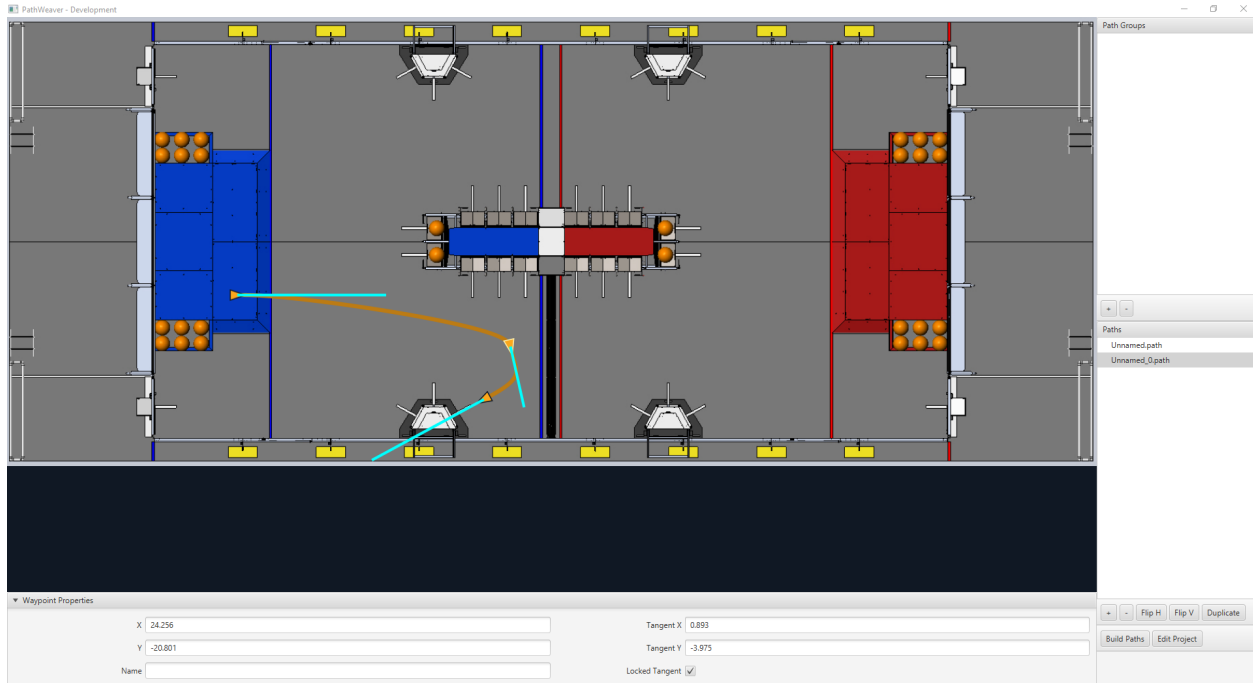
## 13.3.2 Changing a Waypoint Heading

The robot heading can be changed by dragging the tangent vector (teal) line. Here, the final waypoint was dragged to the desired final pose and was rotated to face the rocket.



### 13.3.3 Adding Additional Waypoints to Control the Robot Path

Adding additional waypoints and changing their tangent vectors can affect the path that is followed. Additional waypoints can be added by dragging in the middle of the path. In this case, we added another waypoint in the middle of the path.



### 13.3.4 Locking the Tangent Lines

Locking tangent lines prevents them from changing when the trajectory is being manipulated. The tangent lines will also be locked when the point is moved.

### 13.3.5 More Precise control of Waypoints

While PathWeaver makes it simple to draw trajectories that the robot should follow, it is sometimes hard to precisely set where the waypoints should be placed. In this case, setting the waypoint locations can be done by entering the X and Y value which might come from an accurate CAD model of the field. The points can be entered in the X and Y fields when a waypoint is selected.

## 13.4 Creating Path Groups

Path Groups are a way of visualizing where one path ends and the next one starts. An example is when the robot program drives one path, does something after the path has completed, drives to another location to obtain a game piece, then back again to score it. It's important that the start and end points of each path in the group have common end and start points. By adding all the paths to a single path group and selecting the group, all paths in that group will be shown. Then each path can be edited while viewing all the paths.

### 13.4.1 Creating a Path Group

Press the “plus” button underneath Path Groups. Then drag the Paths from the Paths section into your Path Group.

Each path added to a path group will be drawn in a different color making it easy to figure out what the name is for each path.

If there are multiple paths in a group, selection works as follows:

1. Selecting the group displays all paths in the group making it easy to see the relationship between them. Any waypoint on any of the paths can be edited while the group is selected and it will only change the path containing the waypoint.
2. Selecting on a single path in the group will only display that path, making it easy to precisely see what all the waypoints are doing and preventing clutter in the interface if multiple paths cross over or are close to each other.

## 13.5 Importing a PathWeaver JSON

The `TrajectoryUtil` class can be used to import a PathWeaver JSON into robot code to follow it. This article will go over importing the trajectory. Please visit the [end-to-end trajectory tutorial](#) for more information on following the trajectory.

The `fromPathweaverJson` (Java) / `FromPathweaverJson` (C++) static methods in `TrajectoryUtil` can be used to create a trajectory from a JSON file stored on the roboRIO file system.

---

**Note:** PathWeaver places JSON files in `src/main/deploy/paths` which will automatically be placed on the roboRIO file system in `/home/lvuser/deploy/paths` and can be accessed using `getDeployDirectory` as shown below.

---

Java

```
String trajectoryJSON = "paths/YourPath.wpilib.json";
try {
    Path trajectoryPath = Filesystem.getDeployDirectory().toPath().
    ↪ resolve(trajectoryJSON);
    Trajectory trajectory = TrajectoryUtil.fromPathweaverJson(trajectoryPath);
} catch (IOException ex) {
    DriverStation.reportError("Unable to open trajectory: " + trajectoryJSON, ex.
    ↪ getStackTrace());
}
```

C++

```
#include <frc/Filesystem.h>
#include <frc/trajectory/TrajectoryUtil.h>
#include <wpi/Path.h>
#include <wpi/SmallString.h>

wpi::SmallString<64> deployDirectory;
frc::filesystem::GetDeployDirectory(deployDirectory);
wpi::sys::path::append(deployDirectory, "paths");
```

(continues on next page)

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```
wpi::sys::path::append(deployDirectory, "YourPath.wpilib.json");
frc::Trajectory trajectory = frc::TrajectoryUtil::FromPathweaverJson(deployDirectory);
```

## 13.6 Adding field images to PathWeaver

Here are instructions for adding your own field image using the 2019 game as an example.

Games are loaded from the ~/PathWeaver/Games on Linux and macOS or %USERPROFILE%/PathWeaver/Games directory on Windows. The files can be in either a game-specific subdirectory, or in a zip file in the Games directory. The ZIP file must follow the same layout as a game directory; the JSON file must be in the root of the ZIP file (cannot be in a subdirectory).

Download the example *FIRST* Destination Deep Space field definition [here](#). Other field definitions are available in the [PathWeaver GitHub repository](#).

### 13.6.1 File Layout

```
~/PathWeaver
  /Games
    /Custom Game
      custom-game.json
      field-image.png
    OtherGame.zip
```

### 13.6.2 JSON Format

```
{
  "game": "game name",
  "field-image": "relative/path/to/img.png",
  "field-corners": {
    "top-left": [x, y],
    "bottom-right": [x, y]
  },
  "field-size": [width, length],
  "field-unit": "unit name"
}
```

The path to the field image is relative to the JSON file. For simplicity, the image file should be in the same directory as the JSON file.

The field corners are the X and Y coordinates of the top-left and bottom-right pixels defining the rectangular boundary of the playable area in the field image. Non-rectangular playing areas are not supported.

The field size is the width and length of the playable area of the field in the provided units.

The field units are case-insensitive and can be in meters, cm, mm, inches, feet, yards, or miles. Singular, plural, and abbreviations are supported (e.g. "meter", "meters", and "m" are all valid for specifying meters)





## 14.1 RobotBuilder - Introduction

### 14.1.1 RobotBuilder Overview

RobotBuilder is an application designed to aid the robot development process. RobotBuilder can help you:

Generating boilerplate code. Organize your robot and figure out what its key sub-systems are. Check that you have enough channels for all of your sensors and actuators. Generate wiring diagrams. Easily modify your operator interface. More...

Creating a program with RobotBuilder is a very straight forward procedure by following a few steps that are the same for any robot. This lesson describes the steps that you can follow. You can find more details about each of these steps in subsequent sections of the document.

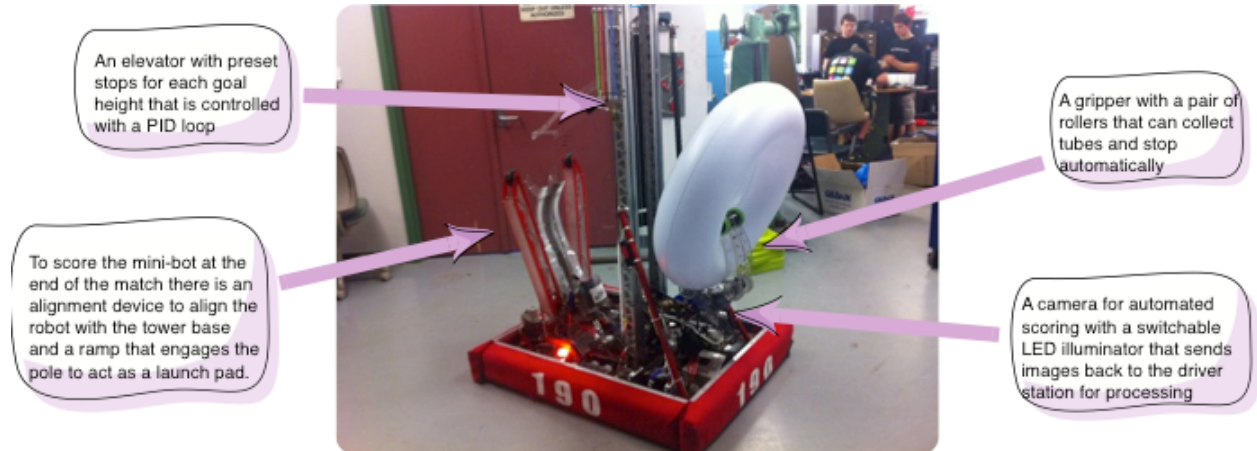
In addition to the text documentation provided here, a [series of videos about RobotBuilder and many other FRC Robotics Engineering topics](#) is also available.

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**Note:** RobotBuilder generates code using the old Command Framework. For more details on the old framework see [\[Old\] Command Based Programming](#).

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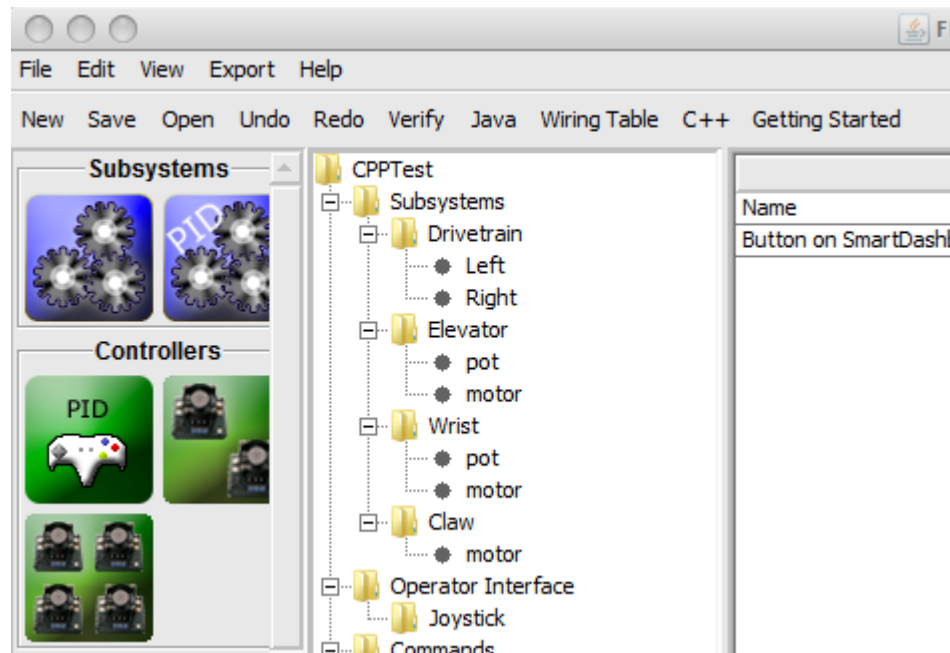
### Divide the Robot into Subsystems



Your robot is naturally made up of a number of smaller systems like the drive trains, arms, shooters, collectors, manipulators, wrist joints, etc. You should look at the design of your robot and break it up into smaller, separately operated subsystems. In this particular example there is an elevator, a minibot alignment device, a gripper, and a camera system. In addition one might include the drive base. Each of these parts of the robot are separately controlled and make good candidates for subsystems.

For more information see [Creating a Subsystem](#).

### Adding each Subsystem to the Project



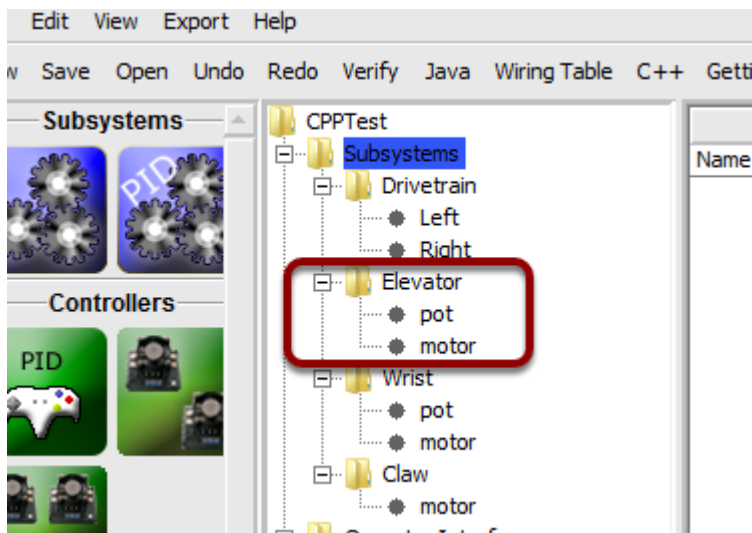
Each subsystem will be added to the "Subsystems" folder in the RobotBuilder and given a meaningful name. For each of the subsystems there are several attributes that get filled in to specify more information about the subsystems. In addition there are two types of subsystems that you might want to create:

1. PIDSubsystems - often it is desirable to control a subsystems operation with a PID controller. This is code in your program that makes the subsystem element, for example arm angle, more quickly to a desired position then stop when reaching it. PIDSubsystems have the PID Controller code built-in and are often more convenient then adding it yourself. PIDSubsystems have a sensor that determines when the device has reached the target position and an actuator (speed controller) that is driven to the setpoint.
2. Regular subsystem - these subsystems don't have an integrated PID controller and are used for subsystems without PID control for feedback or for subsystems requiring more complex control than can be handled with the default embedded PID controller.

As you look through more of this documentation the differences between the subsystem types will become more apparent.

For more information see [Creating a Subsystem](#) and [Writing Code for a Subsystem](#).

### Adding Components to each of the Subsystems



Each subsystem consists of a number of actuators, sensors and controllers that it uses to perform its operations. These sensors and actuators are added to the subsystem with which they are associated. Each of the sensors and actuators comes from the RobotBuilder palette and is dragged to the appropriate subsystem. For each, there are usually other properties that must be set such as port numbers and other parameters specific to the component.

In this example there is an Elevator subsystem that uses a motor and a potentiometer (motor and pot) that have been dragged to the Elevator subsystem.

### Adding Commands That Describe Subsystem Goals

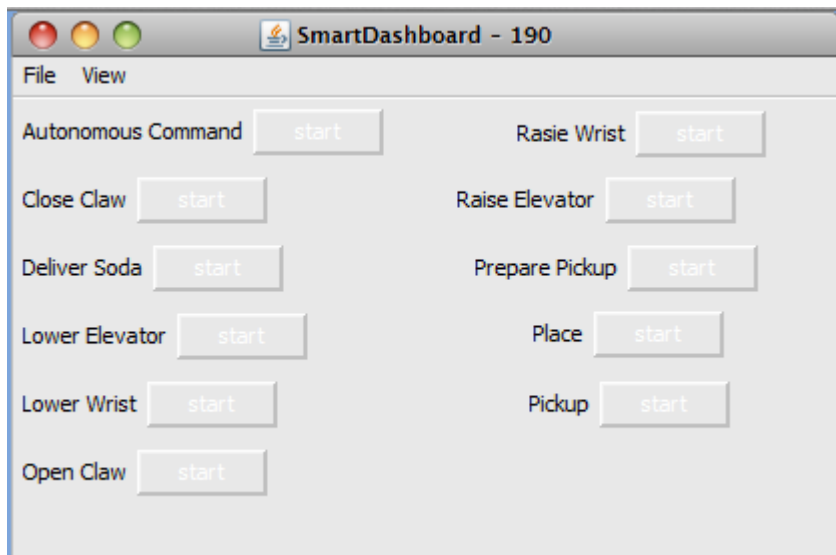
Commands are distinct goals that the robot will perform. These commands are added by dragging the command under the "Commands" folder. When creating a command, there are 3 primary choices (shown on the palette on the left of the picture):

- Normal commands - these are the most flexible command, you have to write all of the code to perform the desired actions necessary to accomplish the goal.

- Command groups - these commands are a combination of other commands running both in a sequential order and in parallel. Use these to build up more complicated actions after you have a number of basic commands implemented.
- Setpoint commands - setpoint commands move a PID Subsystem to a fixed setpoint, or the desired location.

For more information see [Creating a Command](#) and [Writing Command Code](#).

### Testing each Command

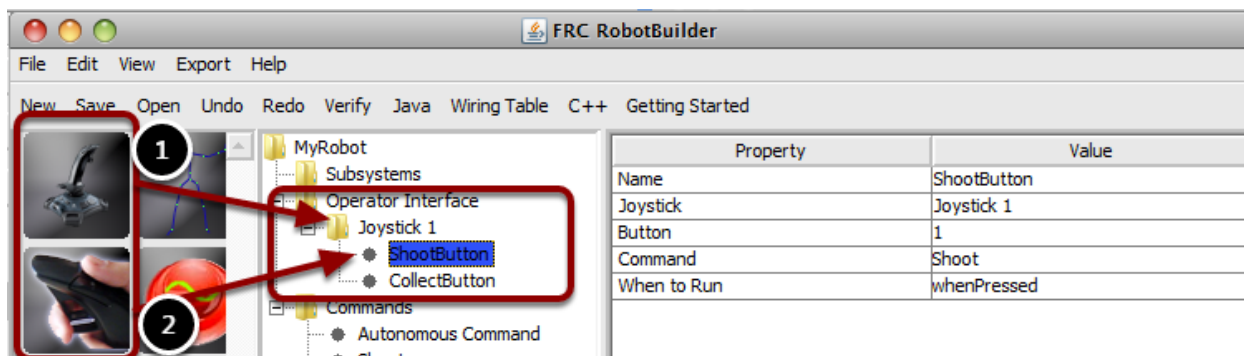


Each command can be run from the SmartDashboard. This is useful for testing commands before you add them to the operator interface or to a command group. As long as you leave the “Button on SmartDashboard” property checked, a button will be created on the SmartDashboard. When you press the start button, the command will run and you can check that it performs the desired action.

By creating buttons, each command can be tested individually. If all the commands work individually, you can be pretty sure that the robot will work as a whole.

For more information see [Testing with Smartdashboard](#).

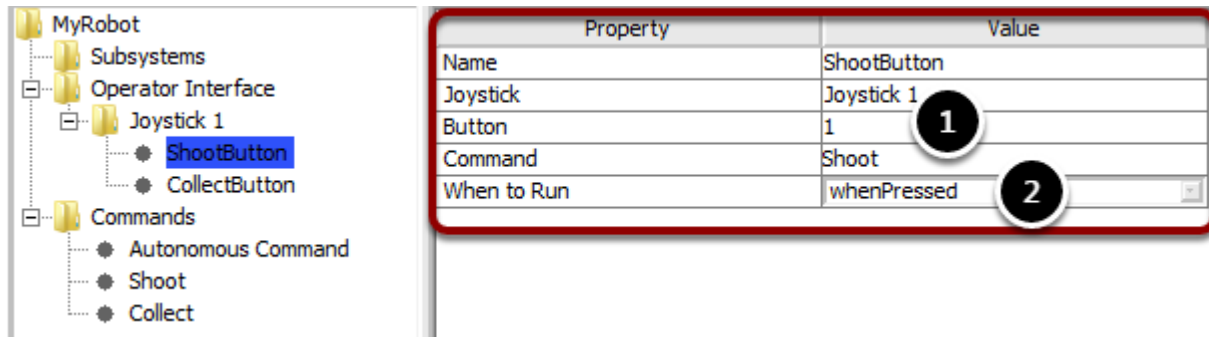
### Adding Operator Interface Components



The operator interface consists of joysticks, gamepads and other HID input devices. You can add operator interface components (joysticks, joystick buttons) to your program in RobotBuilder. It will automatically generate code that will initialize all of the components and allow them to be connected to commands.

The operator interface components are dragged from the palette to the “Operator Interface” folder in the RobotBuilder program. First (1) add Joysticks to the program then put buttons under the associated joysticks (2) and give them meaningful names, like ShootButton.

### Connecting the Commands to the Operator Interface

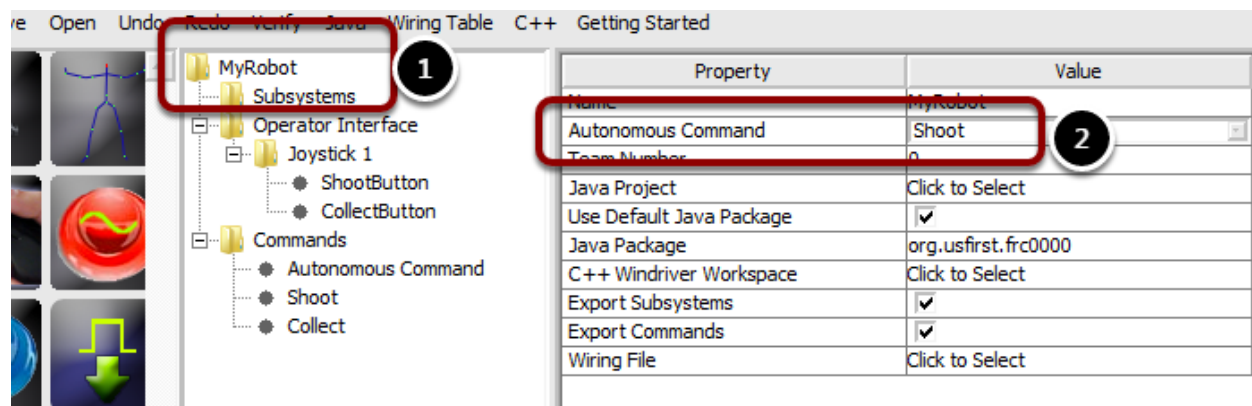


Commands can be associated with buttons so that when a button is pressed the command is scheduled. This should, for the most part, handle most of the tele-operated part of your robot program.

This is simply done by (1) adding the command to the JoystickButton object in the RobotBuilder program, then (2) setting the condition in which the command is scheduled.

For more information see [Connecting the Operator Interface to a Command](#).

### Developing Autonomous Commands

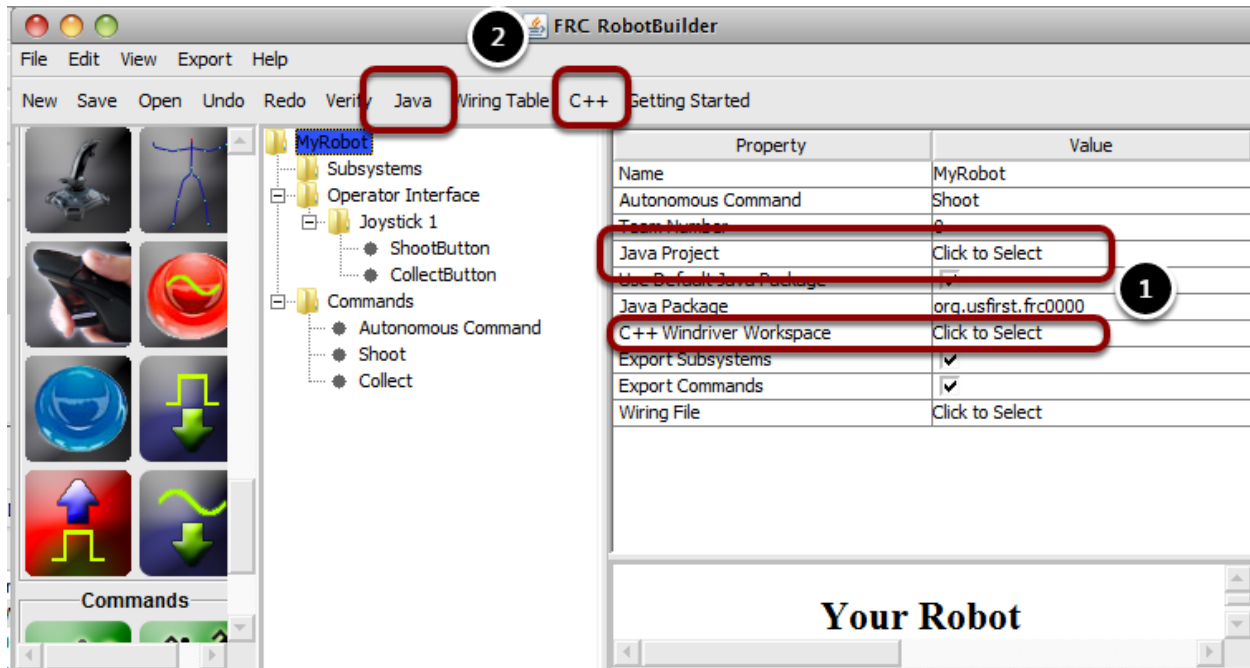


Commands make it simple to develop autonomous programs. You simply specify which command should run when the robot enters the autonomous period and it will automatically be scheduled. If you have tested commands as discussed above, this should simply be a matter of choosing which command should run.

Select the robot at the root of the RobotBuilder project, then edit the Autonomous Command property to choose the command to run. It's that simple!

For more information see [Setting the Default Autonomous Command](#).

### Generating Code



At any point in the process outlined above you can have RobotBuilder generate a C++ or Java program that will represent the project you have created. This is done by specifying the location of the project in the project properties (1), then clicking the appropriate toolbar button to generate the code.

For more information see [Generating RobotBuilder Code](#).

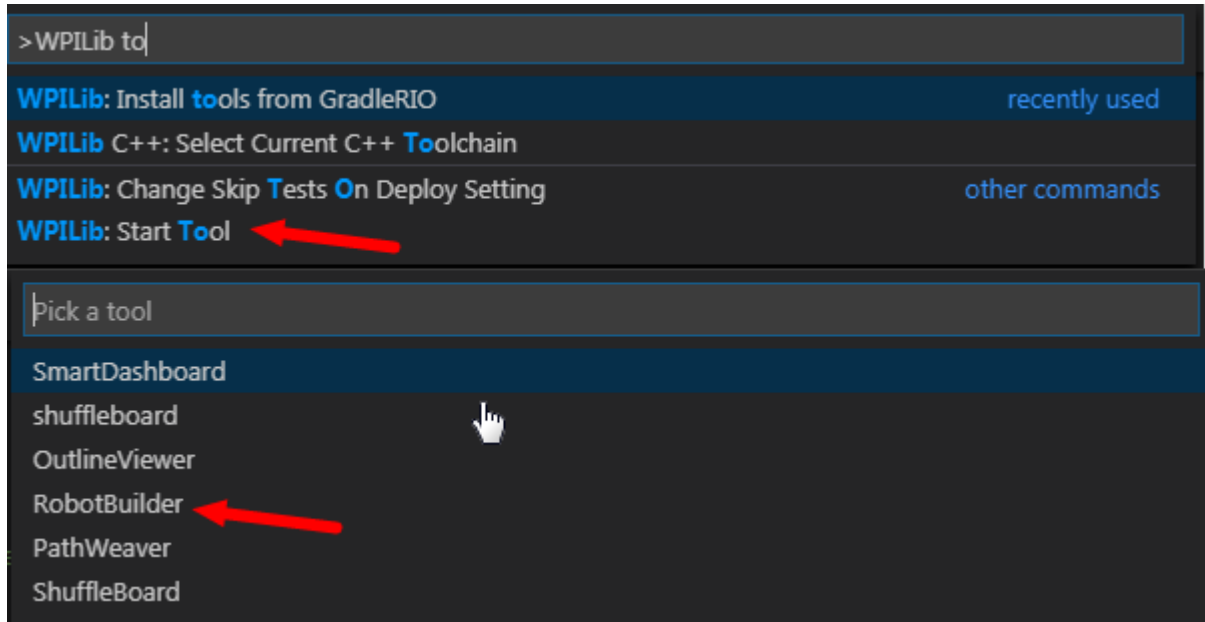
### 14.1.2 Starting RobotBuilder

**Note:** RobotBuilder is a Java program and as such should be able to run on any platform that is supported by Java. We have been running RobotBuilder on macOS, Windows, and various versions of Linux successfully.

### Getting RobotBuilder

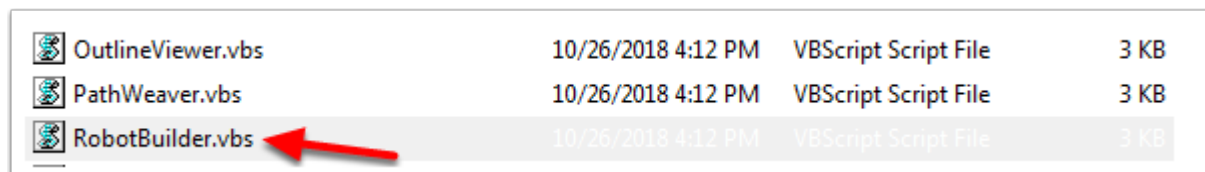
RobotBuilder is downloaded as part of the WPILib Offline Installer. For more information, see the [Windows/macOS/Linux installation guides](#)

## Option 1 - Starting from Visual Studio Code



Press **Ctrl + Shift + P** and type WPILib or click the WPILib logo in the top right to launch the WPILib Command Palette and select **Start Tool**, then select **Robot Builder**.

## Option 2 - Running from the Script

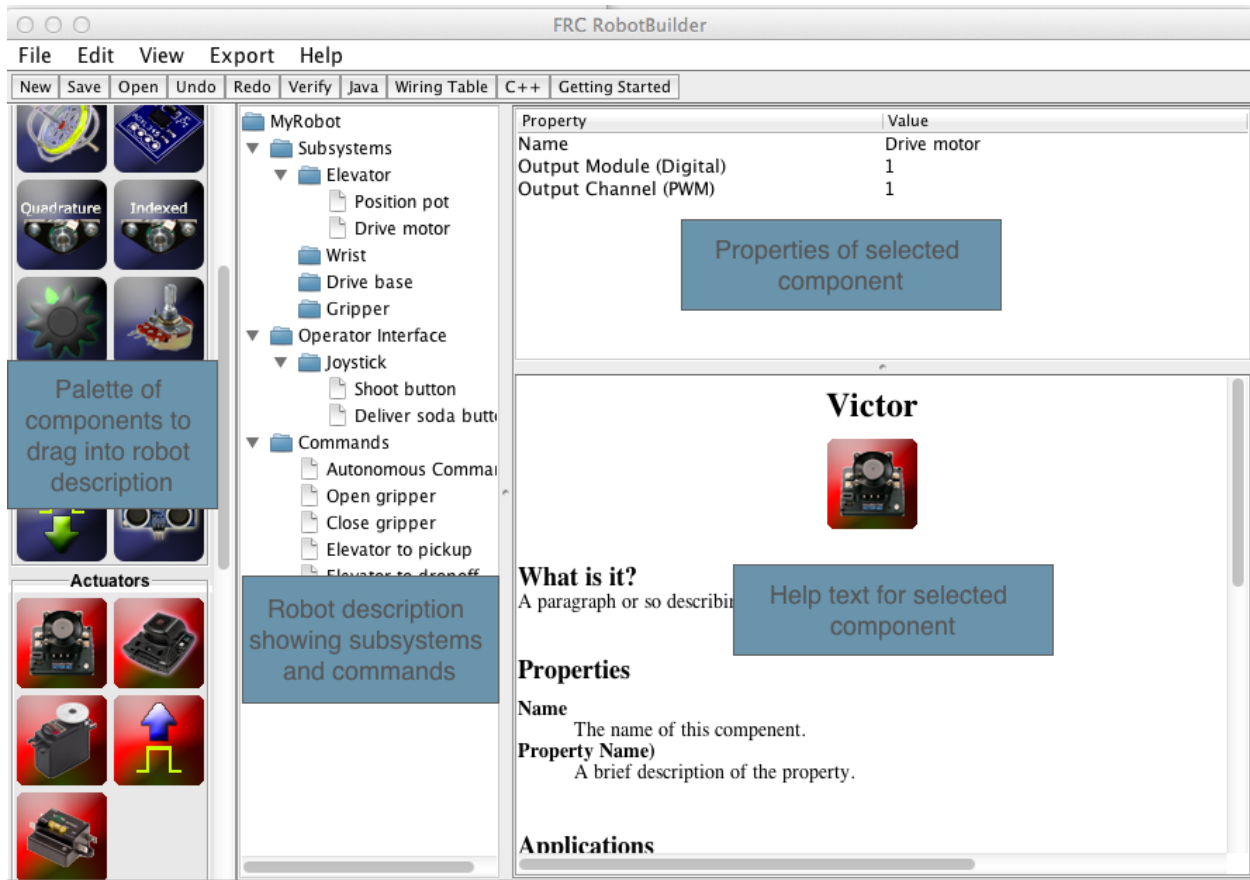


The install process installs the tools to ~/wpilib/YYYY/tools (where YYYY is the year and ~ is C:\Users\Public on Windows).

Inside this folder you will find .vbs (Windows) and .py (macOS/Linux) files that you can use to launch each tool. These scripts help launch the tools using the correct JDK and are what you should use to launch the tools.

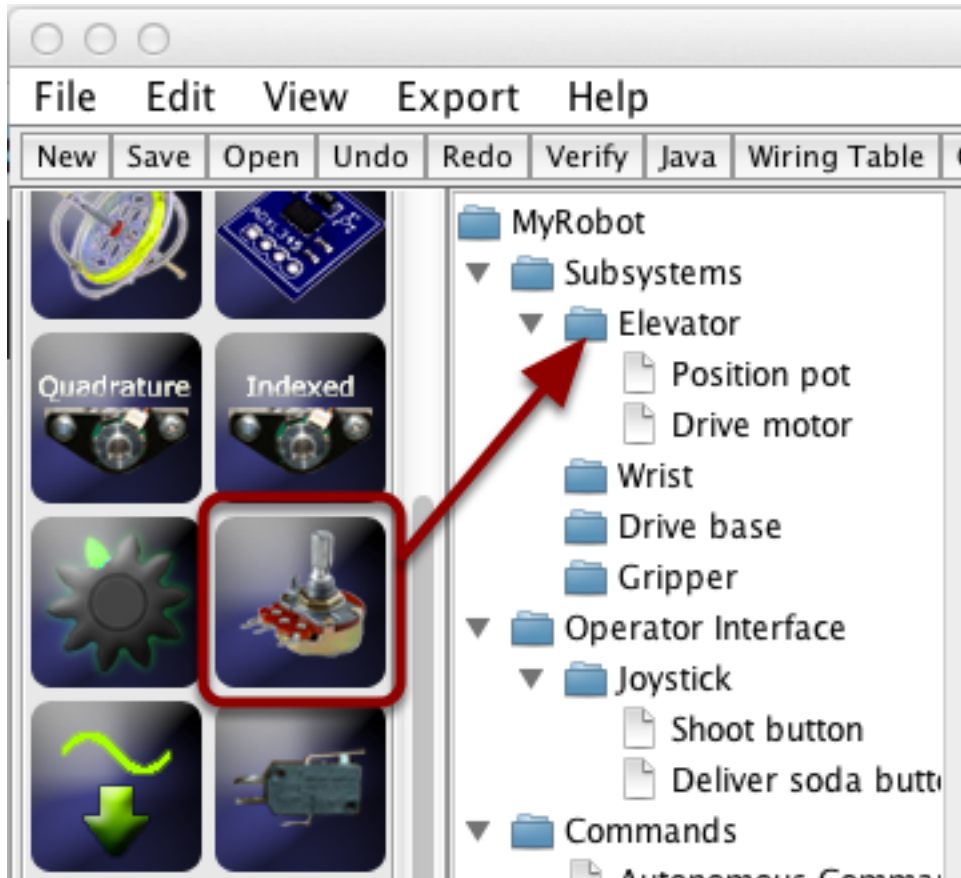


### 14.1.3 RobotBuilder User Interface



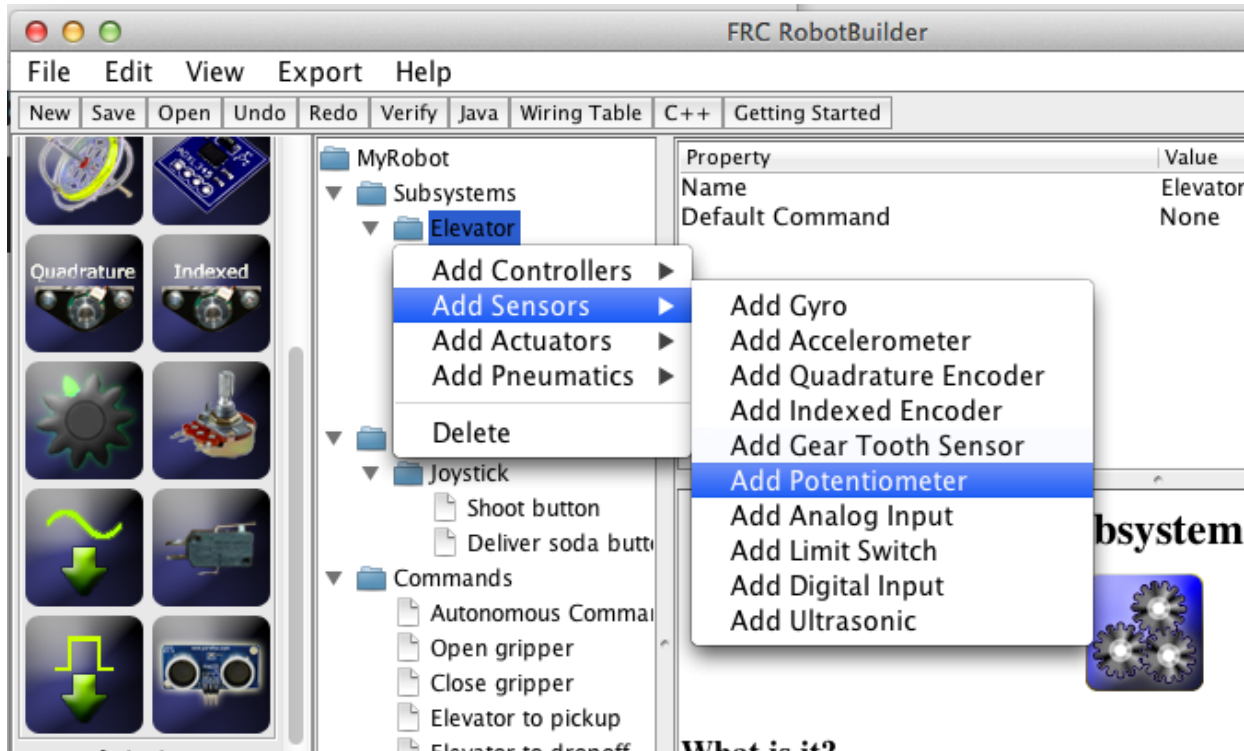
RobotBuilder has a user interface designed for rapid development of robot programs. Almost all operations are performed by drag-and-drop or selecting options from drop-down lists.

### Dragging Items from the Palette to the Robot Description



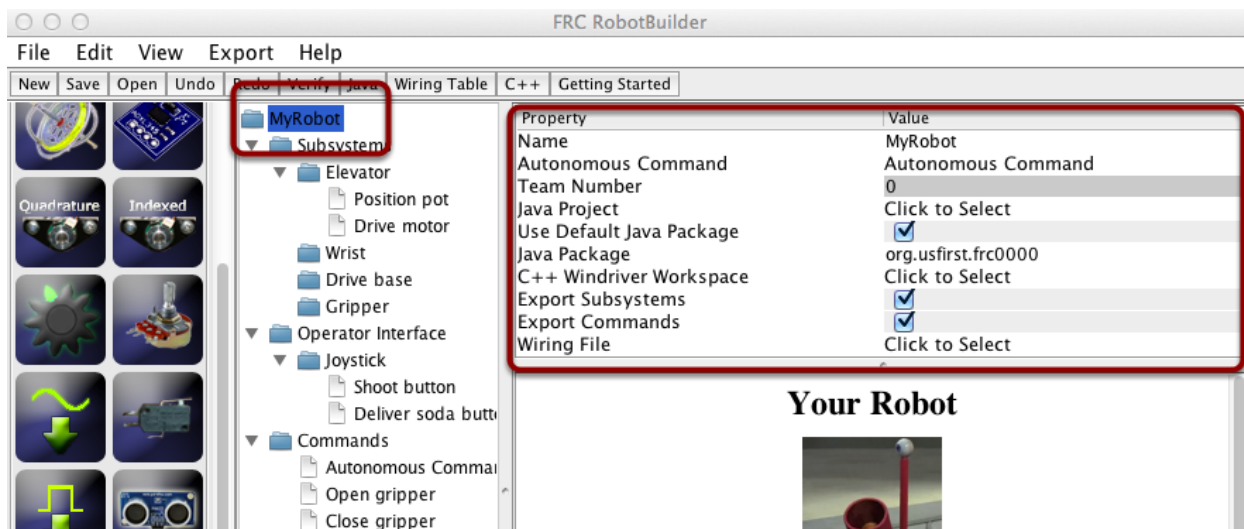
You can drag items from the palette to the robot description by starting the drag on the palette item and ending on the container where you would like the item to be located. In this example, dropping a potentiometer to the Elevator subsystem.

## Adding Components using the Right-Click Context Menu



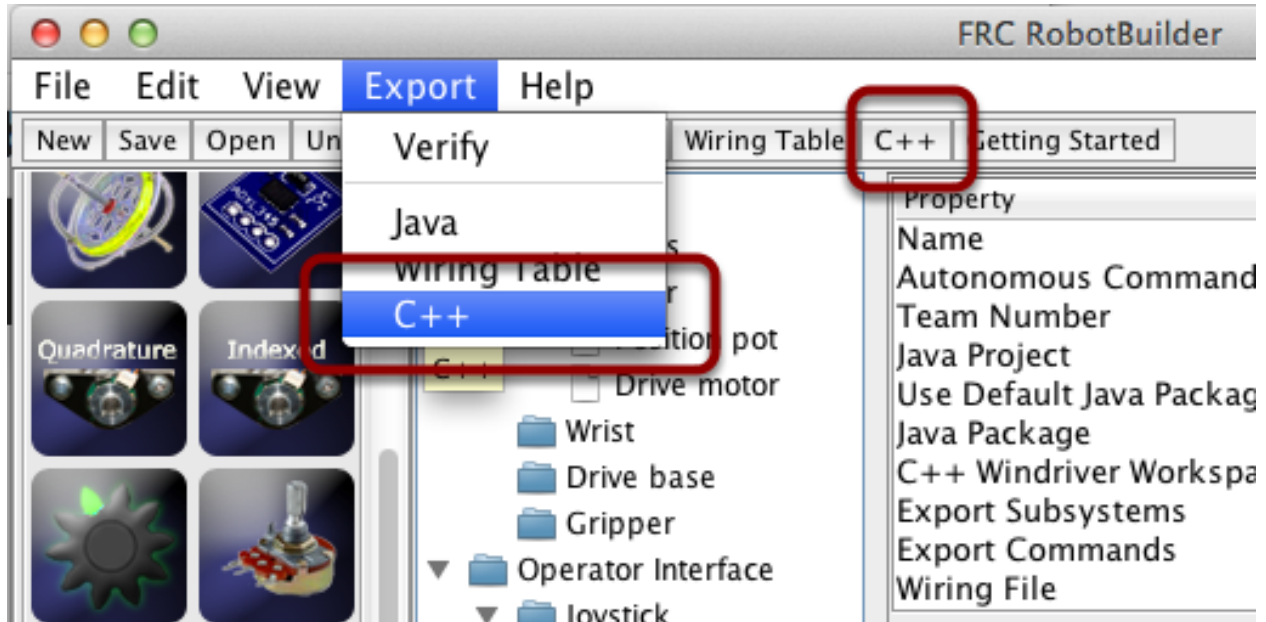
A shortcut method of adding items to the robot description is to right-click on the container object (Elevator) and select the item that should be added (Potentiometer). This is identical to using drag and drop but might be easier for some people.

## Editing Properties of Robot Description Items



The properties for a selected item will appear in the properties viewer. The properties can be edited by selecting the value in the right hand column.

## Using the Menu System



Operations for RobotBuilder can either be selected through the menu system or the equivalent item (if it is available) from the toolbar.

### 14.1.4 Setting up the Robot Project

The RobotBuilder program has some default properties that need to be set up so the generated program and other generated files work properly. This setup information is stored in the properties for robot description (the first line).

#### Robot Project Properties

The properties that describe the robot are:

**Name** - The name of the robot project that is created

**Autonomous Command** - the command that will run by default when the program is placed in autonomous mode

**Team Number** - the team number is used for creating the package names

**Use Default Java Package** - If checked RobotBuilder will use the default package (org.usfirst.frc####). Otherwise you can specify a custom package name to be used.

**Java Package** - The name of the generated Java package used when generating the project code

**Export Directory** - The folder that the java project is generated into when Export to Java is selected

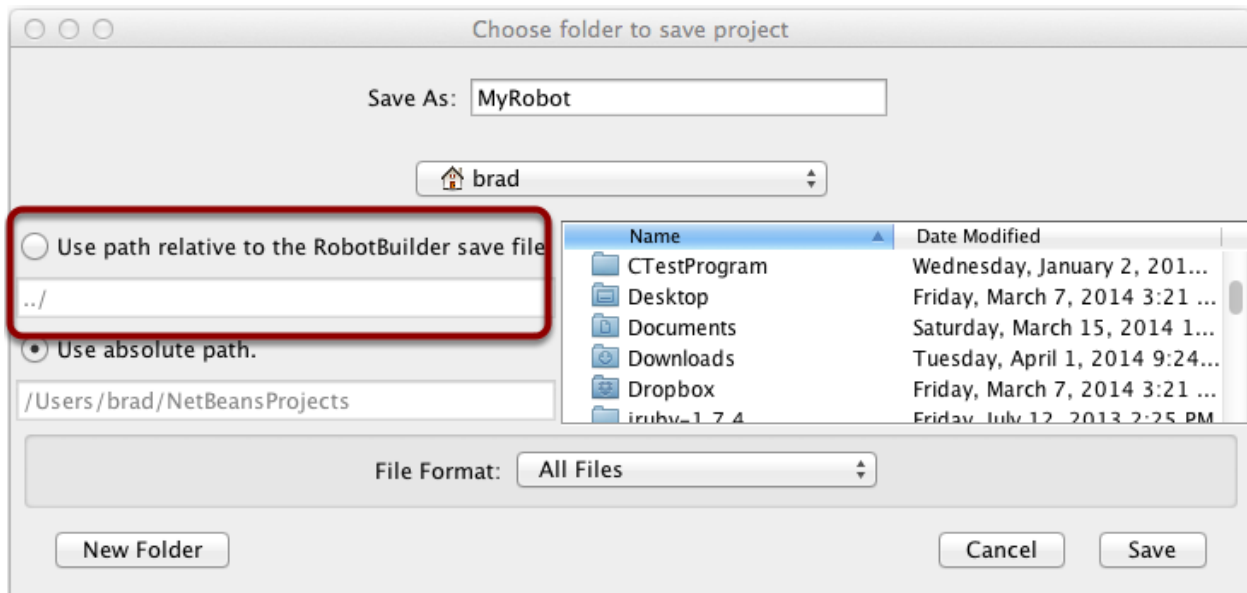
**Export Subsystems** - Checked if RobotBuilder should export the Subsystem classes from your project

**Export Commands** - Checked if RobotBuilder should export the Command classes from your project

**Simulation World File** - The World File that is used for simulation of your robot project

**Wiring File** - the location of the html file that contains the wiring diagram for your robot

### Using Source Control with the RobotBuilder Project

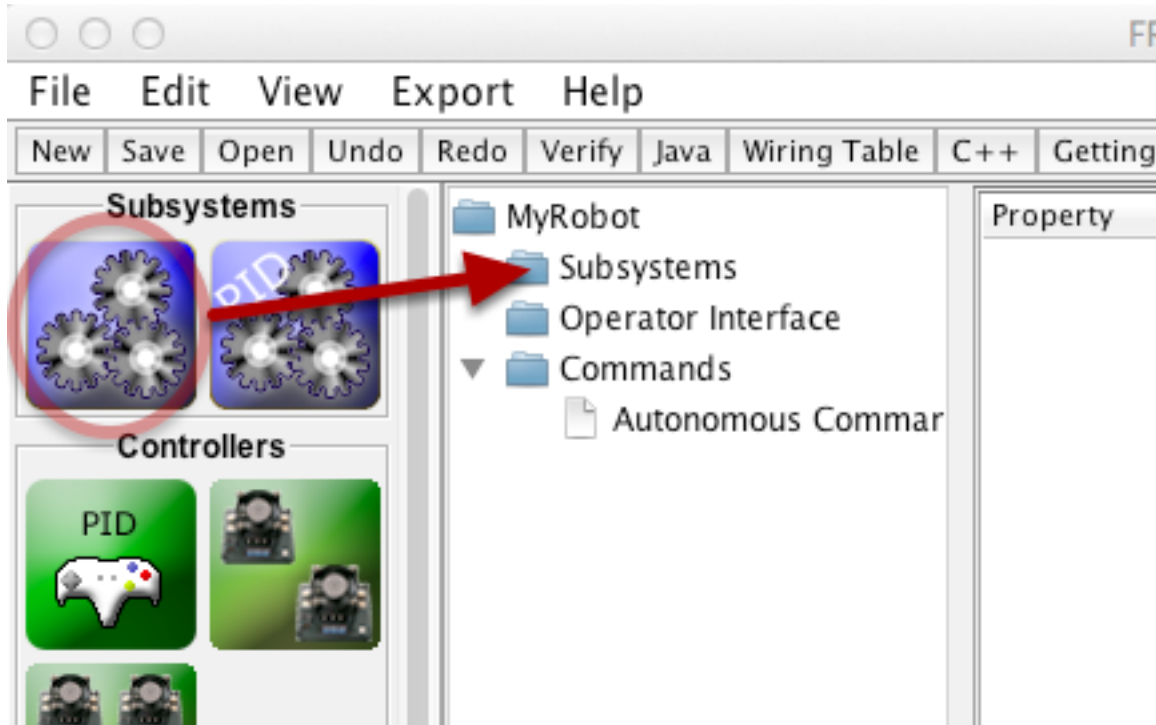


When using source control the project will typically be used on a number of computers and the path to the project directory might be different from one users computer to another. If the RobotBuilder project file is stored using an absolute path, it will typically contain the user name and won't be usable across multiple computers. To make this work, select "relative path" and specify the path as a directory offset from the project files. In the above example, the project file is stored in the folder just above the project files in the file hierarchy. In this case, the user name is not part of the path and it will be portable across all of your computers.

### 14.1.5 Creating a Subsystem

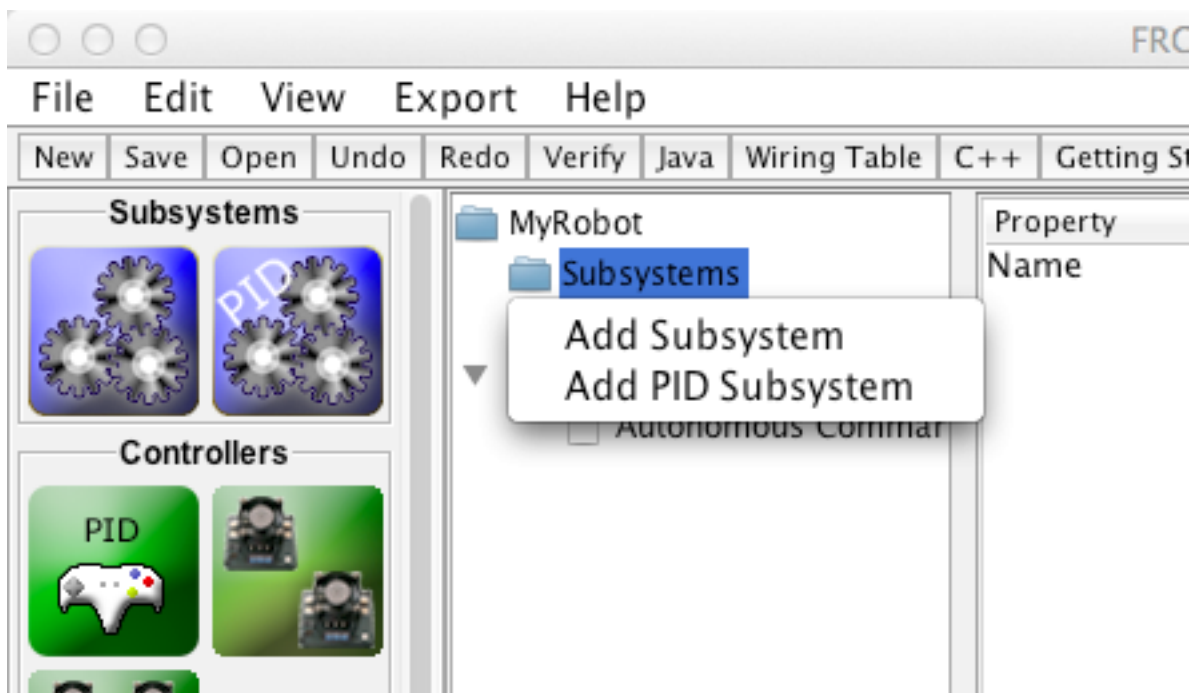
Subsystems are classes that encapsulate (or contain) all the data and code that make a subsystem on your robot operate. The first step in creating a robot program with the RobotBuilder is to identify and create all the subsystems on the robot. Examples of subsystems are grippers, ball collectors, the drive base, elevators, arms, etc. Each subsystem contains all the sensors and actuators that are used to make it work. For example, an elevator might have a Jaguar speed controller and a potentiometer to provide feedback of the robot position.

### Creating a Subsystem using the Palette



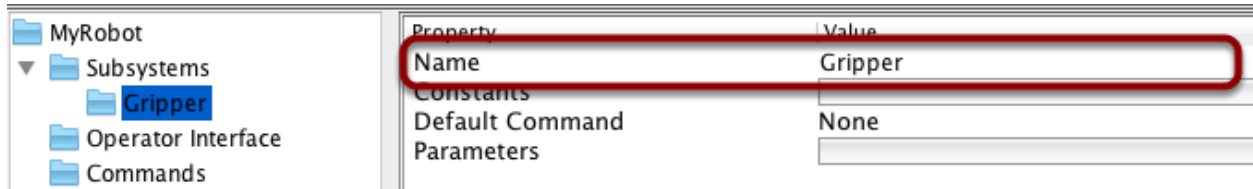
Drag the subsystem icon from the palette to the Subsystems folder in the robot description to create a subsystem class.

### Creating a Subsystem using the Context Menu



Right-click on the Subsystem folder in the robot description to add a subsystem to that folder.

### Name the Subsystem



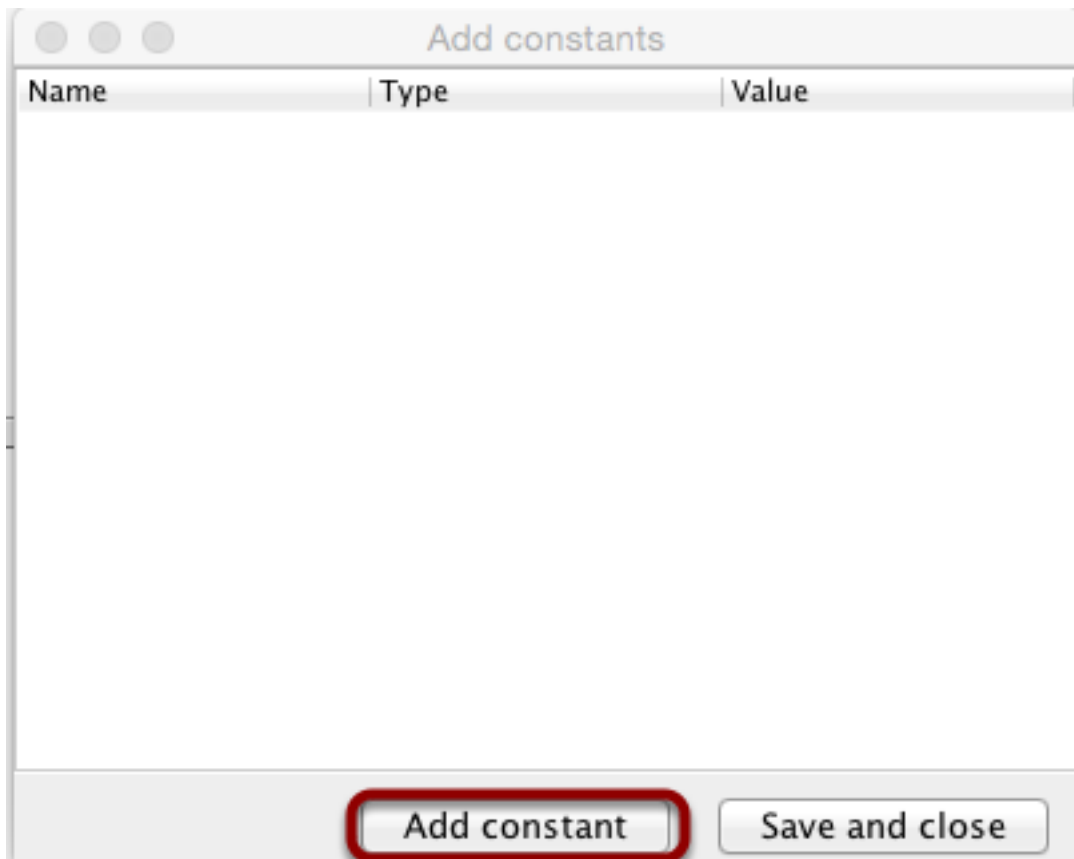
After creating the subsystem by either dragging or using the context menu as described above, simply type the name you would like to give the subsystem. The name can be multiple words separated by spaces, RobotBuilder will concatenate the words to make a proper Java or C++ class name for you.

### Adding Constants (2016 Only)



Constants are very useful to reduce the amount of magic numbers in your code. In subsystems, they can be used to keep track of certain values, such as sensor values for specific heights of an elevator, or the speed at which to drive the robot.

By default, there will be no constants in a subsystem. Press the button next to “Constants” to open a dialog to create some.

**Creating Constants (2016 Only)**

The constants table will be empty at first. Press "Add constant" to add one.



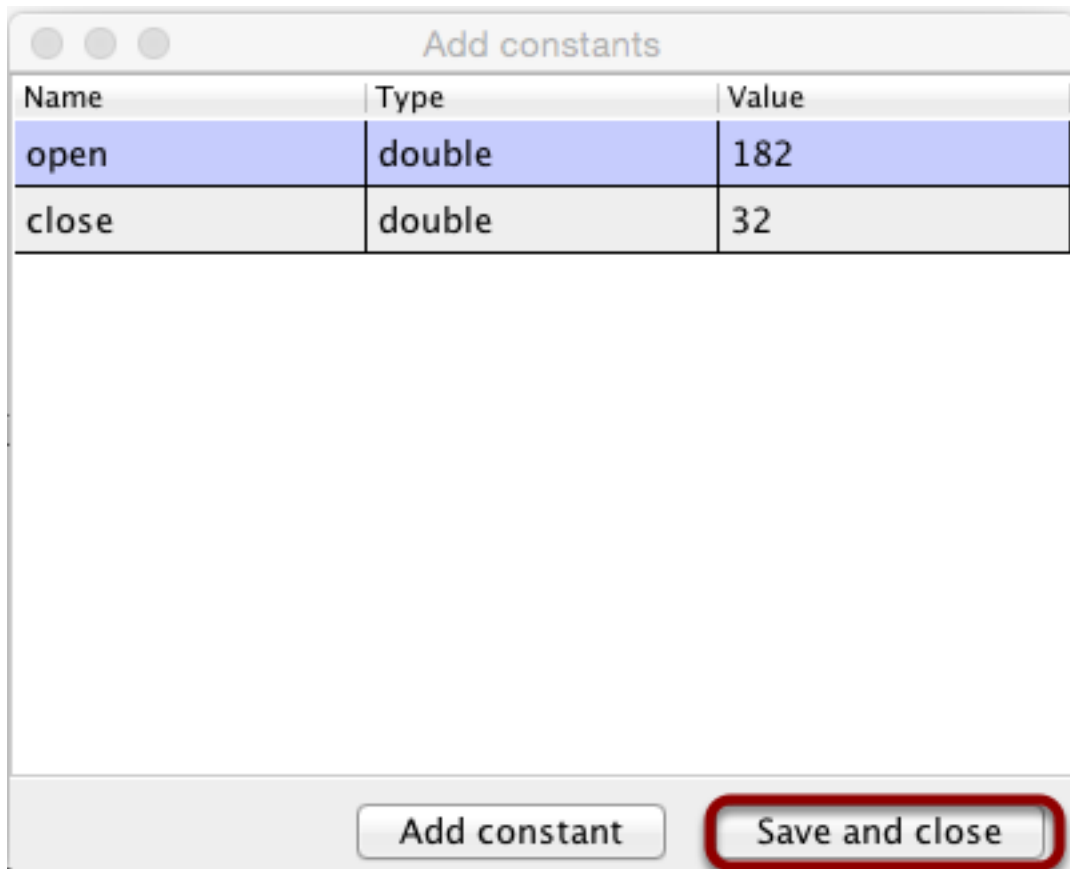
**Add Constants (2016 Only)**

Name	Type	Value
[change me]	String	

Add constant Save and close

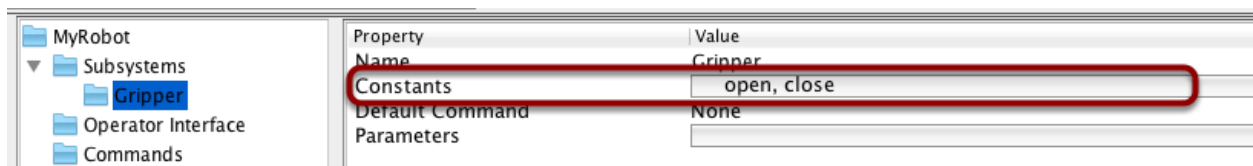
1. The name of the constant. Change this to something descriptive. In this example of a gripper, some good constants might be “open” and “close”.
2. The type of the constant. This will most likely be a double, but you can choose from one of: String, double, int, long int, boolean, or byte.
3. The value of the constant.

## Saving Constants (2016 Only)



After adding constants and setting their values, just press “Save and close” to save the constants and close the dialog. If you don’t want to save, press the exit button on the top of the window.

## After Saving (2016 Only)



After saving constants, the names will appear in the “Constants” button in the subsystem properties.

## Dragging Actuators/Sensors into the Subsystem

There are two steps to adding components to a subsystem:

1. Drag actuators or sensors from the palette into the subsystem as required.
2. Give the actuator or sensor a meaningful name

3. Edit the properties such as module numbers and channel numbers for each item in the subsystem.

RobotBuilder will automatically use incrementing channel numbers for each module on the robot. If you haven't yet wired the robot you can just let RobotBuilder assign unique channel numbers for each sensor or actuator and wire the robot according to the generating wiring table.

This just creates the subsystem in RobotBuilder, and will subsequently generate skeleton code for the subsystem. To make it actually operate your robot please refer to [Writing Code for a Subsystem](#).

### 14.1.6 Creating a Command

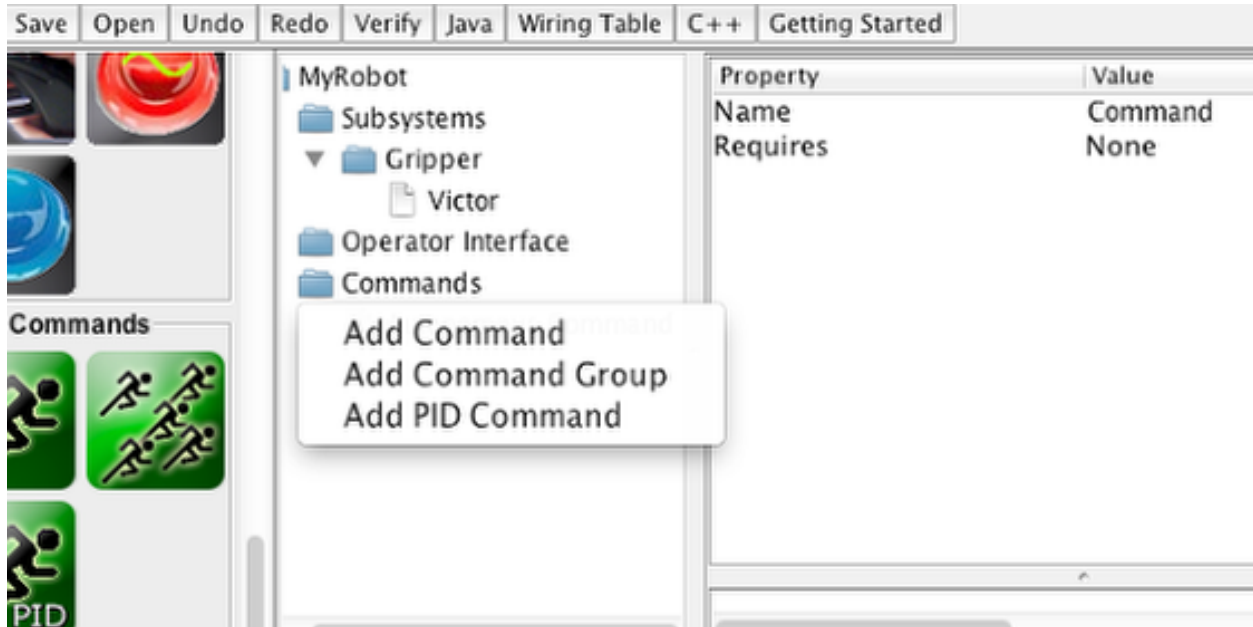
Commands are classes you create that provide behaviors or actions for your subsystems. The subsystem class should set the operation of the subsystem, like MoveElevator to start the elevator moving, or ElevatorToSetPoint to set the elevator's PID setpoint. The commands initiate the subsystem operation and keep track of when it is finished.

#### Drag the Command to the Commands Folder



Simple commands can be dragged from the palette to the robot description. The command will be created under the Commands folder.

## Creating Commands using the Context Menu



You can also create commands using the right-click context menu on the Command folder in the robot description.

## Configuring the Command

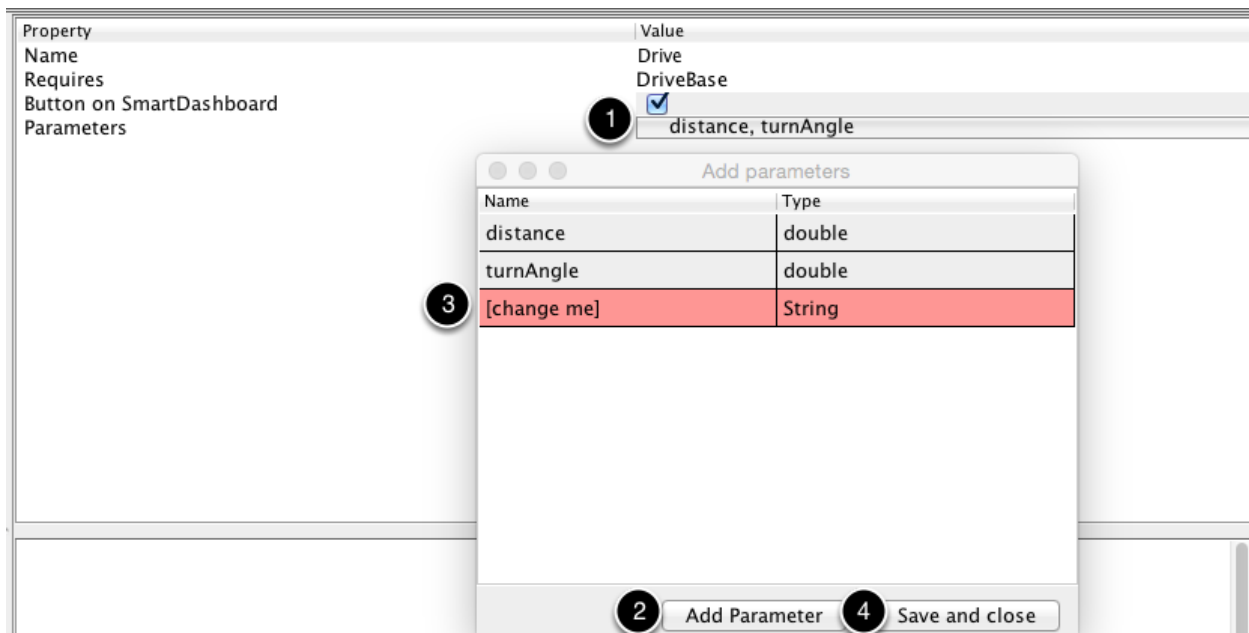
Property	Value
Name	Move Gripper
Requires	Gripper
Button on SmartDashboard	<input checked="" type="checkbox"/>
Parameters	position
Parameter presets	open, close

1. Name the command with something meaningful that describes what the command will do. Commands should be named as if they were in code, although there can be spaces between words.
2. Set the subsystem that is used by this command. When this command is scheduled, it will automatically stop any command currently running that also requires this command. If a command to open the gripper is currently running (requiring the gripper subsystem) and the close gripper command is scheduled, it will immediately stop opening and start closing.
3. Tell RobotBuilder if it should create buttons on the SmartDashboard for the command. A button will be created for each parameter preset.
4. Set the parameters this command takes. A single command with parameters can do the same thing as two or more commands that do not take parameters. For example, "Drive Forward", "Drive Backward", and "Drive Distance" commands can be consolidated into a single command that takes values for direction and distance.

5. Set presets for parameters. These can be used elsewhere in RobotBuilder when using the command, such as binding it to a joystick button or setting the default command for a subsystem.

Setpoint commands come with a single parameter ('setpoint', of type double); parameters cannot be added, edited, or deleted for setpoint commands.

### Adding and Editing Parameters

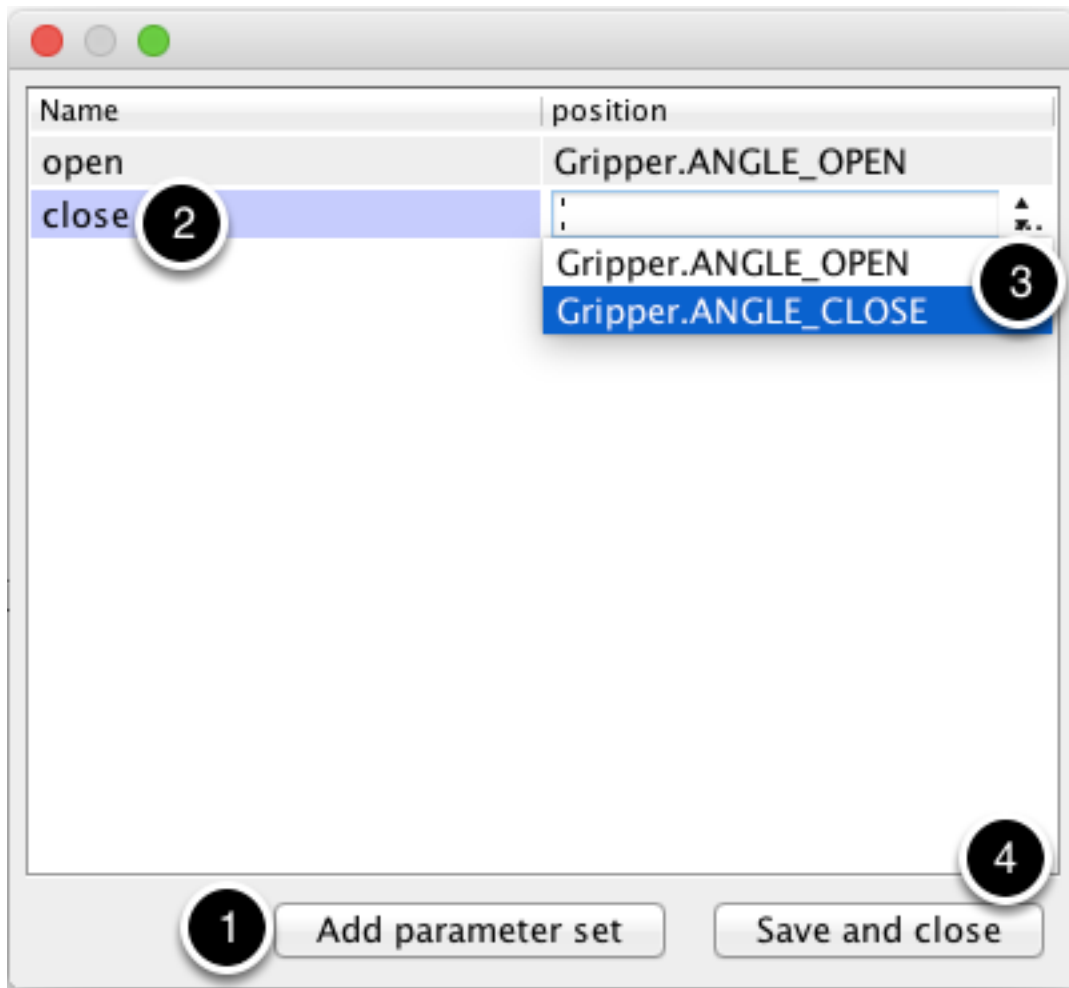


To add or edit parameters:

1. Click the button in the "Value" column of the property table
2. Press the "Add Parameter" button to add a parameter
3. A parameter that has just been added. The name defaults to "[change me]" and the type defaults to String. The default name is invalid, so you will have to change it before exporting. Double click the "Name" cell to start changing the name; double click the "Type" cell to select the type.
4. Save and close button will save all changes and close the window.

Rows can be reordered simply by dragging, and can be deleted by selecting them and pressing delete or backspace.

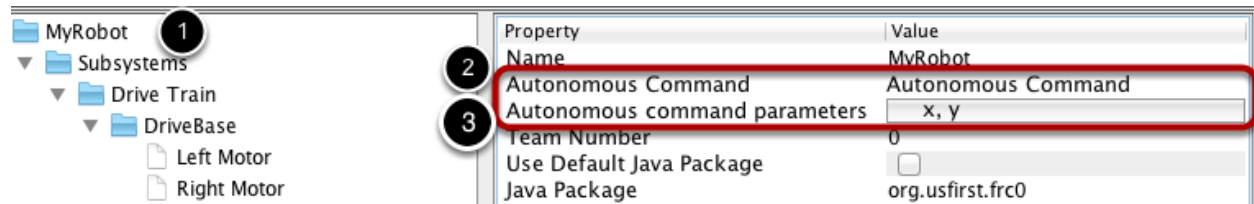
## Adding and Editing Parameter Presets



1. Click “Add parameter set” to add a new preset.
2. Change the name of the preset to something descriptive. The presets in this example are for opening and closing the gripper subsystem.
3. Change the value of the parameter(s) for the preset. You can either type a value in (e.g. “3.14”) or select from constants defined in the subsystem that the command requires. Note that the type of the constant has to be the same type as the parameter - you can’t have an int-type constant be passed to a double-type parameter, for example
4. Click “Save and close” to save changes and exit the dialog; to exit without saving, press the exit button in the top bar of the window.

### 14.1.7 Setting the Default Autonomous Command

Since a command is simply one or more actions (behaviors) that the robot performs, it makes sense to describe the autonomous operation of a robot as a command. While it could be a single command, it is more likely going to be a command group (a group of commands that happen together).



To designate a command that runs when the robot starts during the autonomous period of a competition:

Select the robot in the robot program description. Fill in the Autonomous command field with the command that should run when the robot is placed in autonomous mode. This is a drop-down field and will give you the option to select any command that has been defined. Set the parameters the command takes, if any.

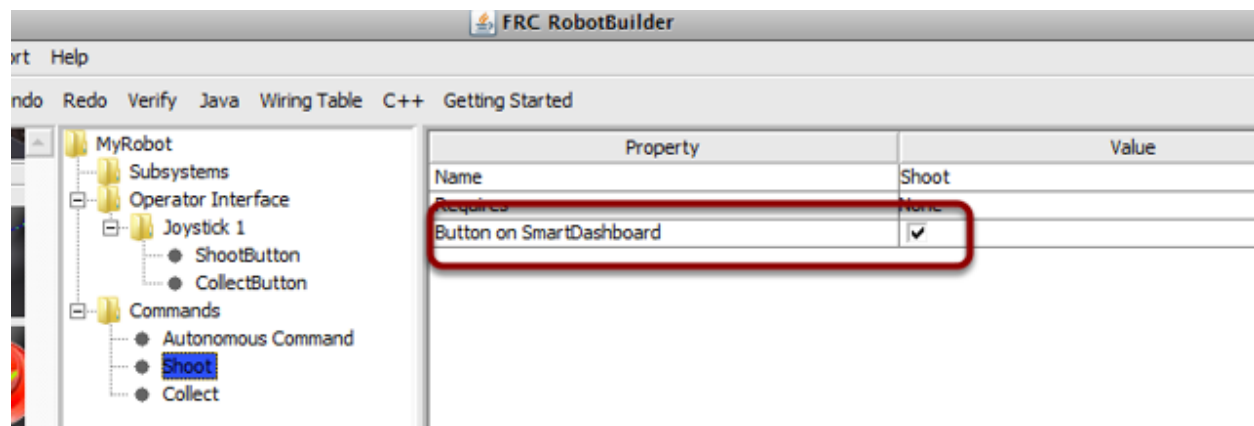
When the robot is put into autonomous mode, the defined Autonomous command will be scheduled.

### 14.1.8 Using SmartDashboard to Test a Command

Commands are easily tested by adding a button to the SmartDashboard to trigger the command. In this way, no integration with the rest of the robot program is necessary and commands can easily be independently tested. This is the easiest way to verify commands since with a single line of code in your program, a button can be created on the SmartDashboard that will run the command. These buttons can then be left in place to verify subsystems and command operations in the future.

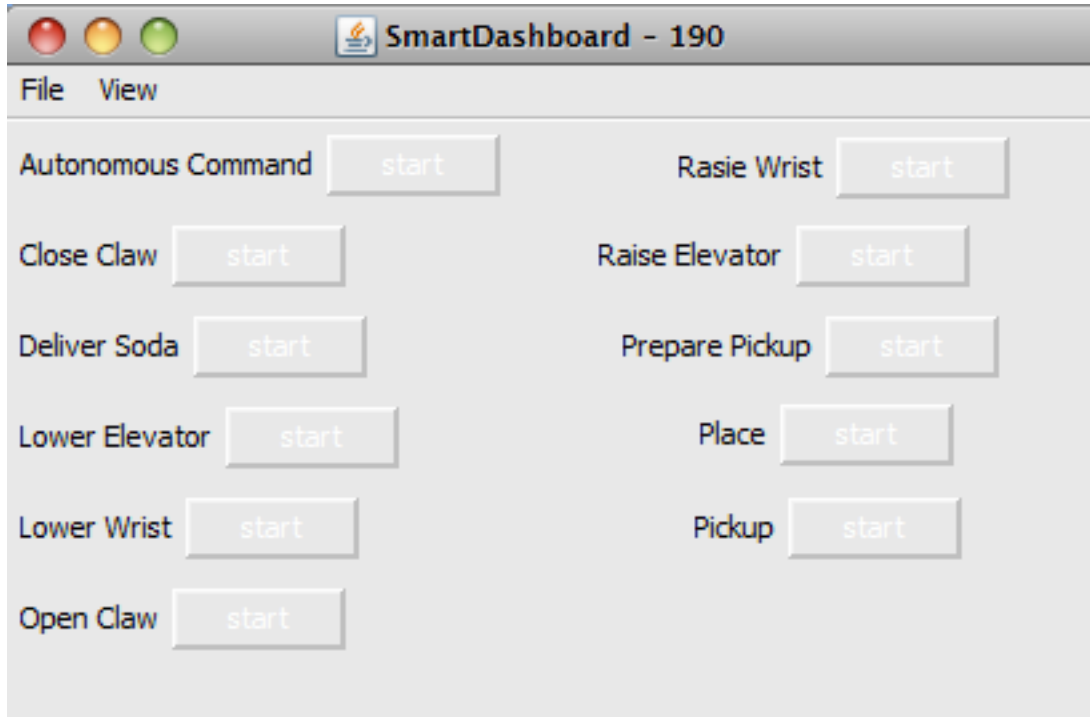
This has the added benefit of accommodating multiple programmers, each writing commands. As the code is checked into the main robot project, the commands can be individually tested.

#### Creating the Button on SmartDashboard



The button is created on the SmartDashboard by putting an instance of the command from the robot program to the dashboard. This is such a common operation that it has been added to RobotBuilder as a checkbox. When writing your commands, be sure that the box is checked, and buttons will be automatically generated for you.

## Operating the Buttons



The buttons will be generated automatically and will appear on the dashboard screen. You can put the SmartDashboard into edit mode, and the buttons can then be rearranged along with other values that are being generated. In this example there are a number of commands, each with an associated button for testing. The button is labeled “Start” and pressing it will run the command. As soon as it is pressed, the label changes to “Cancel” and pressing it will interrupt the command causing the `Interrupted()` method to be called.

## Adding Commands Manually

Java

```
SmartDashboard.putData("Autonomous Command", new AutonomousCommand());
SmartDashboard.putData("Open Claw", new OpenClaw());
SmartDashboard.putData("Close Claw", new CloseClaw());
```

C++

```
SmartDashboard::PutData("Autonomous Command", new AutonomousCommand());
SmartDashboard::PutData("Open Claw", new OpenClaw());
SmartDashboard::PutData("Close Claw", new CloseClaw());
```

Commands can be added to the SmartDashboard manually by writing the code yourself. This is done by passing instances of the command to the `PutData` method along with the name that should be associated with the button on the SmartDashboard. These instances are scheduled whenever the button is pressed. The result is exactly the same as RobotBuilder generated code, although clicking the checkbox in RobotBuilder is much easier than writing all the code by hand.

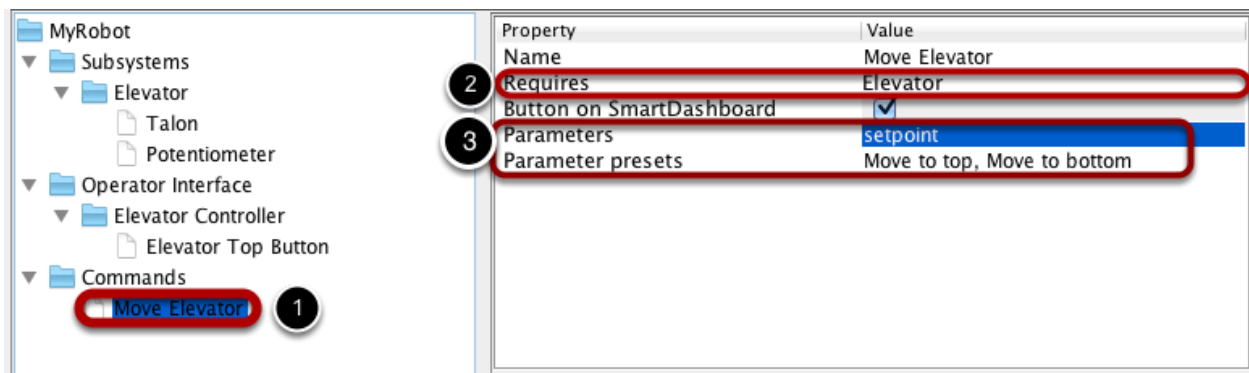


### 14.1.9 Connecting the Operator Interface to a Command

Commands handle the behaviors for your robot. The command starts a subsystem to some operating mode like raising and elevator and continues running until it reaches some setpoint or timeout. The command then handles waiting for the subsystem to finish. That way commands can run in sequence to develop more complex behaviors.

RobotBuilder will also generate code to schedule a command to run whenever a button on your operator interface is pressed. You can also write code to run a command when a particular trigger condition has happened.

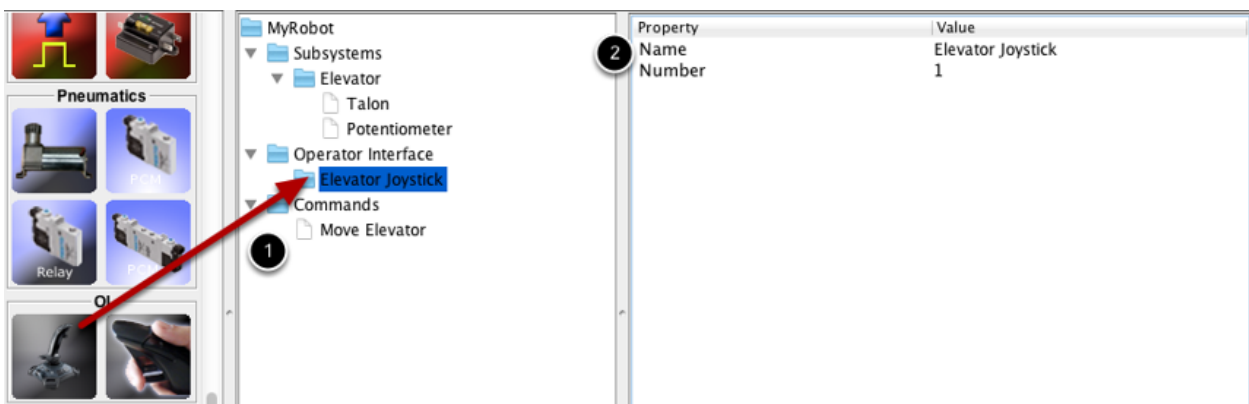
#### Run a Command with a Button Press



In this example we want to schedule the “Move Elevator” command to run whenever joystick button 1 is pressed.

1. The command to run is called “Move Elevator” and its function is to move the elevator on the robot to the top position
2. Notice that the command requires the Elevator subsystem. This will ensure that this command starts running even if there was another operation happening at the same time that used the elevator. In this case the previous command would be interrupted.
3. Parameters make it possible for one command to do multiple things; presets let you define values you pass to the command and reuse them

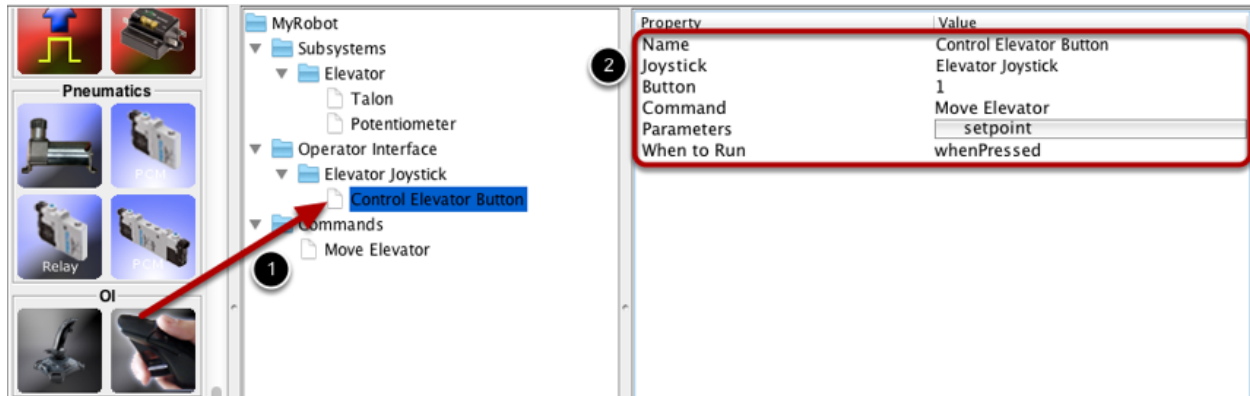
#### Adding the Joystick to the Robot Program



Add the joystick to the robot program

1. Drag the joystick to the Operator Interface folder in the robot program
2. Name the joystick so that it reflects the use of the joystick and set the USB port number

### Linking a Button to the “Move Elevator” Command



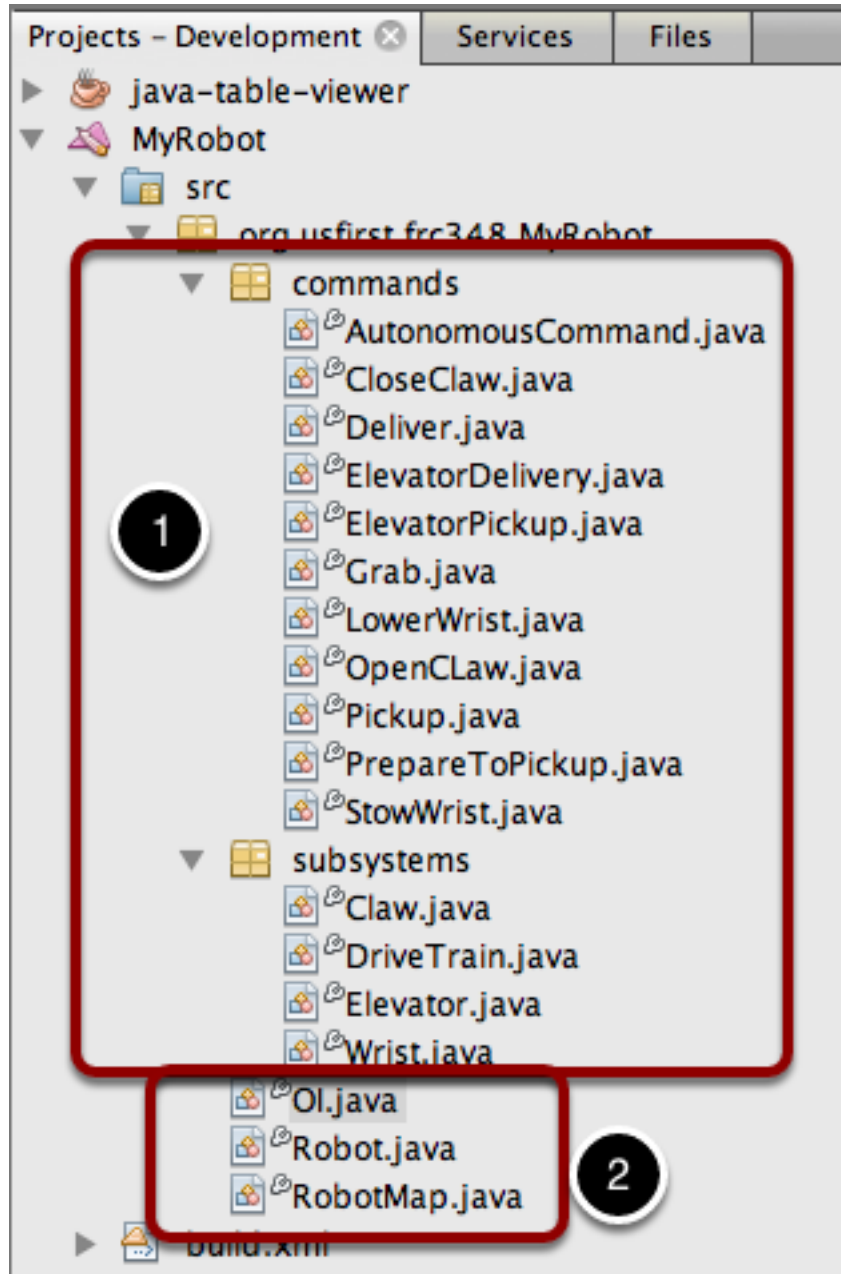
Add the button that should be pressed to the program

1. Drag the joystick button to the Joystick (Driver gamepad) so that it's under the joystick
2. Set the properties for the button: the button number, the command to run when the button is pressed, parameters the command takes, and the “When to run” property to “whenPressed” to indicate that the command should run whenever the joystick button is pressed.

**Note:** Joystick buttons must be dragged to (under) a Joystick. You must have a joystick in the Operator Interface folder before adding buttons.

### 14.1.10 RobotBuilder Created Code

## The Layout of a RobotBuilder Generated Project



A RobotBuilder generated project consists of a package (in Java) or a folder (in C++) for Commands and another for Subsystems (1). Each command or subsystem object is stored under those containers (2). At the top level of the project you'll find the robot main program (Robot.java), the Operator Interface file (OI.java) and the RobotMap that contains the code to create all the subsystem components that were added to the robot description.

## Autogenerated Code

Java

```
// BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
requires(Robot.claw);
// END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
setTimeout(1);
```

C++

```
// BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
Requires(Robot::claw);
// END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
SetTimeout(1);
```

When the robot description is modified and code is re-exported RobotBuilder is designed to not modify any changes you made to the file, thus preserving your code. This makes RobotBuilder a full-lifecycle tool. To know what code is OK to be modified by RobotBuilder, it generates sections that will potentially have to be rewritten delimited with some special comments. These comments are shown in the example above. Don't add any code within these comment blocks, it will be rewritten next time the project is exported from RobotBuilder.

If code inside one of these blocks must be modified, the comments can be removed, but this will prevent further updates from happening later. In the above example, if the //BEGIN and //END comments were removed, then later another required subsystem was added in RobotBuilder, it would not be generated on that next export.

## Main Robot Program

Java

```
12 public class Robot extends TimedRobot { // (1)
13
14     Command autonomousCommand;
15
16     public static OI oi;
17     // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
18     public static Claw claw; // (2)
19     public static Wrist wrist;
20     public static DriveBase driveBase;
21     public static Elevator elevator;
22     // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
23
24     public void robotInit() { // (3)
25         RobotMap.init();
26         // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=CONSTRUCTORS
27         claw = new Claw();
28         wrist = new Wrist();
29         driveBase = new DriveBase();
30         elevator = new Elevator();
31         // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=CONSTRUCTORS
32
33         oi = new OI();
34
35         // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=AUTONOMOUS
36         autonomousCommand = new AutonomousCommand();
37         // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=AUTONOMOUS
38     }
```

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```

39
40     public void disableInit() {}
41
42     public void disabledPeriodic() {
43         Scheduler.getInstance().run();
44     }
45
46     public void autonomousInit() {    // (4)
47         // Schedule the autonomous command (example)
48         if (autonomousCommand != null) autonomousCommand.start();
49     }
50
51     public void autonomousPeriodic() {    // (5)
52         Scheduler.getInstance().run();
53     }
54
55     public void teleopInit() {
56         if (autonomousCommand != null) autonomousCommand.cancel();
57     }
58
59     public void teleopPeriodic() {
60         Scheduler.getInstance().run()
61     }
62
63     public void testPeriodic() {    // (6)
64         LiveWindow.run()
65     }
66 }

```

This is the main program generated by RobotBuilder. There are a number of parts to this program (highlighted sections):

1. This class extends TimedRobot. TimedRobot will call your autonomousPeriodic() and teleopPeriodic() methods every 20ms.
2. Each of the subsystems is declared here. These are public static variables so that they can be referenced from throughout your robot program by writing Robot.<subsystem-name>.method(), for example Robot.elevator.setSetpoint(4).
3. The subsystems are instantiated in the robotInit() method that is called after the constructor runs for this class. It is important to be create the subsystems after the constructor to avoid recursive loops. Also instance of the OI() class (for your operator interface) and the autonomous command are created here.
4. In the autonomousInit() method which is called every 20ms, make one scheduling pass. That will call the isFinished() and execute() methods of every command that is currently scheduled.
5. If there is an autonomous command provided in RobotBuilder robot properties, it is scheduled at the start of autonomous in the autonomousInit() method and canceled at the end of the autonomous period in teleopInit().
6. In the teleopPeriodic method which is called every 20ms, make one scheduling pass.

## RobotMap - Generation of Actuator and Sensor Objects

Java

```

public class RobotMap {
    public static Jaguar DRIVE_TRAIN_LEFT_MOTOR;    // (1)
    public static Jaguar DRIVE_TRAIN_RIGHT_MOTOR;
    public static RobotDrive DRIVE_TRAIN_ROBOT_DRIVE;
    public static Ultrasonic DRIVE_TRAIN_ULTRASONIC;
    public static Victor ELEVATOR_MOTOR;
    public static AnalogChannel ELEVATOR_POTENTIOMETER;
    public static AnalogChannel WRIST_POTENTIOMETER;
    public static Victor WRIST_MOTOR;
    public static Victor CLAW_MOTOR;

    public static void init() {
        DRIVE_TRAIN_LEFT_MOTOR = new Jaguar(1, 2);
        LiveWindow.addActuator("Drive Train ", "Left Motor", DRIVE_TRAIN_LEFT_MOTOR);

        DRIVE_TRAIN_RIGHT_MOTOR = new Jaguar(1, 2);    // (2)
        LiveWindow.addActuator("Drive Train ", "Right Motor", DRIVE_TRAIN_RIGHT_
↪MOTOR);

        DRIVE_TRAIN_ROBOT_DRIVE = new RobotDrive(DRIVE_TRAIN_LEFT_MOTOR, DRIVE_TRAIN_
↪RIGHT_MOTOR);

        DRIVE_TRAIN_ROBOT_DRIVE.setSafetyEnabled(false);    // (3)
        DRIVE_TRAIN_ROBOT_DRIVE.setExpiration(0.1);
        DRIVE_TRAIN_ROBOT_DRIVE.setSensitivity(0.5);
        DRIVE_TRAIN_ROBOT_DRIVE.setMaxOutput(1.0);

        DRIVE_TRAIN_ULTRASONIC = new Ultrasonic(1, 3);

        ELEVATOR_MOTOR = new Victor(1, 6);
        LiveWindow.addActuator("Elevator ", "Motor", ELEVATOR_MOTOR);

        ELEVATOR_POTENTIOMETER = new AnalogChannel(1, 4);
        LiveWindow.addSensor("Elevator ", "Potentiometer", ELEVATOR_POTENTIOMETER)

        WRIST_POTENTIOMETER = new AnalogChannel(1, 2);
        LiveWindow.addSensor("Wrist ", "Potentiometer", WRIST_POTENTIOMETER)

        WRIST_MOTOR = new Victor(1, 5);
        LiveWindow.addActuator("Wrist ", "Motor", WRIST_MOTOR);

        CLAW_MOTOR = new Victor(1, 7);
        LiveWindow.addActuator("Claw ", "Motor", CLAW_MOTOR);
    }
}

```

The RobotMap is a mapping from the ports sensors and actuators are wired into to a variable name. This provides flexibility changing wiring, makes checking the wiring easier and significantly reduces the number of magic numbers floating around. All the definitions of sensors and motors from the robot description are generated here.

Notice that each sensor and actuator is added to the LiveWindow class (3) so that the can be automatically displayed when the SmartDashboard is set to LiveWindow mode. Also any properties for the particular sensor or actuator is set here to reflect the settings made in the robot description. (1)

Each of the references for the objects are declared and instantiated here (2, 3), but they are copied into every subsystem to make it easy and clean to write code that uses them.

## OI Class - The Operator Interface

Java

```
public class OI {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    public JoystickButton joystickButton;
    public JoystickButton joystickButton2;
    public Joystick gamePad;
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS

    public OI() {
        // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=CONSTRUCTORS
        gamePad = new Joystick(1);    // (1)

        joystickButton = new JoystickButton(gamePad, 1);    // (2)
        joystickButton.whenPressed(new OpenClaw());
        joystickButton2 = new JoystickButton(gamePad, 2);
        joystickButton2.whenPressed(new CloseClaw());

        // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=CONSTRUCTORS
    }
}
```

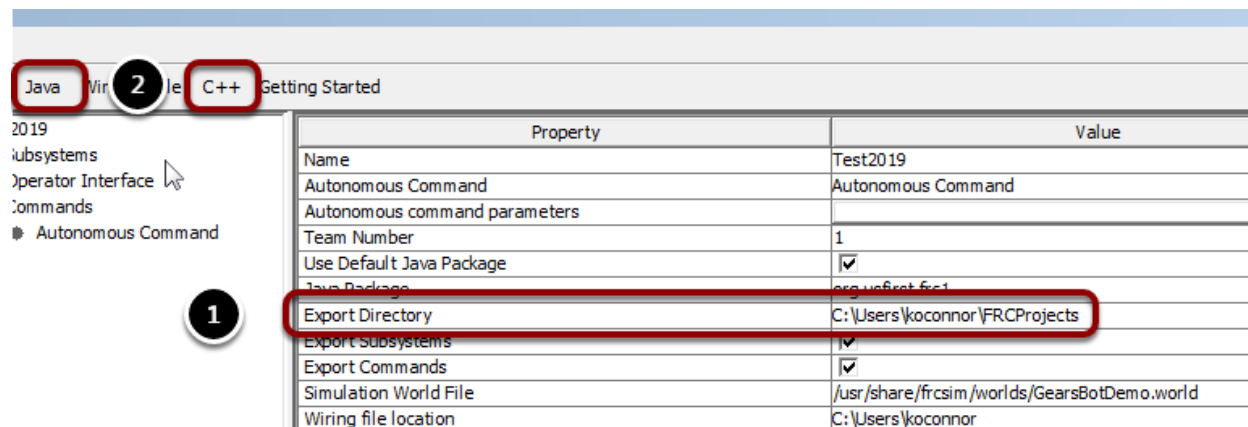
The code for all the operator interface components is generated here (1). In addition the code to link the OI buttons to commands that should run is also generated here (2).

## 14.2 RobotBuilder - Writing the Code

### 14.2.1 Generating Code for a Project

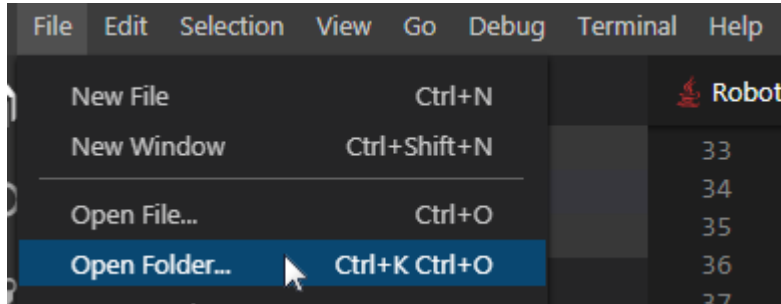
**Note:** After you've set up your robot framework in RobotBuilder, you'll need to export the code and load it into Visual Studio Code. This article describes the process for doing so.

#### Generate the Code for the Project



Verify that the Export Directory points to where you want (1) and then click Java or C++ (2) to generate a VS Code project or update code.

## Open the Project in Visual Studio Code

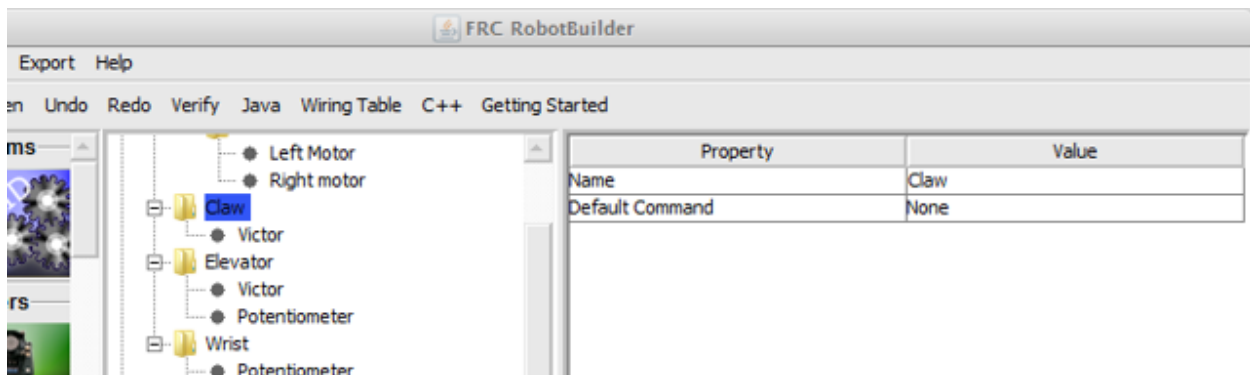


Open VS Code and select **File -> Open Folder**. Navigate to your Export location and click **Select Folder**.

## 14.2.2 Writing the Code for a Subsystem

Adding code to create an actual working subsystem is very straightforward. For simple subsystems that don't use feedback it turns out to be extremely simple. In this section we will look at an example of a Claw subsystem that operates the motor for some amount of time to open or close a claw on the robot arm.

### RobotBuilder Representation of the Claw Subsystem



The claw at the end of a robot arm is a subsystem operated by a single Victor speed controller. There are three things we want the claw to do, start opening, start closing, and stop moving. This is the responsibility of the subsystem. The timing for opening and closing will be handled by a command later in this tutorial.

### Adding Subsystem Capabilities

Java



```
public class Claw extends Subsystem {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    Victor victor = RobotMap.CLAW_VICTOR;
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS

    public void initDefaultCommand() {
        // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DEFAULT_COMMAND
        // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DEFAULT_COMMAND
    }

    public void openClaw() {
        victor.set(1.0);
    }

    public void closeClaw() {
        victor.set(-1.0);
    }

    public void stop() {
        victor.set(0.0);
    }
}
```

C++

```
Claw::Claw() :
    Subsystem("Claw") {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    victor = RobotMap::CLAW_VICTOR;
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
}

void Claw::InitDefaultCommand() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DEFAULT_COMMAND
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DEFAULT_COMMAND
}

void Claw::Open() {
    victor->Set(1);
}

void Claw::Close() {
    victor->Set(-1);
}

void Claw::Stop() {
    victor->Set(0);
}
```

Add methods to the claw.java that will open, close, and stop the claw from moving. Those will be used by commands that actually operate the claw. The comments have been removed from this file to make it easier to see the changes for this document. Notice that a member variable called “victor” is created by RobotBuilder so it can be used throughout the subsystem. Each of your dragged-in palette items will have a member variable with the name given in RobotBuilder.

## Adding the Method Declarations to the Header File (C++ Only)

C++

```
#pragma once

#include "frc/commands/Subsystem.h"
#include "frc/Victor.h"

class Claw: public Subsystem {
private:
public:
    //BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    Victor* victor;

    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS

    Claw();
    void InitDefaultCommand();

    void Open();
    void Close();
    void Stop();
};
```

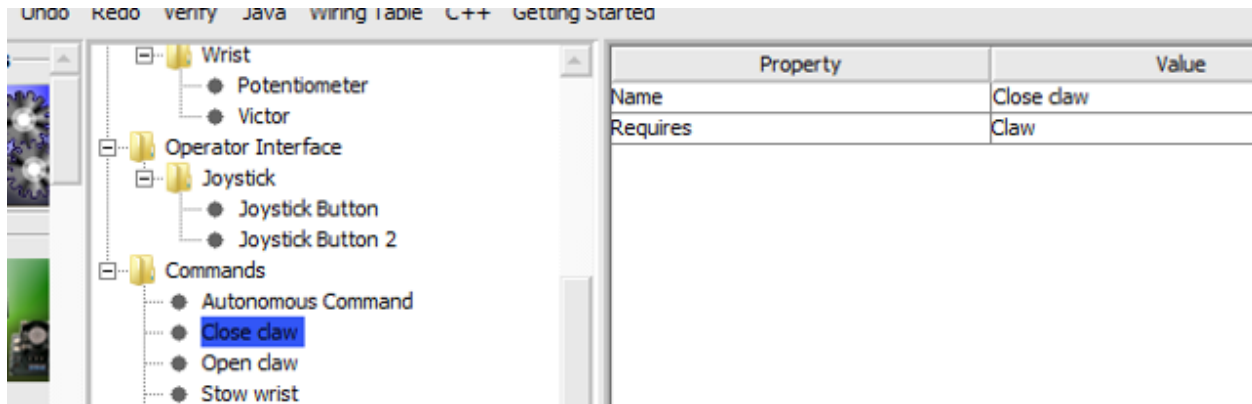
In addition to adding the methods to the class implementation file, Claw.cpp, the declarations for the methods need to be added to the header file, Claw.h. Those declarations that must be added are shown here.

To add the behavior to the claw subsystem to operate it to handle opening and closing you need to *define commands*.

### 14.2.3 Writing the Code for a Command

Subsystem classes get the mechanisms on your robot moving, but to get it to stop at the right time and sequence through more complex operations you write Commands. Previously in *writing the code for a subsystem* we developed the code for the Claw subsystem on a robot to start the claw opening, closing, or to stop moving. Now we will write the code for a command that will actually run the Claw motor for the right time to get the claw to open and close. Our claw example is a very simple mechanism where we run the motor for 1 second to open it or 0.9 seconds to close it.

## Closeclaw Command in RobotBuilder



This is the definition of the Closeclaw command in RobotBuilder. Notice that it requires the Claw subsystem. This is explained in the next step.

## Generated Closeclaw Class

Java

```
public class Closeclaw() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
}

// Called just before this Command runs the first time
protected void initialize() {
    setTimeout(1.0);
    Robot.claw.closeClaw();
}

// Called repeatedly when this Command is scheduled to run
protected boolean execute() {
}

protected boolean isFinished() {
    return isTimedOut();
}

// Called once after isFinished returns true
protected void end() {
    Robot.claw.stop();
}

// Called when another command which requires one or more
// subsystems is scheduled to run
protected void interrupted() {
    end();
}
```

C++

```

#include "Closeclaw.h"

Closeclaw::Closeclaw() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    Requires(Robot::claw);
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    SetTime(1);
}

void Closeclaw::Initialize() {
    Robot::claw->Close();
}

void Closeclaw::Execute() {
}

bool Closeclaw::IsFinished() {
    return IsTimedOut();
}

void Closeclaw::End() {
    Robot::claw->Stop();
}

void Closeclaw::Interrupted() {
    End();
}

```

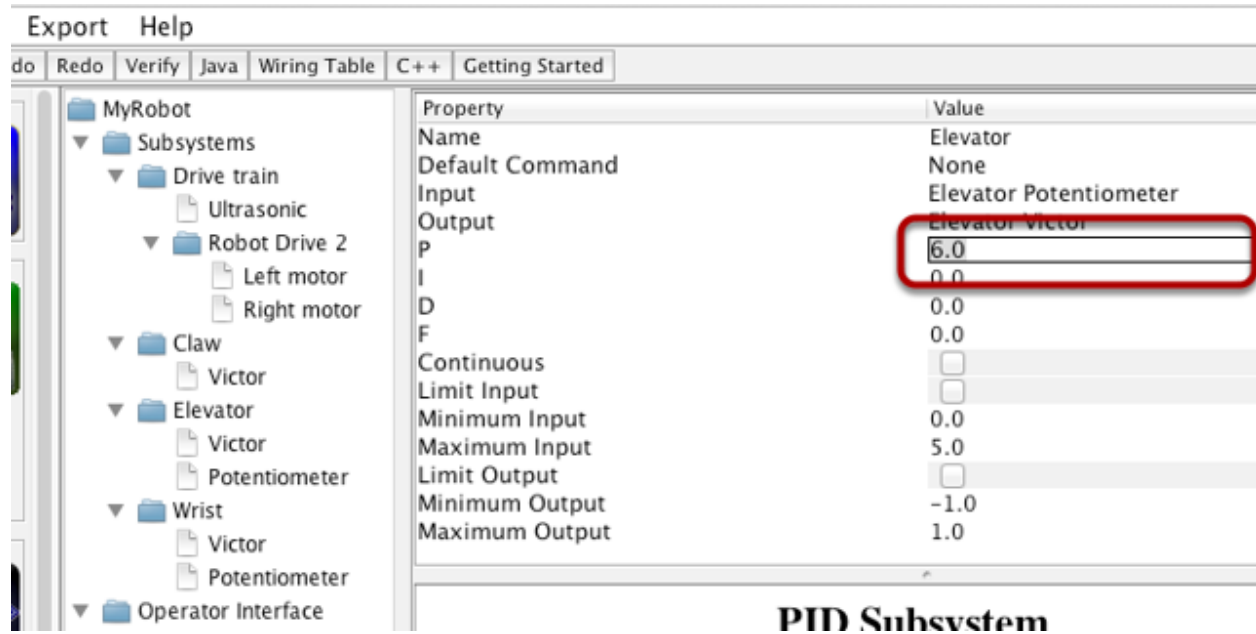
RobotBuilder will generate the class files for the Closeclaw command. The command represents the behavior of the claw, that is the operation over time. To operate this very simple claw mechanism the motor needs to operate for 1 second in the close direction. The Claw subsystem has methods to start the motor running in the right direction and to stop it. The commands responsibility is to run the motor for the correct time. The lines of code that are shown in the boxes are added to add this behavior.

1. Set the one second timeout for this command. When the command is scheduled, a timer will be started so the one second operation can easily be tested.
2. Start the claw motor moving in the closing direction by calling the Close method that was added to the Claw subsystem.
3. This command is finished when the timer runs out which happens after one second has passed. This is the timer set in step 1.
4. The End() method is called when the command is finished and is a place to clean up. In this case, the motor is stopped since the time has run out.
5. The Interrupted() method is called if this command is interrupted if another command that also requires the Claw subsystem is scheduled before this finishes. For example, if the Closeclaw command was scheduled and running, then the Openclaw command was scheduled it would interrupt the Openclaw command, call its Interrupted() method, and the motor would stop.

### 14.2.4 Writing the Code for a PIDSubsystem

PIDSubsystems use feedback to control the actuator and drive it to a particular position. In this example we use an elevator with a 10-turn potentiometer connected to it to give feedback on the height. The skeleton of the PIDSubsystem is generated by the RobotBuilder and we have to fill in the rest of the code to provide the potentiometer value and drive the motor with the output of the embedded PIDController.

#### Setting the PID Constants



Make sure the Elevator PID subsystem has been created in the RobotBuilder. In the case of our elevator we use a proportional constant of 6.0 and 0 for the I and D terms. Once it's all set, generate Java/C++ code for the project using the Export menu or the Java/C++ toolbar menu.

#### Add Constants for Elevator Preset Positions

Java

```
public class Elevator extends PIDSubsystem {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATION
    AnalogChannel potentiometer = RobotMap.ELEVATOR_POTENTIOMETER;
    Victor victor = RobotMap.ELEVATOR_VICTOR;
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATION

    public static final double BOTTOM = 4.6,
                               STOW = 1.65,
                               TABLE_HEIGHT = 1.58;

    public Elevator() {
        // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=PID
        super("Elevator", 1.0, 0.0, 0.0);
    }
}
```

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```

    getPIDController().setContinuous(false);
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=PID

    setSetpoint(STOW);
    enable();
}

public void initDefaultCommand() {
}

protected double returnPIDInput() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=SOURCE
    return potentiometer.pidGet();
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=SOURCE
}

protected void usePIDOutput(double output) {
}
}

```

C++

```

#include "Elevator.h"
#include "../Robotmap.h"
#include "SmartDashboard/SmartDashboard.h"

// BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=PID
Elevator::Elevator() : PIDSubsystem("Elevator", 1.0, 0.0, 0.0) {
    GetPIDController()->SetContinuous(false);

    // END AUTOGENERATED COD, SOURCE=ROBOTBUILDER ID=PID
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=DECLARATIONS

    potentiometer = RobotMap::ELEVATOR_POTENTIOMETER;
    victor = RobotMap::ELEVATOR_VICTOR;

    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=DECLARATIONS
    SetSetpoint(STOW);
    Enable();
}

```

To make it easier to drive the elevator to preset positions, we added preset positions for the bottom, stow, and table height. Then the elevator is set to the STOW position by setting the PID setpoint and the PID controller is enabled. This will cause the elevator to move to the stowed position when the robot is enabled.

### Adding the Constants to the Header File (C++ Only)

C++

```

#pragma once

```

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```

#include "frc/commands/PIDSubsystem.h"
#include "frc/AnalogInput.h"
#include "frc/Victor.h"

class Elevator: public PIDSubsystem {
public:
    static const double BOTTOM = 4.6;
    static const double STOW = 1.65;
    static const double TABLE_HEIGHT = 1.58;

    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS
    AnalogInput* potentiometer;
    Victor* victor;
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=DECLARATIONS

    Elevator();
    double ReturnPIDInput();
    void UsePIDOutput(double output);
    void InitDefaultCommand();
};

```

## Return PID Input Values

Java

```

protected double returnPIDInput() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=SOURCE
    return potentiometer.pidGet();
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER, ID=SOURCE
}

```

C++

```

double Elevator::ReturnPIDInput() {
    // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=SOURCE
    return potentiometer->PIDGet();
    // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=SOURCE
}

```

The `returnPIDInput()` method is used to set the value of the sensor that is providing the feedback for the PID controller. In this case, the code is automatically generated and returns the potentiometer raw analog input value (a number that ranges from 0-1023). In our case we would like the PID controller to be based on the average voltage read by the analog input for the potentiometer, not the raw value.

If we just change the line:

`return potentiometer.pidGet();` for Java or `return potentiometer->PIDGet();` for C++

it will be overwritten by RobotBuilder next time we export to Java. You can tell which lines are automatically generated by looking at the “//BEGIN AUTOGENERATED CODE” and “//END AUTOGENERATED CODE” comments. Any code in-between those markers will be overwritten next time RobotBuilder is run. You’re free to change anything outside of those blocks.

## Return the Average Voltage

Java

```
protected double returnPIDInput() {
    return potentiometer.getAverageVoltage();
}
```

C++

```
double Elevator::ReturnPIDInput() {
    return potentiometer->GetAverageVoltage();
}
```

To get around the problem from the last step, the comment blocks can be removed. Then if the line is changed as shown, it will no longer be overwritten by RobotBuilder.

Remember, if we just wanted to add code to a method it could be added safely outside of the comment blocks.

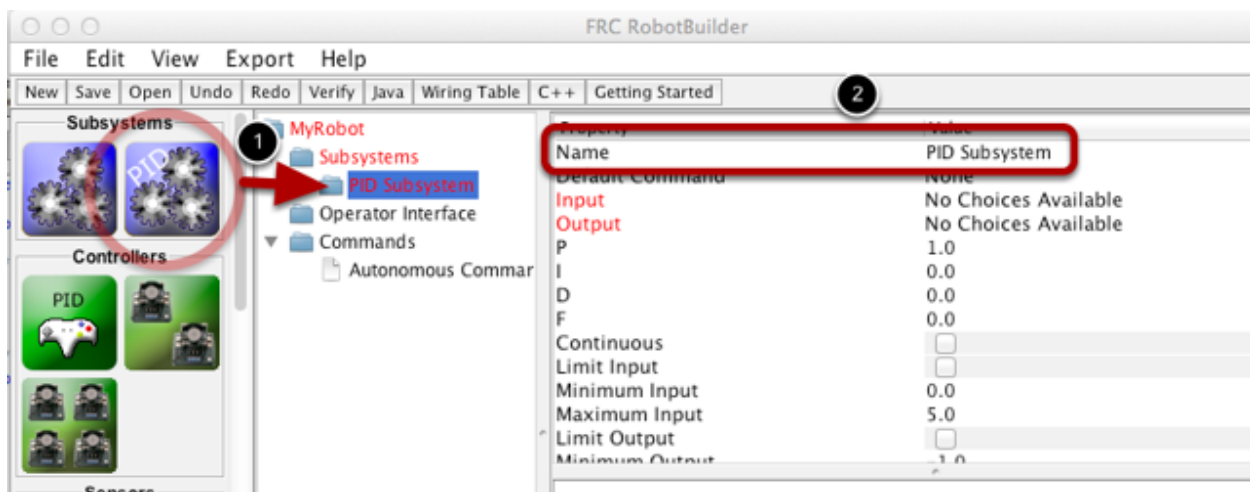
That's all that is required to create the Elevator PIDSubsystem.

## 14.3 RobotBuilder - Advanced

### 14.3.1 Using PIDSubsystem to Control Actuators

More advanced subsystems will use sensors for feedback to get guaranteed results for operations like setting elevator heights or wrist angles. The PIDSubsystem has a built-in PIDController to automatically set the correct setpoints for these types of mechanisms.

#### Create a PIDSubsystem



Creating a subsystem that uses feedback to control the position or speed of a mechanism is very easy.

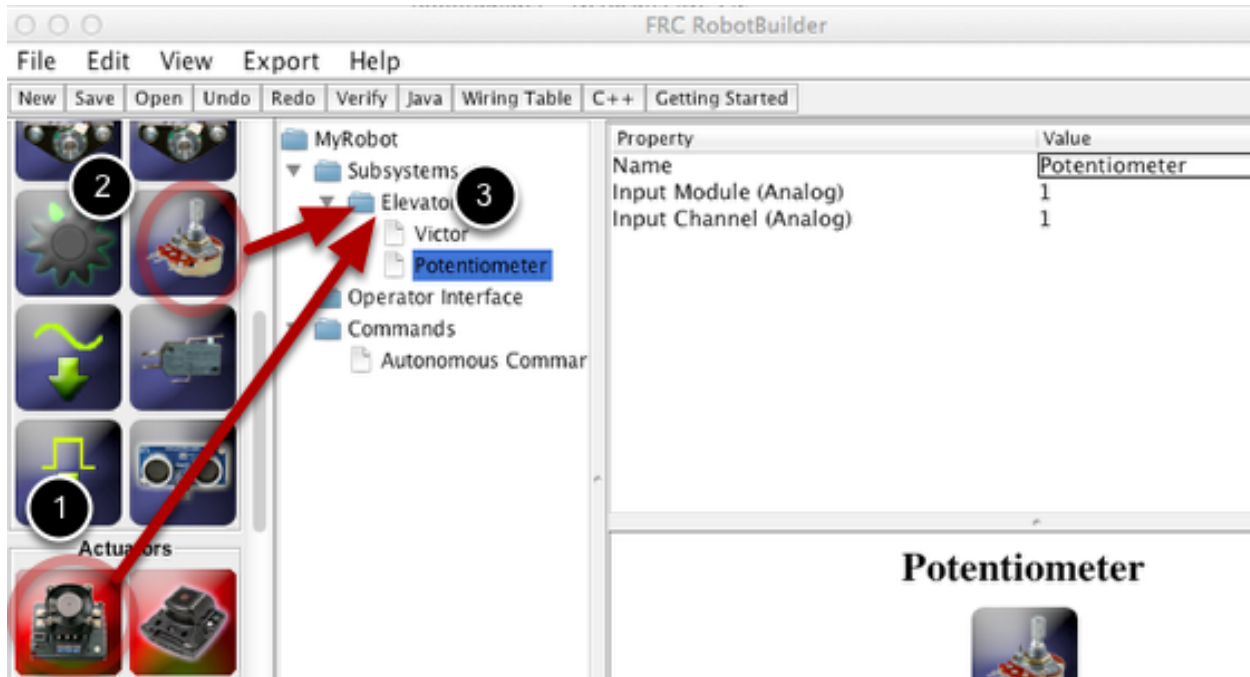
1. Drag a PIDSubsystem from the palette to the Subsystems folder in the robot description



2. Rename the PID Subsystem to a more meaningful name for the subsystem

Notice that some of the parts of the robot description have turned red. This indicates that these components (the PIDSubsystem) haven't been completed and need to be filled in. The properties that are either missing or incorrect are shown in red.

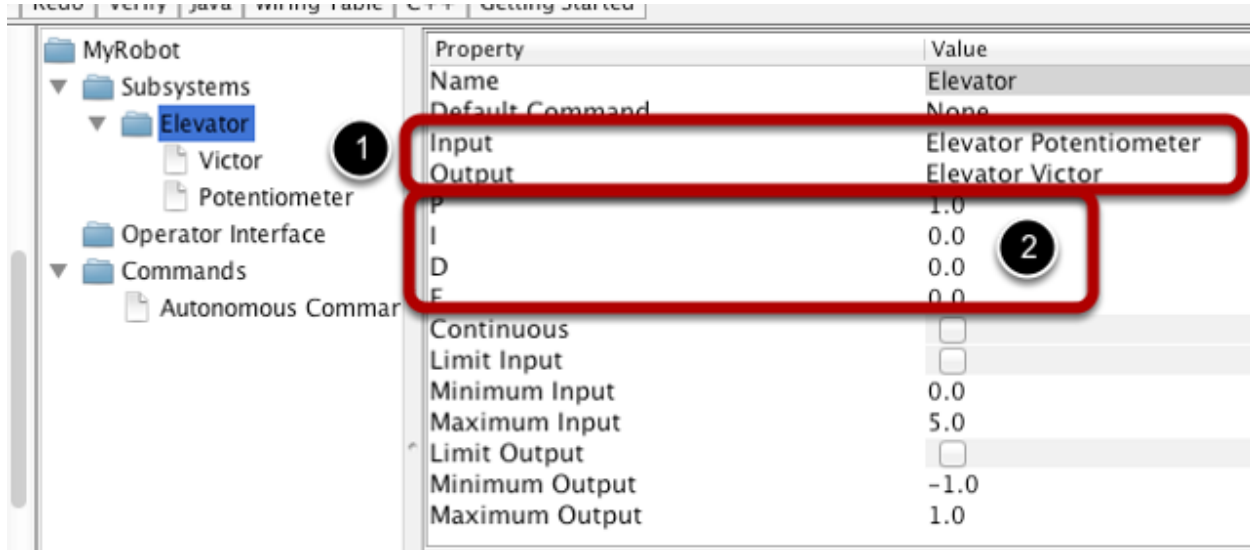
### Adding Sensors and Actuators to the PIDSubsystem



Add the missing components for the PIDSubsystem

1. Drag in the actuator (a speed controller) to the particular subsystem - in this case the Elevator
2. Drag the sensor that will be used for feedback to the subsystem, in this case the sensor is a potentiometer that might give elevator height feedback.

## Fill in the PIDSubsystem Parameters



There are a number of parameters for the PIDSubsystem but only a few need to be filled in for most cases

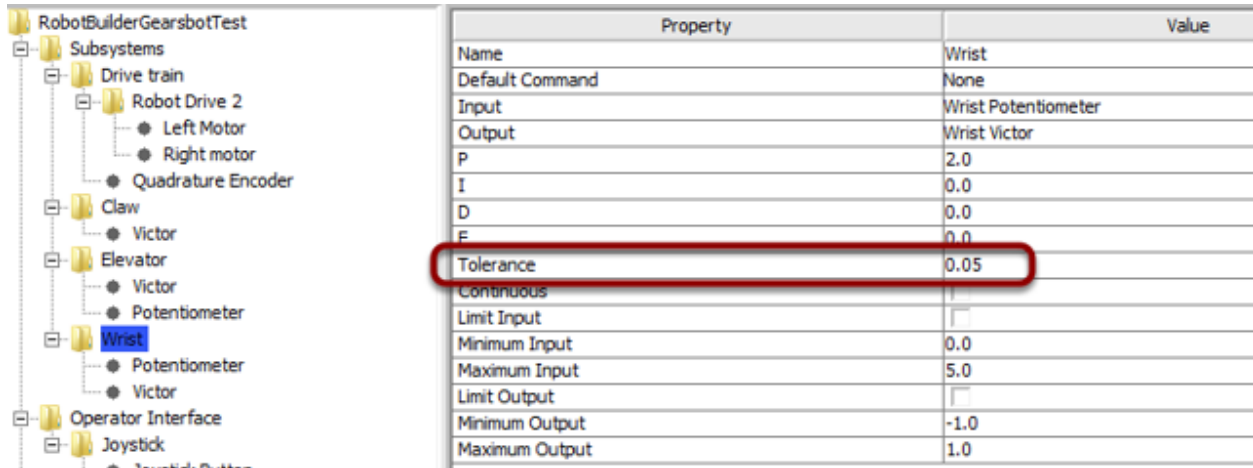
1. The Input and Output components will have been filled in automatically from the previous step when the actuator and sensor were dragged into the PIDSubsystem
2. The P, I, and D values need to be filled in to get the desired sensitivity and stability of the component

See [Writing the Code for a PIDSubsystem](#)

### 14.3.2 Setpoint Command

A common use case in robot programs is to drive an actuator to a particular angle or position that is measured using a potentiometer or encoder. This happens so often that there is a shortcut in RobotBuilder to do this task. It is called the Setpoint command and it's one of the choices on the palette or the right-click context menu that can be inserted under "Commands".

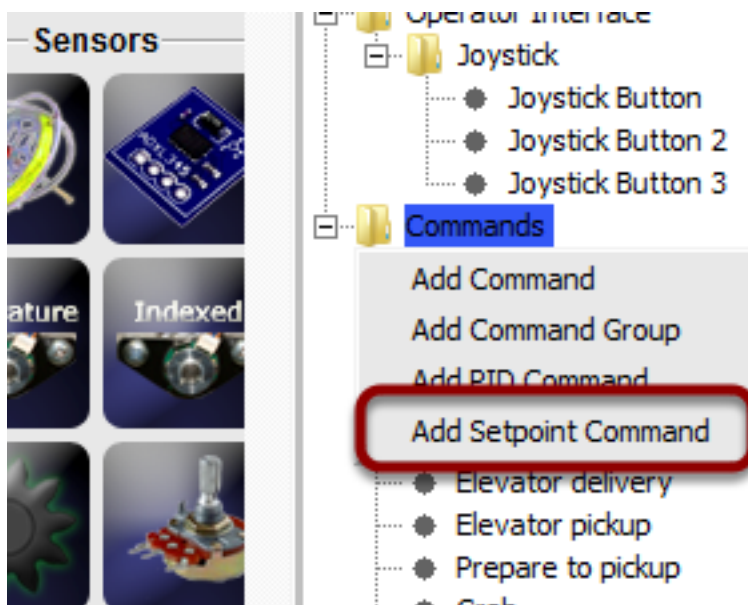
## Start with a PIDSubsystem



Suppose in a robot there is a wrist joint with a potentiometer that measures the angle. First *create a PIDSubsystem* that include the motor that moves the wrist joint and the potentiometer that measures the angle. The PIDSubsystem should have all the PID constants filled in and working properly.

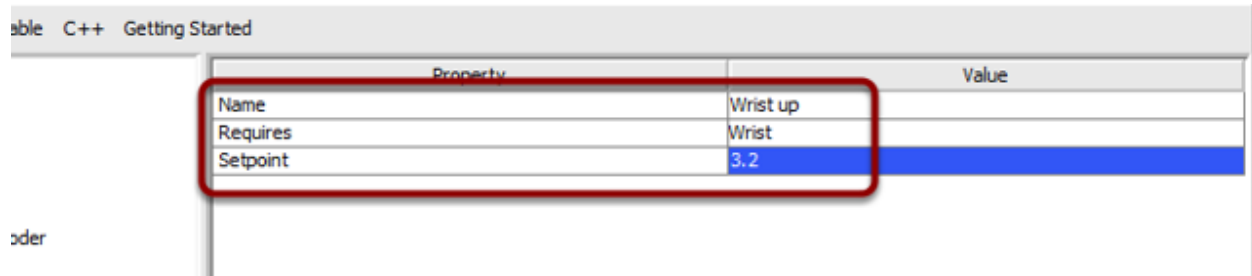
It is important to set the **Tolerance** parameter. This controls how far off the current value can be from the setpoint and be considered on target. This is the criteria that the Setpoint-Command uses to move onto the next command.

## Creating the Setpoint Command



Right-click on the Commands folder in the palette and select “Add Setpoint command”.

## Setpoint Command Parameters



Fill in the name of the new command. The Requires field is the PIDSubsystem that is being driven to a setpoint and the Setpoint parameter is the setpoint value for the PIDSubsystem. There is no need to fill in any code for this command, it is automatically created by RobotBuilder.

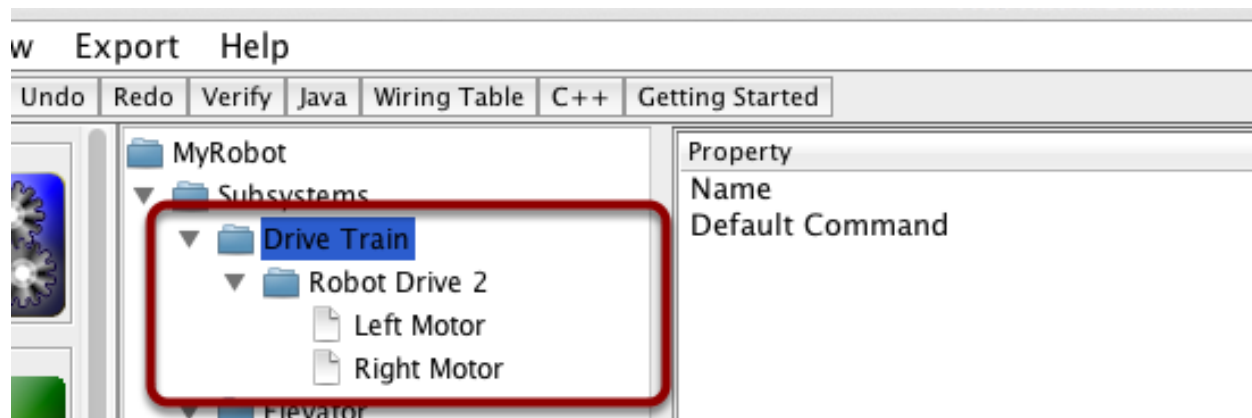
Whenever this command is scheduled, it will automatically drive the subsystem to the specified setpoint. When the setpoint is reached within the tolerance specified in the PIDSubsystem, the command ends and the next command starts. It is important to specify a tolerance in the PIDSubsystem or this command might never end because the tolerance is not achieved.

### 14.3.3 Driving the Robot with Tank Drive and Joysticks

A common use case is to have a joystick that should drive some actuators that are part of a subsystem. The problem is that the joystick is created in the OI class and the motors to be controlled are in the subsystem. The idea is to create a command that, when scheduled, reads input from the joystick and calls a method that is created on the subsystem that drives the motors.

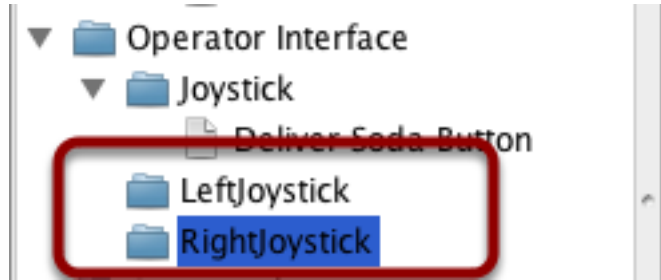
In this example a drive base subsystem is shown that is operated in tank drive using a pair of joysticks.

#### Create a Drive Train Subsystem



Create a subsystem called Drive Train. Its responsibility will be to handle the driving for the robot base. Inside the Drive Train is a Robot Drive object for a two motor drive robot (in this case). There is a left motor and right motor as part of the Robot Drive 2 class.

### Add the Joysticks to the Operator Interface



Add two joysticks to the Operator Interface, one is the left stick and the other is the right stick. The y-axis on the two joysticks are used to drive the robots left and right sides.

---

**Note:** Be sure to export your program to C++ or Java before continuing to the next step.

---

### Create a Method to Write the Motors on the Subsystem

Java

```
public class DriveTrain extends Subsystem {
    RobotDrive robotDrive2 = RobotMap.DRIVE_TRAIN_ROBOT_DRIVE_2;
    Jaguar rightMotor = RobotMap.DRIVE_TRAIN_RIGHT_MOTOR;
    Jaguar leftMotor = RobotMap.DRIVE_TRAIN_LEFT_MOTOR;

    public void initDefaultCommand() {
    }

    public void takeJoystickInputs(Joystick left, Joystick right) {
        robotDrive2.tankDrive(left, right);
    }

    public void stop() {
        robotDrive2.drive(0, 0);
    }
}
```

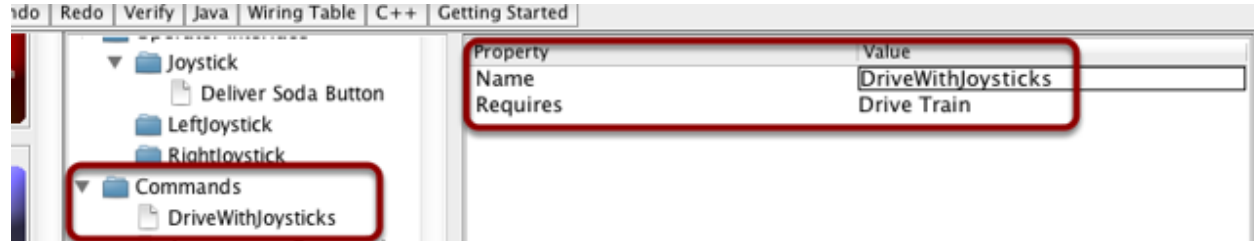
Create a method that takes the joystick inputs, in this case the the left and right driver joystick. The values are passed to the RobotDrive object that in turn does tank steering using the joystick values. Also create a method called stop() that stops the robot from driving, this might come in handy later.

---

**Note:** The extra RobotBuilder comments have been removed to format the example for the documentation.

---

## Read Joystick Values and Call the Subsystem Methods



Create a command, in this case called DriveWithJoysticks. Its purpose will be to read the joystick values and send them to the Drive Base subsystem. Notice that this command Requires the Drive Train subsystem. This will cause it to stop running whenever anything else tries to use the Drive Train.

**Note:** Be sure to export your program to C++ or Java before continuing to the next step.

## Add the Code to do the Driving

Java

```
public class DriveWithJoysticks extends Command {
    public DriveWithJoysticks() {
        // BEGIN AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
        requires(Robot.driveTrain);
        // END AUTOGENERATED CODE, SOURCE=ROBOTBUILDER ID=REQUIRES
    }

    protected void initialize() {

    }

    protected void execute() {
        Robot.driveTrain.takeJoystickInputs(Robot.oi.getLeftJoystick(), Robot.oi.
        getRightJoystick());
    }

    protected boolean isFinished() {
        return false;
    }

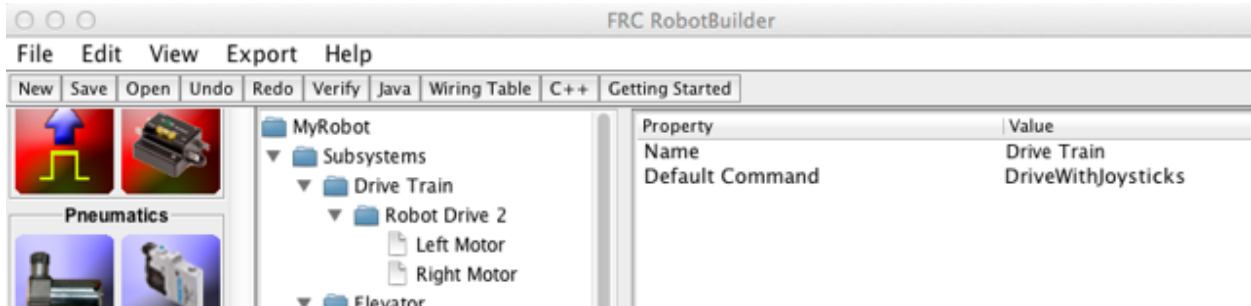
    protected void end() {
        Robot.driveTrain.stop();
    }

    protected void interrupted() {
        end();
    }
}
```

Add code to the execute method to do the actual driving. All that is needed is to get the Joystick objects for the left and right drive joysticks and pass them to the Drive Train subsystem. The subsystem just uses them for the tank steering method on its RobotDrive object. And we get tank steering.

We also filled in the `end()` and `interrupted()` methods so that when this command is interrupted or stopped, the motors will be stopped as a safety precaution.

### Make Default Command



The last step is to make the `DriveWithJoysticks` command be the “Default Command” for the Drive Train subsystem. This means that whenever no other command is using the Drive Train, the Joysticks will be in control. This is probably the desirable behavior. When the autonomous code is running, it will also require the drive train and interrupt the “`DriveWithJoystick`” command. When the autonomous code is finished, the `DriveWithJoysticks` command will restart automatically (because it is the default command), and the operators will be back in control. If you write any code that does teleop automatic driving, those commands should also “require” the `DriveTrain` so that they too will interrupt the `DriveWithJoysticks` command and have full control.

---

**Note:** Be sure to export your program to C++ or Java before continuing.

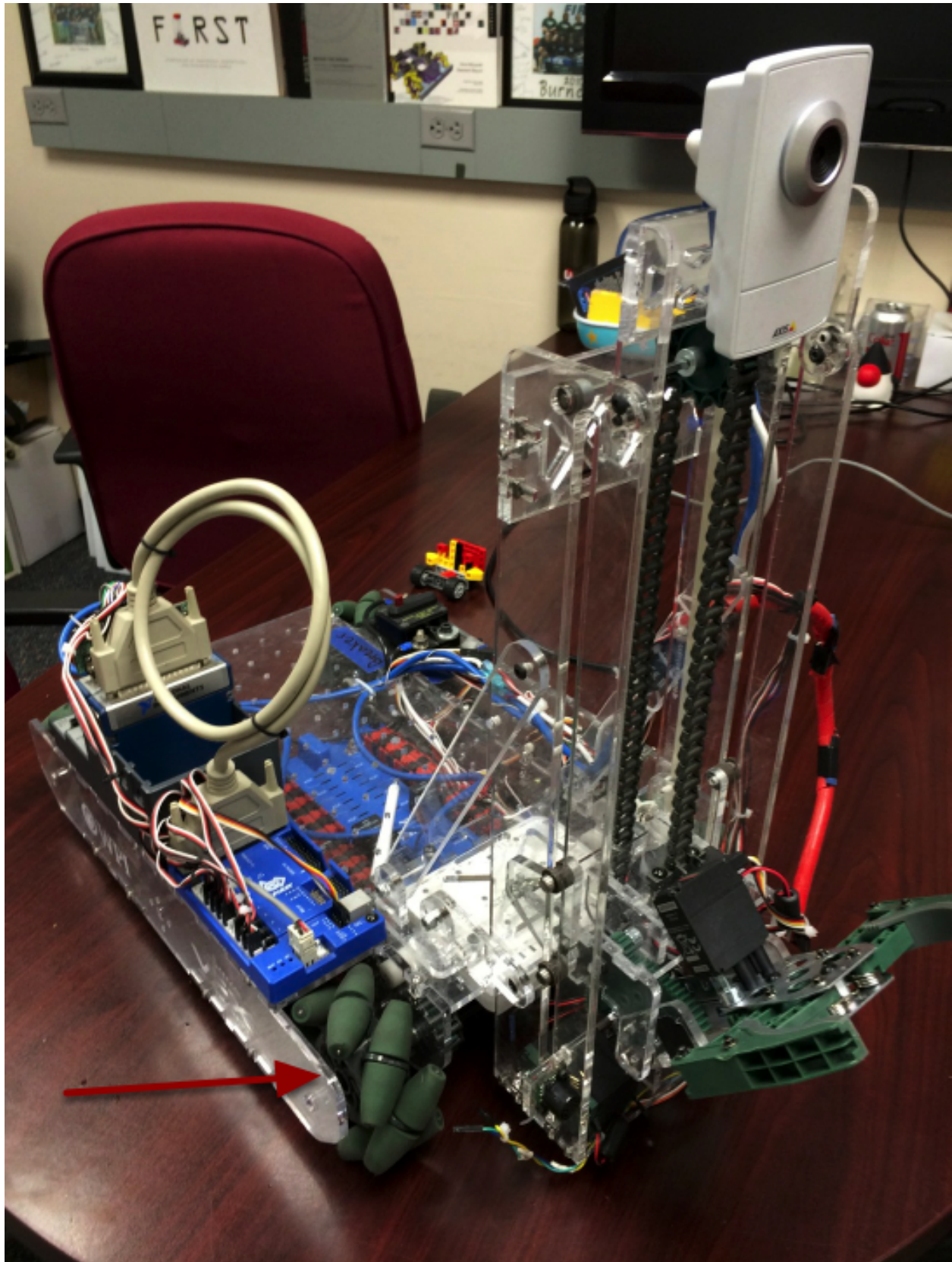
---

### 14.3.4 Driving a Robot using Mecanum Drive

Mecanum drive is a method of driving using specially designed wheels that allow the robot to drive in any direction without changing the orientation of the robot. A robot with a conventional drivetrain (4 or six wheels) must turn in the direction it needs to drive. A mecanum robot can move in any direction without first turning and is called a holonomic drive.



## Mecanum Wheels





The wheels shown in this robot have rollers that cause the forces from driving to be applied at a 45 degree angle rather than straight forward as in the case of a conventional drive. You might guess that varying the speed of the wheels results in travel in any direction. You can look up how mecanum wheels work on various web sites on the internet.

### Code for Driving with Mecanum Wheels

C++

```
#include "frc/Joystick.h"
#include "frc/RobotDrive.h"
/**
 * Simplest program to drive a robot with mecanum drive using a single Logitech
 * Extreme 3D Pro joystick and 4 drive motors connected as follows:
 * - PWM 1 - Connected to front left drive motor
 * - PWM 2 - Connected to rear left drive motor
 * - PWM 3 - Connected to front right drive motor
 * - PWM 4 - Connected to rear right drive motor
 */
class MecanumDefaultCode : public TimedRobot
{
    RobotDrive *m_robotDrive;    // RobotDrive object using PWM 1-4 for drive motors
    Joystick *m_driveStick;      // Joystick object on USB port 1 (mecanum drive)
public:
    /**
     * Constructor for this "MecanumDefaultCode" Class.
     */
    MecanumDefaultCode(void)
    {
        // Create a RobotDrive object using PWMS 1, 2, 3, and 4
        m_robotDrive = new RobotDrive(1, 2, 3, 4);
        // Define joystick being used at USB port #1 on the Drivers Station
        m_driveStick = new Joystick(1);
        // Twist is on Axis 3 for the Extreme 3D Pro
        m_driveStick->SetAxisChannel(Joystick::kTwistAxis, 3);
    }
    /**
     * Gets called once for each new packet from the DS.
     */
    void TeleopPeriodic(void)
    {
        m_robotDrive->MecanumDrive_Cartesian(m_driveStick->GetX(), m_driveStick->GetY(),
        ↪ m_driveStick->GetTwist());
    }
};
START_ROBOT_CLASS(MecanumDefaultCode);
```

Here's a sample program that shows the minimum code to drive using a single joystick and mecanum wheels. It uses the RobotDrive object that is available in both C++ and Java so even though this example is in C++ similar code will work in Java. The idea is to create the RobotDrive object with 4 PWM ports for the 4 speed controllers on the robot. The joystick XY position represents a direction vector that the robot should follow regardless of its orientation. The twist axis on the joystick represents the rate of rotation for the robot while it's driving.

Thanks to **FRC Team 2468** in Austin, TX for developing this example.

## Field-Oriented Driving

I would be remiss in not mentioning that is a 4th parameter to the `MecanumDrive_Cartesian()` method that is the angle returned from a Gyro sensor. This will adjust the rotation value supplied, in this case, from the twist axis of the joystick to be relative to the field rather than relative to the robot. This is particularly useful with mecanum drive since, for the purposes of steering, the robot really has no front, back or sides. It can go in any direction. Adding the angle in degrees from a gyro object will cause the robot to move away from the drivers when the joystick is pushed forwards, and towards the drivers when it is pulled towards them - regardless of what direction the robot is facing!

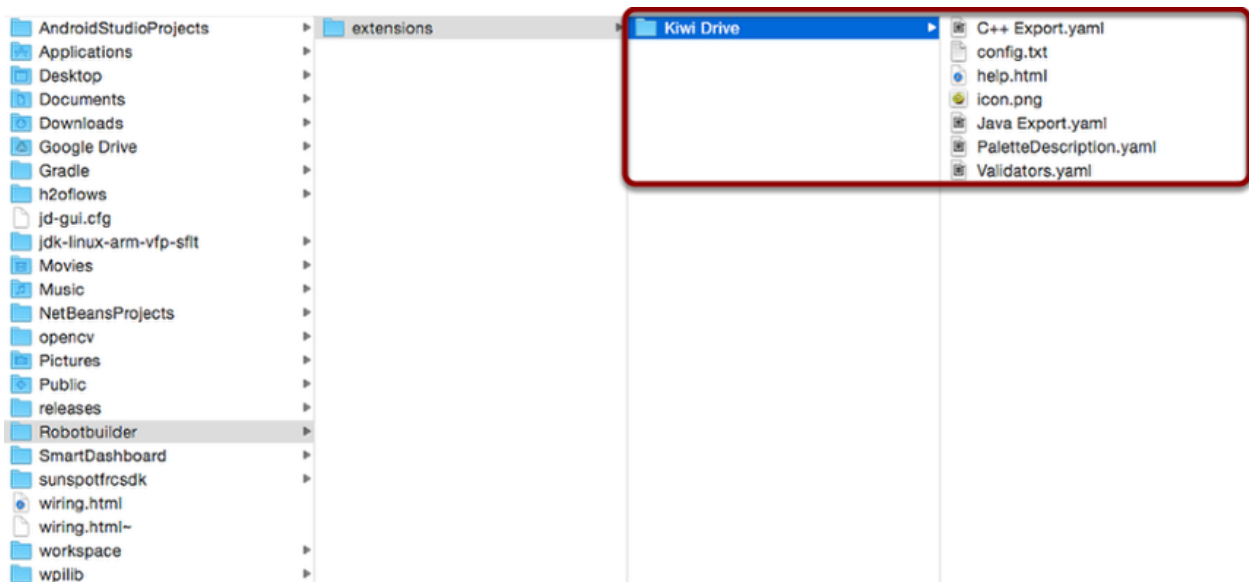
The use of field-oriented driving makes often makes the robot much easier to drive, especially compared to a “robot-oriented” drive system where the controls are reversed when the robot is facing the drivers.

Just remember to get the gyro angle each time `MecanumDrive_Cartesian()` is called.

### 14.3.5 Adding Custom Components

RobotBuilder works very well for creating robot programs that just use WPILib for motors, controllers, and sensors. But for teams that use custom classes, RobotBuilder doesn't have any support for those classes, so a few steps need to be taken to use them in RobotBuilder

#### Custom Component Structure



Custom components all go in `~/wpilib/YYYY/Robotbuilder/extensions` where `~` is `C:\Users\Public` on Windows and `YYYY` is the FRC year.

There are seven files and one folder that are needed for a custom component. The folder contains the files describing the component and how to export it. It should have the same name as the component (e.g. “Kiwi Drive” for a kiwi drive controller, “Robot Drive 6” for a six-motor drive controller, etc.). The files should have the same names and extensions as the ones shown here. Other files can be in the folder along with these seven, but the seven must be present for RobotBuilder to recognize the custom component.

## PaletteDescription.yaml

```

1  !Component
2      name: Kiwi Drive
3      type: Controller
4      supports: {PIDOutput: 3}
5      help: A type of drivetrain with three omni wheels
6      properties:
7          - !ChildSelectionProperty
8              name: Motor 1
9              type: PIDOutput
10             validators: [KiwiDriveValidator, ChildDropdownSelected]
11          - !ChildSelectionProperty
12              name: Motor 2
13              type: PIDOutput
14             validators: [KiwiDriveValidator, ChildDropdownSelected]
15          - !ChildSelectionProperty
16              name: Motor 3
17              type: PIDOutput
18             validators: [KiwiDriveValidator, ChildDropdownSelected]

```

Line-by-line:

- **!Component:** Declares the beginning of a new component
- **name:** The name of the component. This is what will show up in the palette/tree – this should also be the same as the name of the containing folder
- **type:** the type of the component (these will be explained in depth later on)
- **supports:** a map of the amount of each type of component this can support. Motor controllers in RobotBuilder are all PIDOutputs, so a kiwi drive can support three PIDOutputs. If a component doesn't support anything (such as sensors or motor controllers), just leave this line out
- **help:** a short string that gives a helpful message when one of these components is hovered over
- **properties:** a list of the properties of this component. In this kiwi drive example, there are three very similar properties, one for each motor. A ChildSelectionProperty allows the user to choose a component of the given type from the subcomponents of the one being edited (so here, they would show a dropdown asking for a PIDOutput - i.e. a motor controller - that has been added to the kiwi drive)

The types of component RobotBuilder supports (these are case-sensitive):

- Command
- Subsystem
- PIDOutput (speed controller)
- PIDSource (sensor that implements PIDSource e.g. analog potentiometer, encoder)

- Sensor (sensor that does not implement PIDSource e.g. limit switch)
- Controller (robot drive, PID controller, etc.)
- Actuator (an output that is not a motor, e.g. solenoid, servo)
- Joystick
- Joystick Button

## **Properties**

The properties relevant for a custom component:

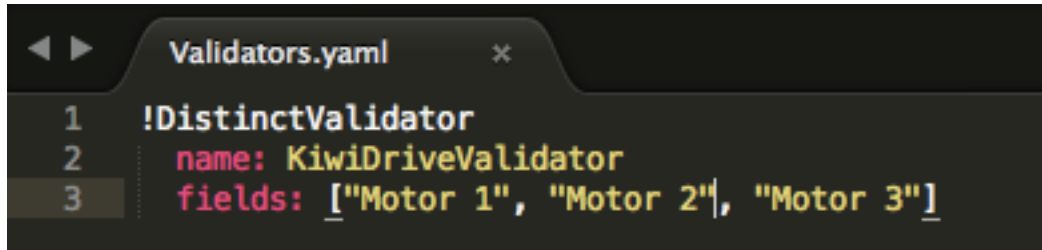
- `StringProperty`: used when a component needs a string e.g. the name of the component
- `BooleanProperty`: used when a component needs a boolean value e.g. putting a button on the SmartDashboard
- `DoubleProperty`: used when a component needs a number value e.g. PID constantsChoicesProperty
- `ChildSelectionProperty`: used when you need to choose a child component e.g. speed controllers in a RobotDrive
- `TypeSelectionProperty`: used when you need to choose any component of the given type from anywhere in the program e.g. input and output for a PID command

The fields for each property are described below:

A property is one of:

- **!StringProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.
- **!BooleanProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.
- **!DoubleProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.
- **!FileProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.  
extension: The extension at the end of this file without the '.'  
folder: Whether or not to select folders instead of files
- **!ChoicesProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.  
choices: List of choices to present to the user.
- **!ChildSelectionProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.  
type: Type of the child to select.
- **!TypeSelectionProperty**  
name: The name of this property, should be unique within this component  
validator: Optional. The validator that should be used to validate this property.  
default: The default value when no other is presented.  
type: Type of component to select.

## Validators.yaml



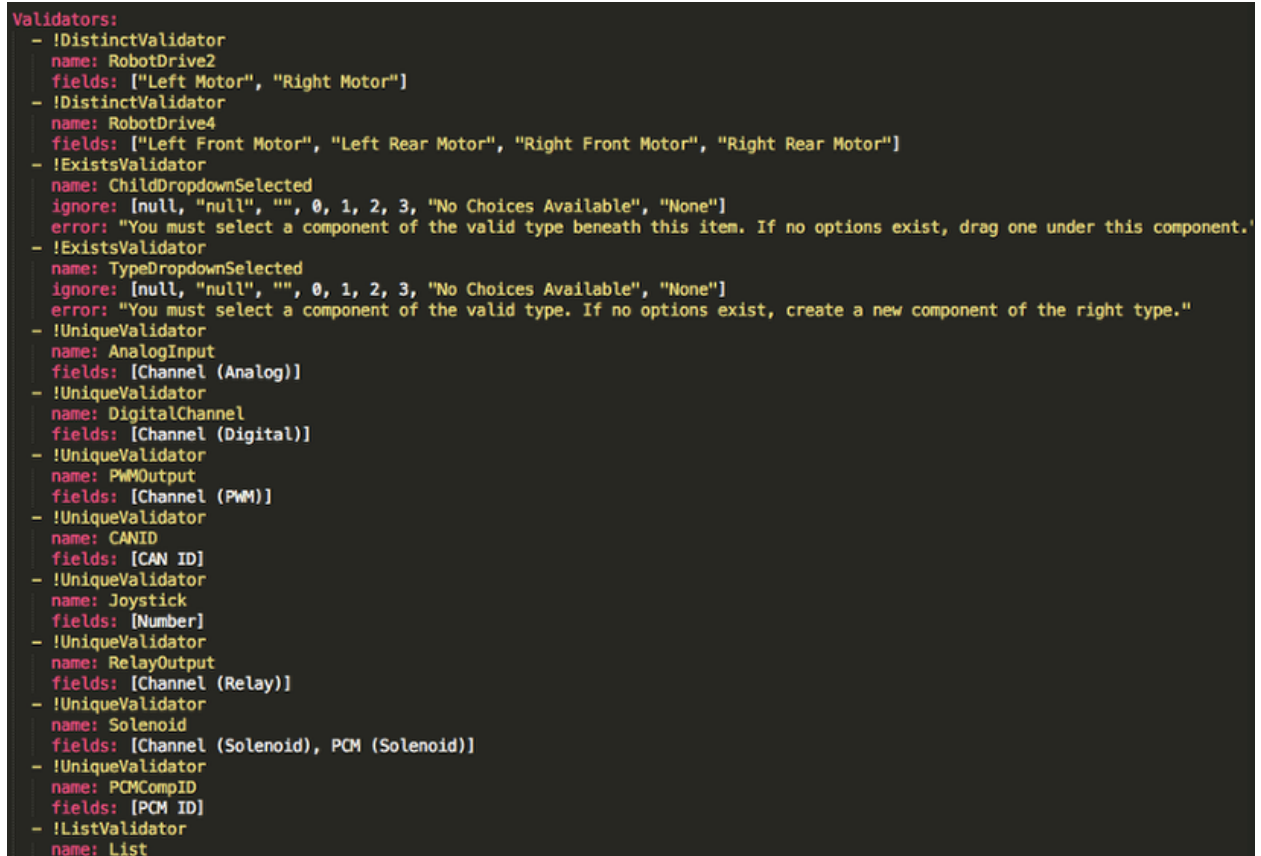
```

1  !DistinctValidator
2      name: KiwiDriveValidator
3      fields: ["Motor 1", "Motor 2", "Motor 3"]

```

You may have noticed “KiwiDriveValidator” in the validators entry of each of the motor properties in PaletteDescription.yaml. It’s not a built-in validator, so it had to be defined in Validators.yaml. This example validator is very simple - it just makes sure that each of the named fields has a different value than the others.

## Built-in Validators and Validator Types



```

Validators:
- !DistinctValidator
  name: RobotDrive2
  fields: ["Left Motor", "Right Motor"]
- !DistinctValidator
  name: RobotDrive4
  fields: ["Left Front Motor", "Left Rear Motor", "Right Front Motor", "Right Rear Motor"]
- !ExistsValidator
  name: ChildDropdownSelected
  ignore: [null, "null", "", 0, 1, 2, 3, "No Choices Available", "None"]
  error: "You must select a component of the valid type beneath this item. If no options exist, drag one under this component."
- !ExistsValidator
  name: TypeDropdownSelected
  ignore: [null, "null", "", 0, 1, 2, 3, "No Choices Available", "None"]
  error: "You must select a component of the valid type. If no options exist, create a new component of the right type."
- !UniqueValidator
  name: AnalogInput
  fields: [Channel (Analog)]
- !UniqueValidator
  name: DigitalChannel
  fields: [Channel (Digital)]
- !UniqueValidator
  name: PWMOutput
  fields: [Channel (PWM)]
- !UniqueValidator
  name: CANID
  fields: [CAN ID]
- !UniqueValidator
  name: Joystick
  fields: [Number]
- !UniqueValidator
  name: RelayOutput
  fields: [Channel (Relay)]
- !UniqueValidator
  name: Solenoid
  fields: [Channel (Solenoid), PCM (Solenoid)]
- !UniqueValidator
  name: PCMCompID
  fields: [PCM ID]
- !ListValidator
  name: List

```

The built-in validators are very useful (especially the UniqueValidators for port/channel use), but sometimes a custom validator is needed, like in the previous step

- DistinctValidator: Makes sure the values of each of the given fields are unique
- ExistsValidator: Makes sure that a value has been set for the property using this validator
- UniqueValidator: Makes sure that the value for the property is unique globally for the given fields

- ListValidator: Makes sure that all the values in a list property are valid

### C++ Export.yaml



```
1 Kiwi Drive:
2 Defaults: "CustomComponent,None"
3 ClassName: "KiwiDrive"
4 Construction: "#variable($Name).reset(new ${ClassName}({variable($Motor_1), #variable($Motor_2), #variable($Motor_3)});"
```

A line-by-line breakdown of the file:

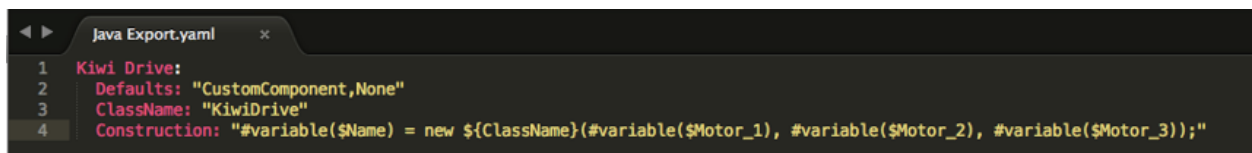
- Kiwi Drive: the name of the component being exported. This is the same as the name set in PaletteDescription.yaml, and the name of the folder containing this file
- Defaults: provides some default values for includes needed by this component, the name of the class, a construction template, and more. The CustomComponent default adds an include for Custom/\${ClassName}.h to every generated file that uses the component (e.g. RobotDrive.h would have #include "Custom/KiwiDrive.h" at the top of the file)
- ClassName: the name of the custom class you're adding.
- Construction: an instruction for how the component should be constructed. Variables will be replaced with their values ("\${ClassName}" will be replaced with "KiwiDrive"), then macros will be evaluated (for example, #variable(\$Name) may be replaced with drivebaseKiwiDrive).

This example expects a KiwiDrive class with the constructor

```
KiwiDrive(shared_ptr<SpeedController>, shared_ptr<SpeedController>, shared_ptr<SpeedController>)
```

If your team uses Java, this file can be empty.

### Java Export.yaml



```
1 Kiwi Drive:
2 Defaults: "CustomComponent,None"
3 ClassName: "KiwiDrive"
4 Construction: "#variable($Name) = new ${ClassName}({variable($Motor_1), #variable($Motor_2), #variable($Motor_3)});"
```

Very similar to the C++ export file; the only difference should be the Construction line. This example expects a KiwiDrive class with the constructor

```
KiwiDrive(SpeedController, SpeedController, SpeedController)
```

If your team uses C++, this file can be empty.

### Using Macros and Variables

Macros are simple functions that RobotBuilder uses to turn variables into text that will be inserted into generated code. They always start with the "#" symbol, and have a syntax similar to functions: <macro\_name>( arg0, arg1, arg2, ...). The only macro you'll probably need to use is #variable( component\_name )



`#variable` takes a string, usually the a variable defined somewhere (i.e. "Name" is the name given to the component in RobotBuilder, such as "Arm Motor"), and turns it into the name of a variable defined in the generated code. For example, `#variable("Arm Motor")` results in the string `ArmMotor`

Variables are referenced by placing a dollar sign ("\$\$") in front of the variable name, which an optionally be placed inside curly braces to easily distinguish the variable from other text in the file. When the file is parsed, the dollar sign, variable name, and curly braces are replaced with the value of the variable (e.g. `#{ClassName}` is replaced with `KiwiDrive`).

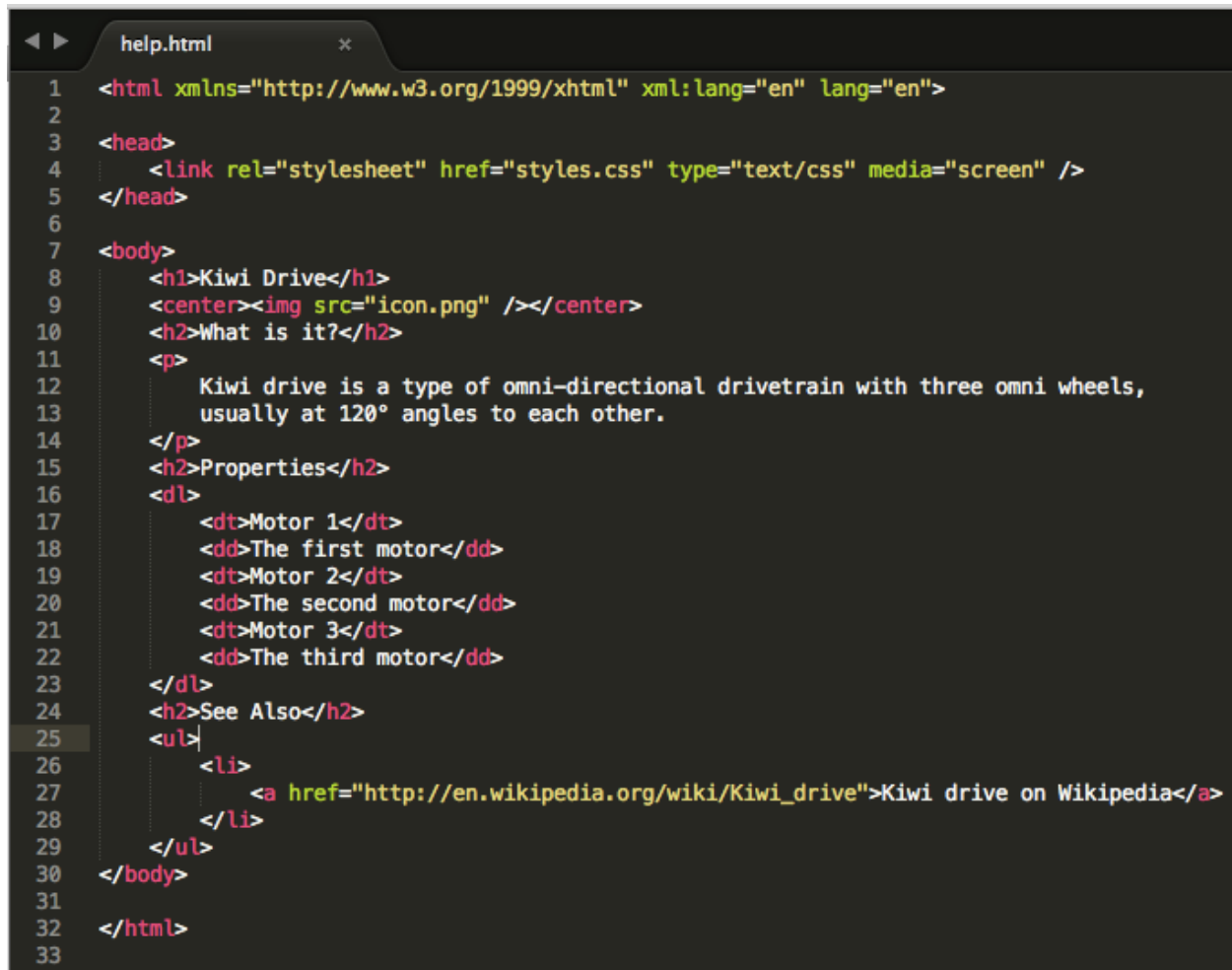
Variables are either component properties (e.g. "Motor 1", "Motor 2", "Motor 3" in the kiwi drive example), or one of the following:

1. `Short_Name`: the name given to the component in the editor panel in RobotBuilder
2. `Name`: the full name of the component. If the component is in a subsystem, this will be the short name appended to the name of the subsystem
3. `Export`: The name of the file this component should be created in, if any. This should be "RobotMap" for components like actuators, controllers, and sensors; or "OI" for things like gamepads or other custom OI components. Note that the "CustomComponent" default will export to the RobotMap.
4. `Import`: Files that need to be included or imported for this component to be able to be used.
5. `Declaration`: an instruction, similar to `Construction`, for how to declare a variable of this component type. This is taken care of by the default "None"
6. `Construction`: an instruction for how to create a new instance of this component
7. `LiveWindow`: an instruction for how to add this component to the LiveWindow
8. `Extra`: instructions for any extra functions or method calls for this component to behave correctly, such as encoders needing to set the encoding type.
9. `Prototype (C++ only)`: The prototype for a function to be created in the file the component is declared in, typically a getter in the OI class
10. `Function`: A function to be created in the file the component is declared in, typically a getter in the OI class
11. `PID`: An instruction for how to get the PID output of the component, if it has one (e.g. `#variable($Short_Name)->PIDGet()`)
12. `ClassName`: The name of the class that the component represents (e.g. `KiwiDrive` or `Joystick`)

If you have variables with spaces in the name (such as "Motor 1", "Right Front Motor", etc.), the spaces need to be replaced with underscores when using them in the export files.



## help.html



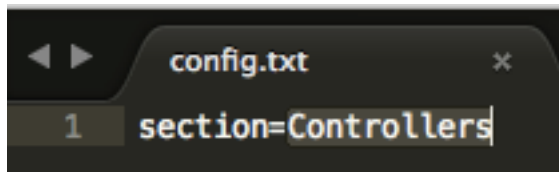
```

1 <html xmlns="http://www.w3.org/1999/xhtml" xml:lang="en" lang="en">
2
3 <head>
4   <link rel="stylesheet" href="styles.css" type="text/css" media="screen" />
5 </head>
6
7 <body>
8   <h1>Kiwi Drive</h1>
9   <center></center>
10  <h2>What is it?</h2>
11  <p>
12    Kiwi drive is a type of omni-directional drivetrain with three omni wheels,
13    usually at 120° angles to each other.
14  </p>
15  <h2>Properties</h2>
16  <dl>
17    <dt>Motor 1</dt>
18    <dd>The first motor</dd>
19    <dt>Motor 2</dt>
20    <dd>The second motor</dd>
21    <dt>Motor 3</dt>
22    <dd>The third motor</dd>
23  </dl>
24  <h2>See Also</h2>
25  <ul>
26    <li>
27      <a href="http://en.wikipedia.org/wiki/Kiwi_drive">Kiwi drive on Wikipedia</a>
28    </li>
29  </ul>
30 </body>
31
32 </html>
33

```

A HTML file giving information on the component. It is better to have this be as detailed as possible, though it certainly isn't necessary if the programmer(s) are familiar enough with the component, or if it's so simple that there's little point in a detailed description.

## config.txt



```

1 section=Controllers

```

A configuration file to hold miscellaneous information about the component. Currently, this only has the section of the palette to put the component in.

The sections of the palette (these are case sensitive):

- Subsystems
- Controllers

- Sensors
- Actuators
- Pneumatics
- OI
- Commands

### **icon.png**

The icon that shows up in the palette and the help page. This should be a 64x64 .png file.

It should use the color scheme and general style of the section it's in to avoid visual clutter, but this is entirely optional. Photoshop .psd files of the icons and backgrounds are in [src/main/icons/icons](#) and png files of the icons and backgrounds are in [src/main/resources/icons](#).

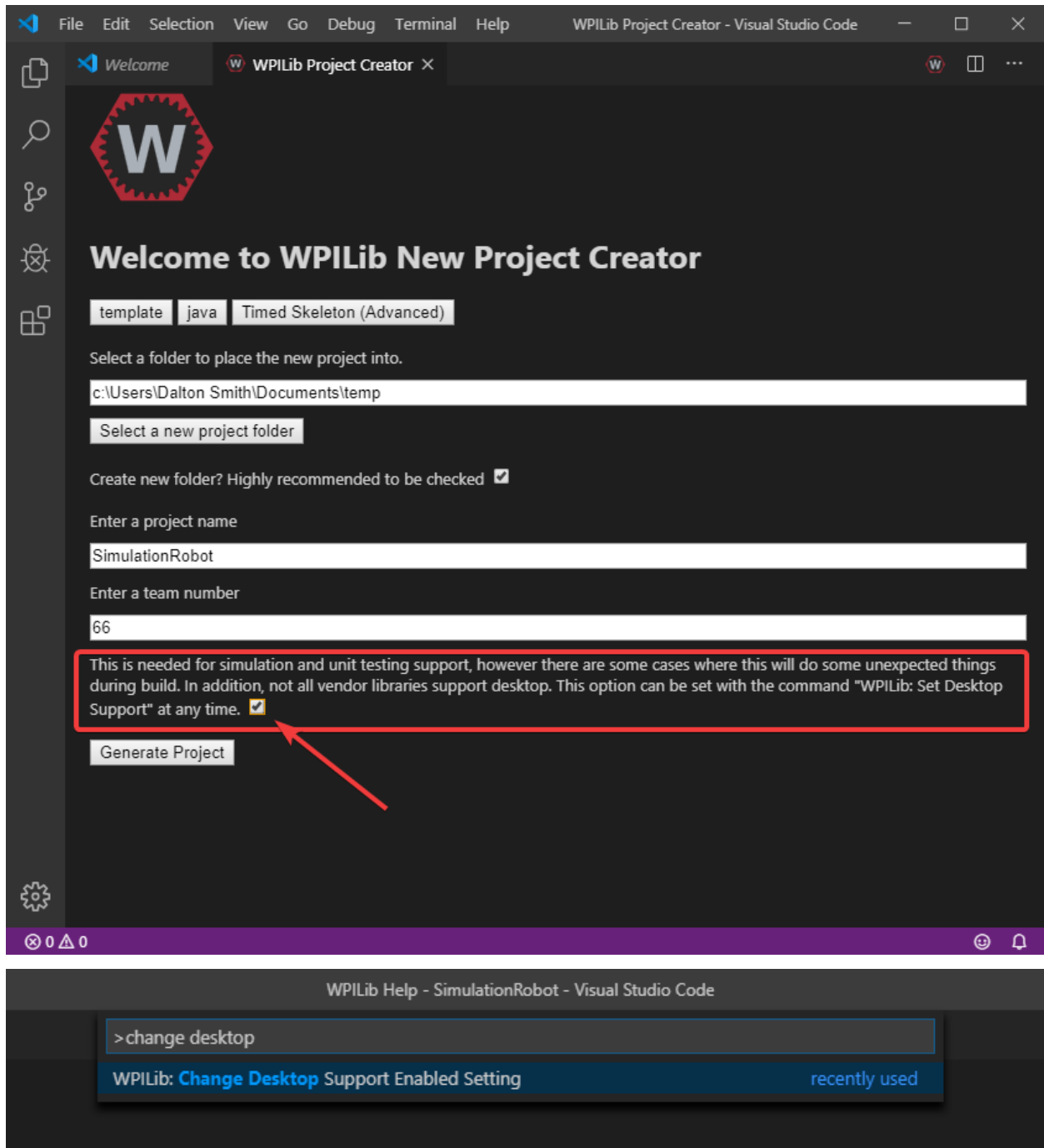


## **15.1 Introduction to Robot Simulation**

Often a team may want to test their code without having an actual robot available. WPILib provides teams with the ability to simulate various robot features using simple gradle commands.

### **15.1.1 Enabling Desktop Support**

Use of the Desktop Simulator requires Desktop Support to be enabled. This can be done by checking the “Enable Desktop Support Checkbox” when creating your robot project or by running “WPILib: Change Desktop Support Enabled Setting” from the Visual Studio Code command palette.



Desktop support can also be enabled by manually editing your `build.gradle` file located at the root of your robot project. Simply change `includeDesktopSupport = false` to `includeDesktopSupport = true`

```
def includeDesktopSupport = true
```

**Important:** It is important to note that enabling desktop/simulation support can have unintended consequences. Not all vendors will support this option, and code that uses their

libraries may even crash when attempting to run simulation!

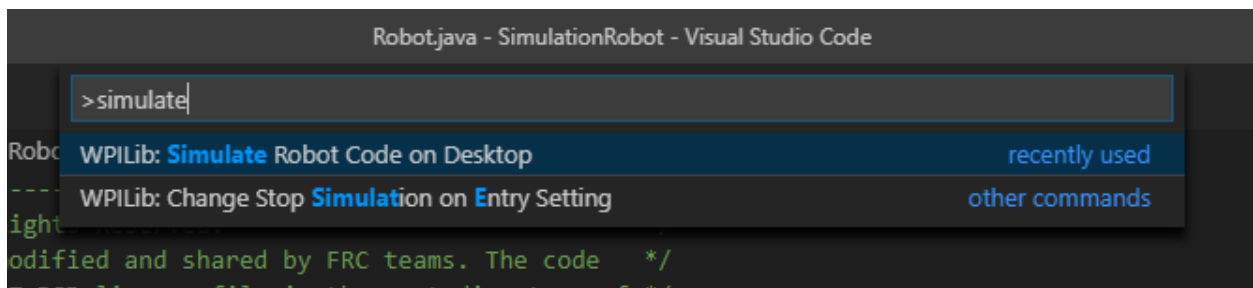
If at any point in time you want to disable Desktop Support, simply re-run the “WPILib: Change Desktop Support Enabled Setting” from the command palette.

### Additional C++ Dependency

C++ robot simulation requires that a native compiler to be installed. For Windows, this would be [Visual Studio 2019](#) (**not** VS Code), macOS requires [Xcode](#), and Linux (Ubuntu) requires the build-essential package.

## 15.1.2 Running Robot Simulation

Basic robot simulation can be run using VS Code. This can be done without using any commands by using VS Code’s command palette.



Your console output in Visual Studio Code should look like the below. However, teams probably will want to actually *test* their code versus just running the simulation. This can be done using [WPILib’s Simulation GUI](#).

```
***** Robot program starting *****
Default disabledInit() method... Override me!
Default disabledPeriodic() method... Override me!
Default robotPeriodic() method... Override me!
```

**Important:** Simulation can also be run outside of VS Code using `./gradlew simulateJava`. It’s important to note that C++ simulation is not available through command-line at this time.

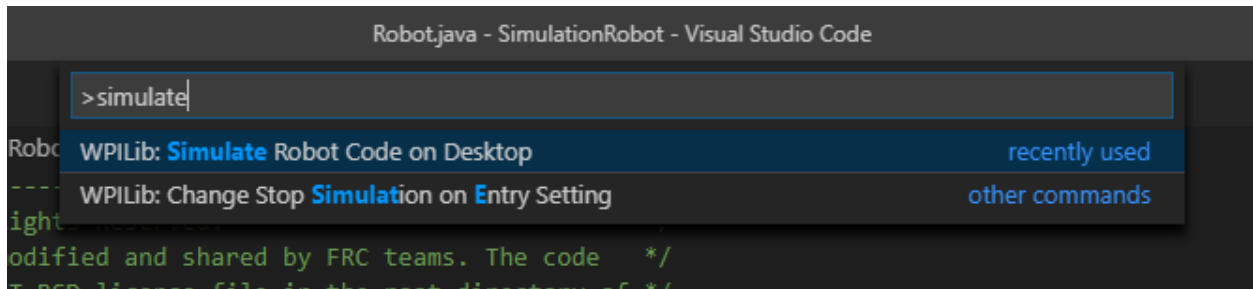
**Note:** macOS users should be aware of the [simulation fails to launch known issue](#)

## 15.2 Simulation User Interface

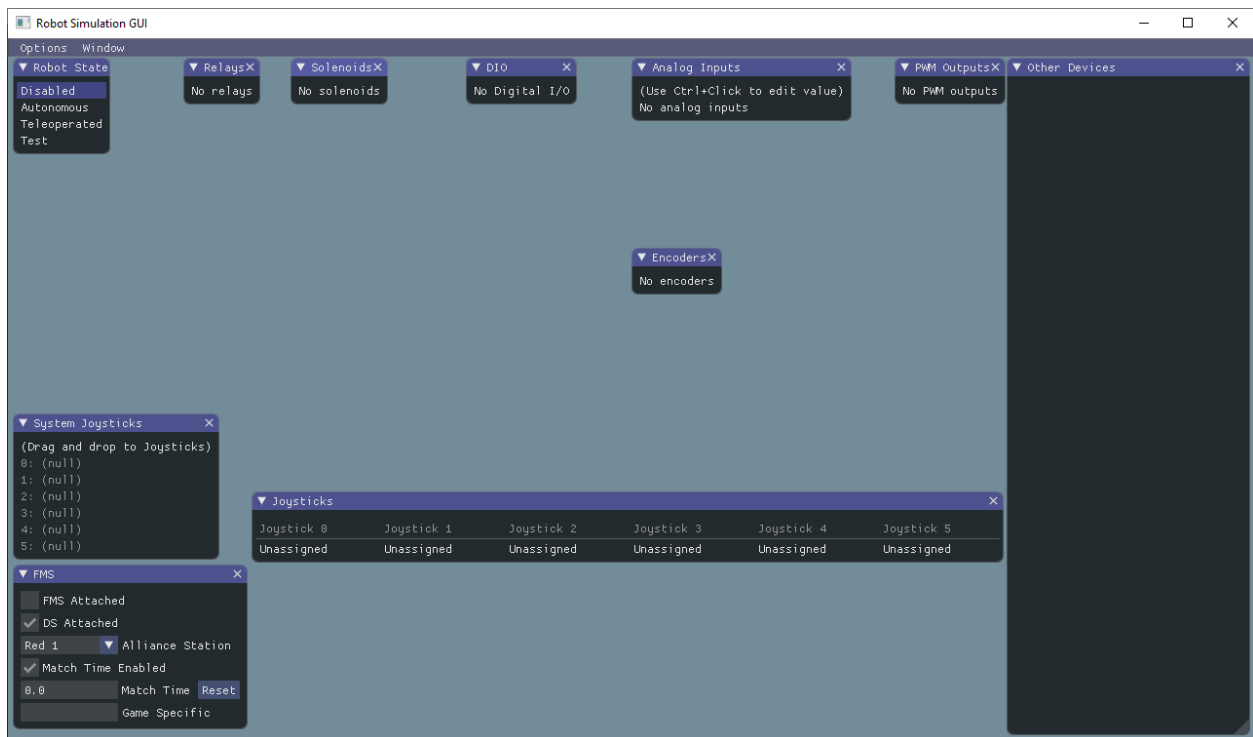
WPILib has extended robot simulation to introduce a graphical user interface (GUI) component. This allows teams to easily visualize their robot’s inputs and outputs.

## 15.2.1 Running the GUI

You can simply launch the GUI via the **Run Simulation** command palette option.



And the `halsim_gui.dll` option should popup in a new dialog. Select this and press **Ok**. This will now launch the Simulation GUI!



## 15.2.2 Using the GUI

## Learning the Layout

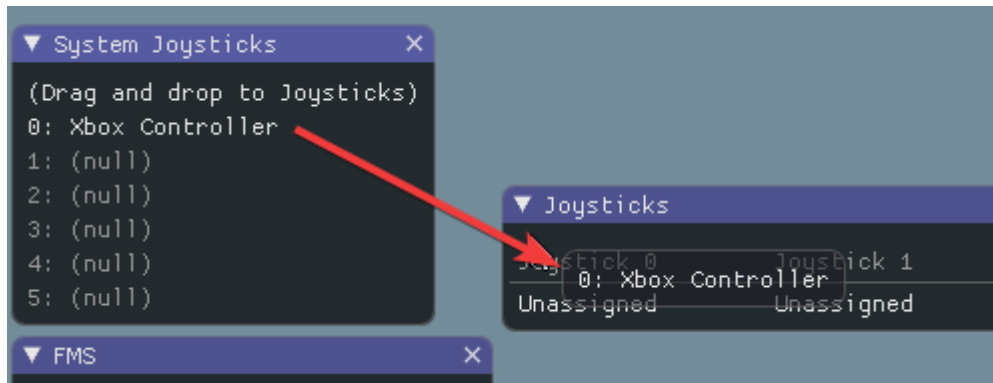


- 1. Robot State** - This is the robot's current state or "mode". You can click on the labels to change mode as you would on the normal Driver Station.
- 2. Relays** - This includes any relay devices. This includes VEX Spike relays.
- 3. Solenoids** - This is a list of "connected" solenoids. When you create a solenoid object and push outputs, these are shown here.
- 4. DIO** - (Digital Input Output) This includes any devices that use the **DIO** connector on the roboRIO.
- 5. Analog Inputs** - This includes any devices that would normally use the **ANALOG IN** connector on the roboRIO, such as any Analog based gyros.
- 6. PWM Outputs** - This is a list of instantiated PWM devices. This will appear as many devices as you instantiate in robot code, as well as their outputs.
- 7. Encoders** - This will show any instantiated devices that extend or use the Encoder class.
- 8. System Joysticks** - This is a list of joysticks connected to your system currently.
- 9. FMS** - This is used for simulating many of the common FMS systems.
- 10. Joysticks** - This is joysticks that the robot code can directly pull from.
- 11. Other Devices** - This includes devices that do not fall into any of the other categories, such as the ADXRS450 gyro that is included in the Kit of Parts.

## Adding a System Joystick to Joysticks

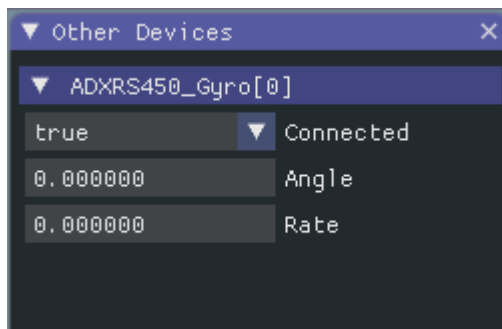
To add a joystick from the list of system joysticks, simply click and drag a shown joystick under the "System Joysticks" menu to the "Joysticks" menu".





### Modifying ADXRS450 Inputs

Using the ADXRS450 object is a fantastic way to test gyro based outputs. This will show up in the “Other Devices” menu. A drop down menu is then exposed that shows various options such as “Connected”, “Angle”, and “Rate”. All of these values are values that you can change, and that your robot code can use on-the-fly.



### 15.2.3 Determining Simulation from Robot Code

In cases where vendor libraries do not compile when running the robot simulation, you can wrap their content with `RobotBase.isReal()` which returns a boolean.

Java

```
TalonSRX motorLeft;
TalonSRX motorRight;

public Robot() {
    if (RobotBase.isReal()) {
        motorLeft = new TalonSRX(0);
        motorRight = new TalonSRX(1);
    }
}
```

**Note:** Reassigning value types in C++ requires move or copy assignment; vendors classes that both do not support the SIM and lack a move or copy assignment operator cannot be worked around with conditional allocation unless a pointer is used, instead of a value type.

## 16.1 Introduction to Robot Characterization

The characterization tools consist of a python application that runs on the user's PC and matching robot code that runs on the user's robot. The PC application will send control signals to the robot over network tables, while the robot sends data back to the application. The application then processes the data and determines characterization parameters for the user's robot mechanism, as well as producing diagnostic plots. Data can be saved (in JSON format) for future use, if desired.

### 16.1.1 What is “Characterization?”

“Characterization” - or, more formally, [system identification](#) - is the process of determining a mathematical model for the behavior of a system through statistical analysis of its inputs and outputs.

In FRC, the most common system that we're interested in characterizing is the [permanent-magnet DC motor](#). In particular, we're interested in figuring out which motor *input* (i.e. voltage from the motor controller) is required to achieve our desired *outputs* (i.e. velocity and acceleration of the motor).

Fortunately, it is not so difficult to do this. A permanent-magnet DC motor (with no load other than friction and inertia) will obey the following “voltage-balance equation” (for more information, see [this paper](#)):

$$V = kS \cdot \text{sgn}(\dot{d}) + kV \cdot \dot{d} + kA \cdot \ddot{d}$$

where  $V$  is the applied voltage,  $d$  is the displacement (position) of the motor,  $\dot{d}$  is its velocity, and  $\ddot{d}$  is its acceleration (the “overdot” notation traditionally denotes the [derivative](#) with respect to time).

Heuristically, we can interpret the coefficients in the above equation as follows:

$kS$  is the voltage needed to overcome the motor's static friction, or in other words to just barely get it moving; it turns out that this static friction (because it's, well, static) has the same effect regardless of velocity or acceleration. That is, no matter what speed you're going or how fast you're accelerating, some constant portion of the voltage you've applied to your motor (depending on the specific mechanism assembly) will be going towards overcoming

the static friction in your gears, bearings, etc; this value is your  $kS$ . Note the presence of the **signum function**, because friction force always opposes the direction-of-motion.

$kV$  describes how much voltage is needed to hold (or “cruise”) at a given constant velocity while overcoming the **electromagnetic resistance in the motor** and any additional friction that increases with speed (known as **viscous drag**). The relationship between speed and voltage (at constant acceleration) is almost entirely linear (with FRC components, anyway) because of how permanent-magnet DC motors work.

$kA$  describes the voltage needed to induce a given acceleration in the motor shaft. As with  $kV$ , the relationship between voltage and acceleration (at constant velocity) is almost perfectly linear for FRC components.

Once these coefficients have been determined (here accomplished by a **multiple linear regression**), we can then take a given desired velocity and acceleration for the motor and calculate the voltage that should be applied to achieve it. This is very useful - not only for, say, following motion profiles, but also for making mechanisms more controllable in open-loop control, because your joystick inputs will more closely match the actual mechanism motion.

Some of the tools in this toolsuite introduce additional terms into the above equation to account for known differences from the simple case described above - details for each tool can be found below:

### 16.1.2 Included Characterization Tools

---

**Note:** Many other types of mechanisms can be characterized by simply adapting the existing code in this library.

---

The robot characterization toolsuite currently supports characterization for:

- Simple Motor Setups
- Drivetrains
- Arms
- Elevators

#### Simple Motor Characterization

The simple motor characterization tool determines the best-fit parameters for the equation:

$$V = kS \cdot \text{sgn}(\dot{d}) + kV \cdot \dot{d} + kA \cdot \ddot{d}$$

where  $V$  is the applied voltage,  $d$  is the displacement (position) of the drive,  $\dot{d}$  is its velocity, and  $\ddot{d}$  is its acceleration. This is the model for a permanent-magnet dc motor with no loading other than friction and inertia, as mentioned above, and is an accurate model for flywheels, turrets, and horizontal linear sliders.

#### Drivetrain Characterization

The drivetrain characterization tool determines the best-fit parameters for the equation:

$$V = kS \cdot \text{sgn}(\dot{d}) + kV \cdot \dot{d} + kA \cdot \ddot{d}$$

where  $V$  is the applied voltage,  $d$  is the displacement (position) of the drive,  $\dot{d}$  is its velocity, and  $\ddot{d}$  is its acceleration. This is the same modeling equation as is used in the simple motor characterization - however, the drivetrain characterizer is specifically set up to run on differential drives, and will characterize each side of the drive independently if desired.

The drivetrain characterizer can also determine the effective trackwidth of your robot using a gyro.

### Arm Characterization

The arm characterization tool determines the best-fit parameters for the equation:

$$V = kS \cdot \text{sgn}(\dot{\theta}) + kCos \cdot \cos(\theta) + kV \cdot \dot{\theta} + kA \cdot \ddot{\theta}$$

where  $V$  is the applied voltage,  $\theta$  is the angular displacement (position) of the arm,  $\dot{\theta}$  is its angular velocity, and  $\ddot{\theta}$  is its angular acceleration. The cosine term ( $kCos$ ) is added to correctly account for the effect of gravity.

### Elevator Characterization

The elevator characterization tool determines the best-fit parameters for the equation:

$$V = kG + kS \cdot \text{sgn}(\dot{d}) + kV \cdot \dot{d} + kA \cdot \ddot{d}$$

where  $V$  is the applied voltage,  $d$  is the displacement (position) of the drive,  $\dot{d}$  is its velocity, and  $\ddot{d}$  is its acceleration. The constant term ( $kG$ ) is added to correctly account for the effect of gravity.

## 16.1.3 Prerequisites

To use the Robot Characterization Toolsuite, you must have Python 3.7 installed on your computer, as well as the standard WPILib programming toolsuite.

[Python 3.7](#)

**Warning:** Do not install Python from the Microsoft Store. Please use the link above to download and install Python.

## 16.1.4 Installing and Launching the Toolsuite

To install the Robot Characterization Toolsuite, open a console and enter the following command

```
pip install frc-characterization
```

The toolsuite, and all of its dependencies, should be automatically downloaded and installed. If you are using a Windows machine and the command pip is not recognized, ensure that your python scripts folder [has been added to the PATH](#).

**Note:** If you are on Ubuntu, you will have to manually install tkinter with `sudo apt-get install python3-tk`. You will also have to use the `pip3` command instead of `pip` as `pip` refers to Python 2 on Ubuntu distributions.

---

If you already have the toolsuite installed, be sure to update it regularly to benefit from bug-fixes and new features additions:

```
pip install --upgrade frc-characterization
```

Once the toolsuite has been installed, launch a new drive characterization project to ensure that it works by running the following command from powershell or a terminal window.

```
frc-characterization drive new
```

The new project GUI should open momentarily. To launch other characterization projects, simply replace `drive` with the desired characterization type.

While the new project GUI has buttons for launching both the logging tool and the analyzer tool, these can also be launched directly from the CLI by replacing `new` with `logger` or `analyzer`.

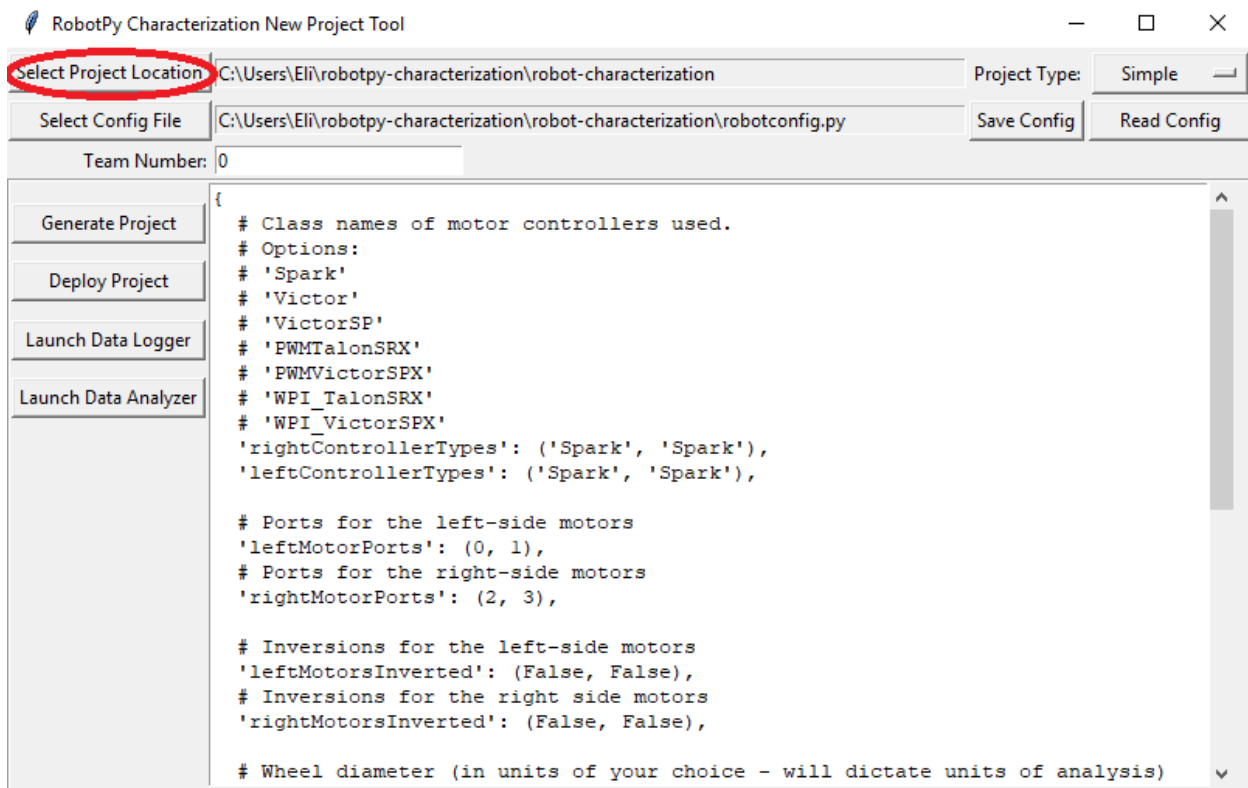
For more information on CLI usage, enter `frc-characterization -h`.

## 16.2 Generating a Project

To use the toolsuite, we first need to generate a robot project.

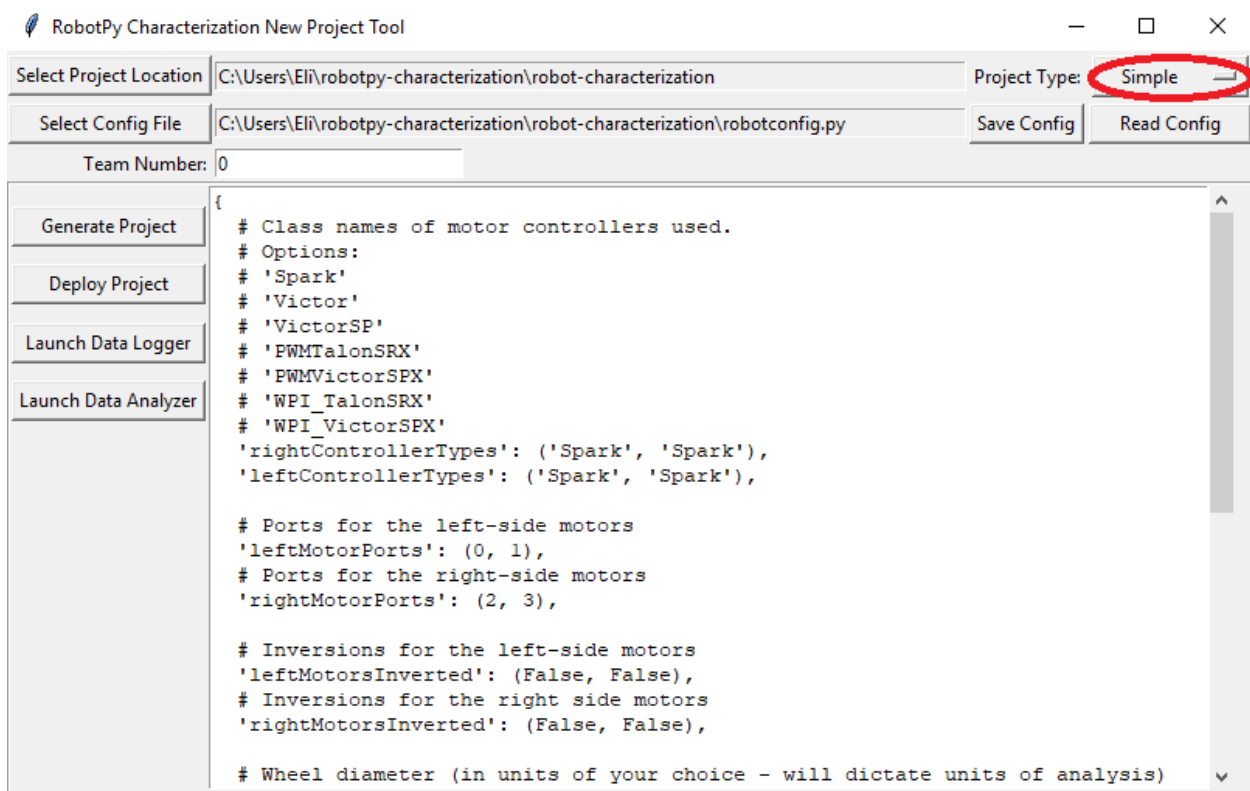
### 16.2.1 Select Project Location

First, select the desired project location on the new project GUI:



### 16.2.2 Select Project Type

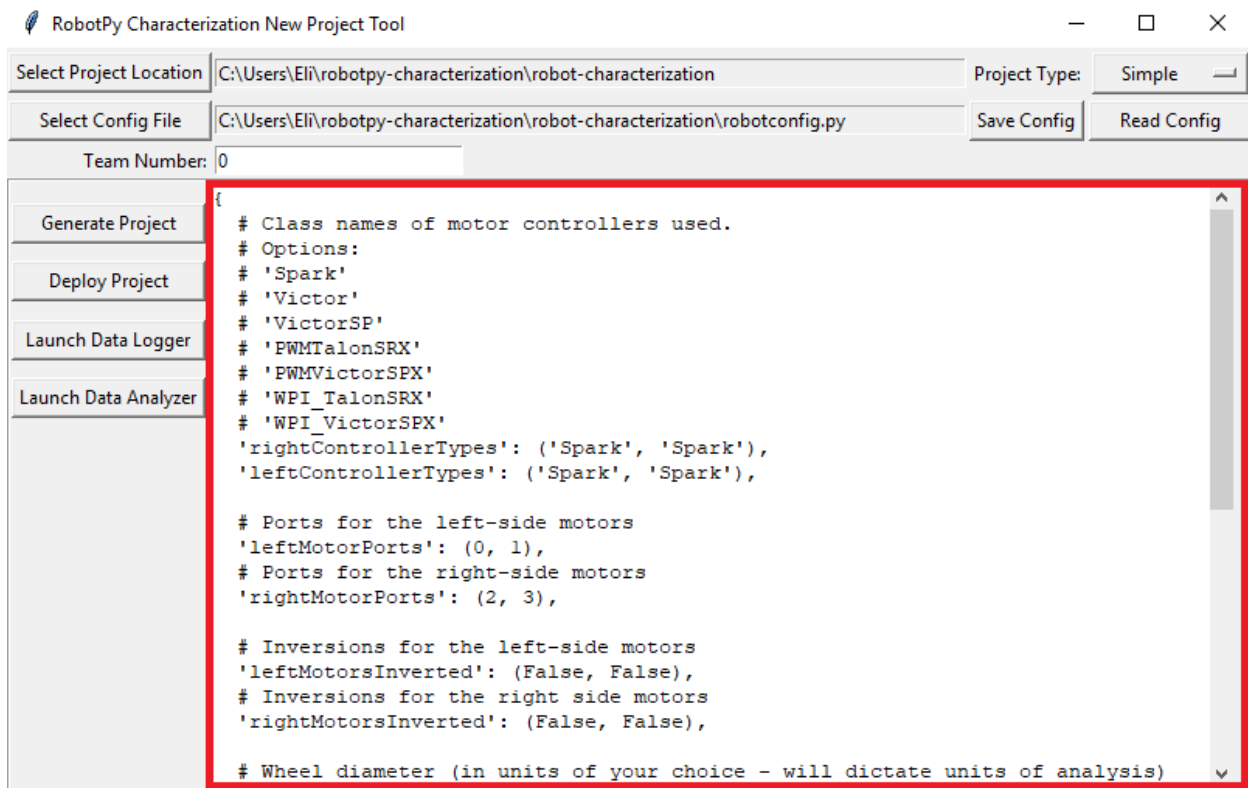
Next, select your project type from the drop-down menu:



- **Simple** projects use encoders plugged into the RIO's DIO ports, and measure voltage with the PDP.
- **Talon** projects use encoders plugged into a Talon SRX, and measure voltage with the Talon.
- **SparkMax (Brushed)** projects use encoders plugged into a SparkMax motor controller with a *brushed* motor, and measure voltage with the Spark.
- **SparkMax (Brushless/Neo)** projects use the internal encoder of a NEO motor, and measure voltage with the SparkMax motor controller.
- More project types may be added in the future.

### 16.2.3 Configure Project Parameters

In order to run on your robot, the tool must know some parameters about how your robot is set up. Project config settings are formatted as a [Python dictionary literal](#). These can be modified via the in-window config editor:

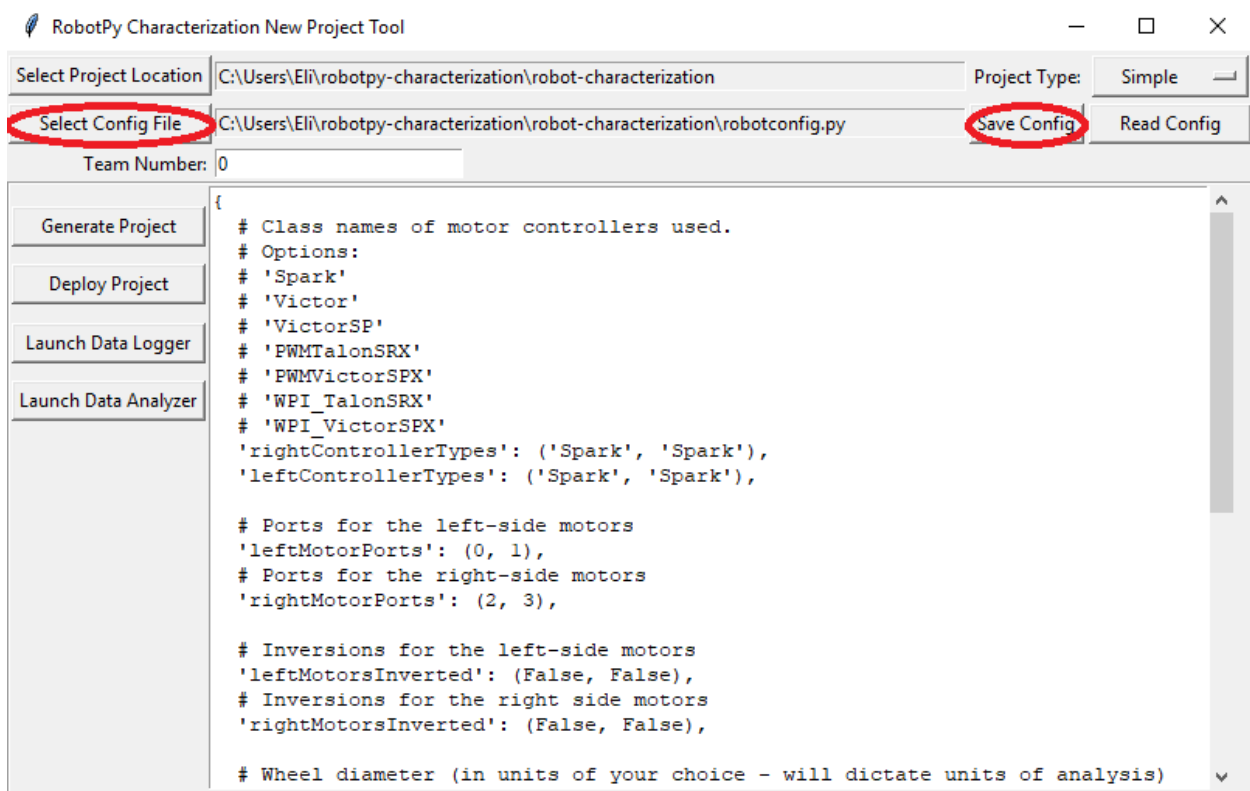


Take care of the following caveats when entering your robot specifications:

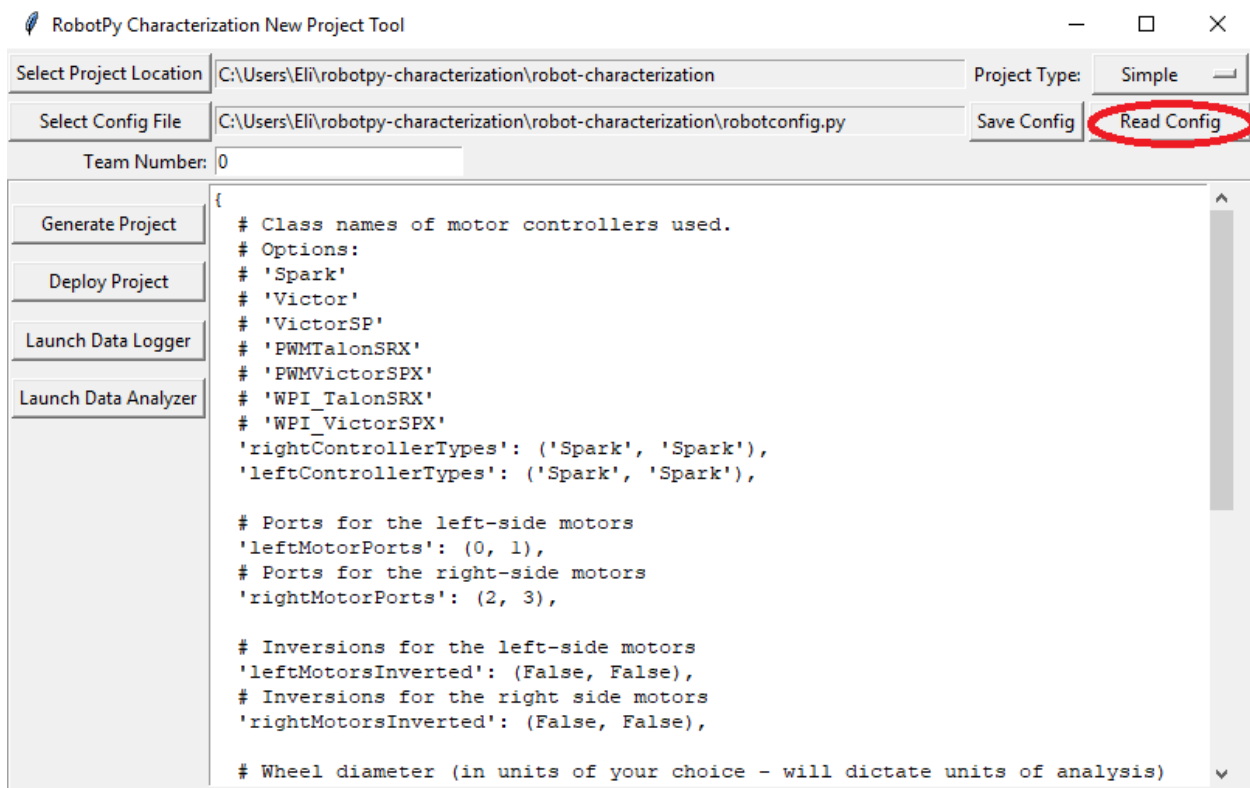
- The key names must *not be changed*, as they are hard-coded for each project type. Only the values (i.e. the things on the right-hand side of the colons) should be modified.
- True and False *must* be capitalized, as they are evaluated as native Python.
- All string values (e.g. controller names and unit types) *must* be wrapped in quotes and *must* correspond exactly to one of the options described.

Once your robot configuration is set, you may save it to a location/name of your choice:



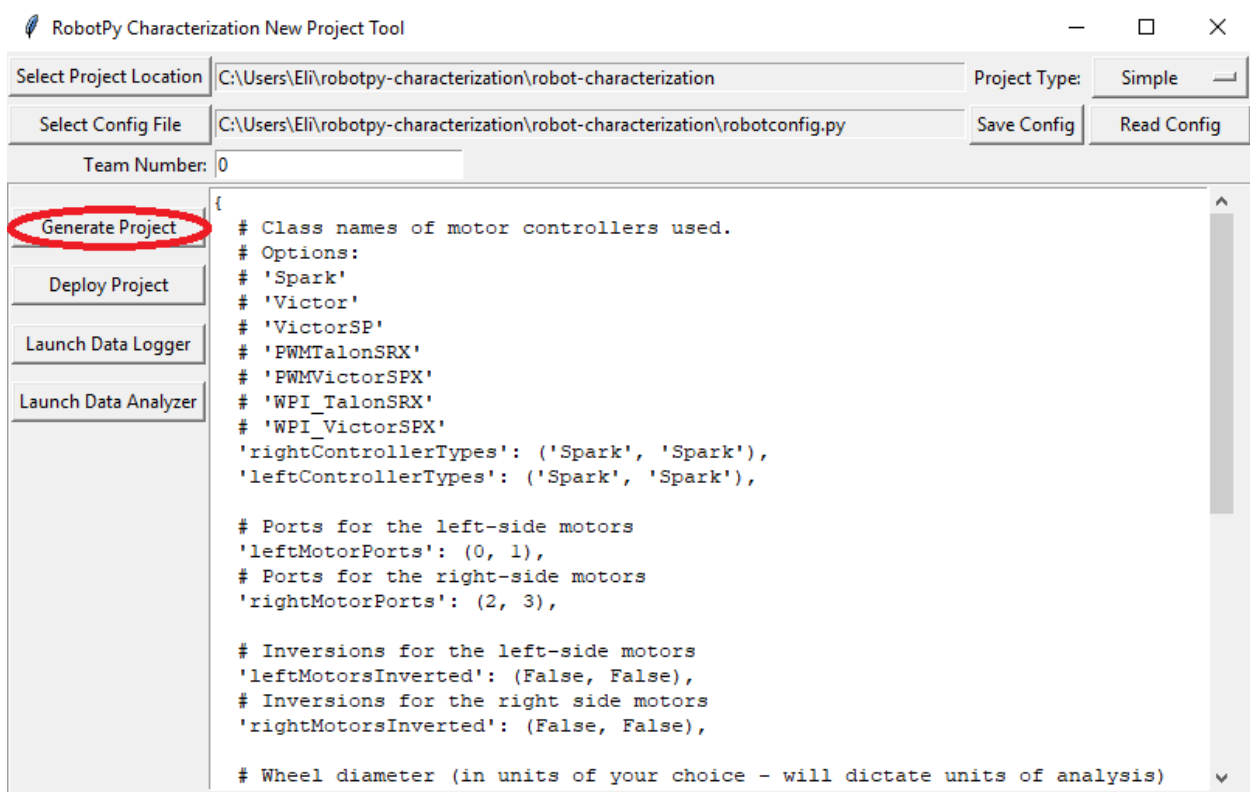


Accordingly, you can also load an existing config file (config files are project-type-specific):



## 16.2.4 Generate Project

Once your project has been configured, it's time to generate a deployable robot project to run the characterization:



A generated robot project will be placed in a subfolder (named characterization-project) of your specified project location.

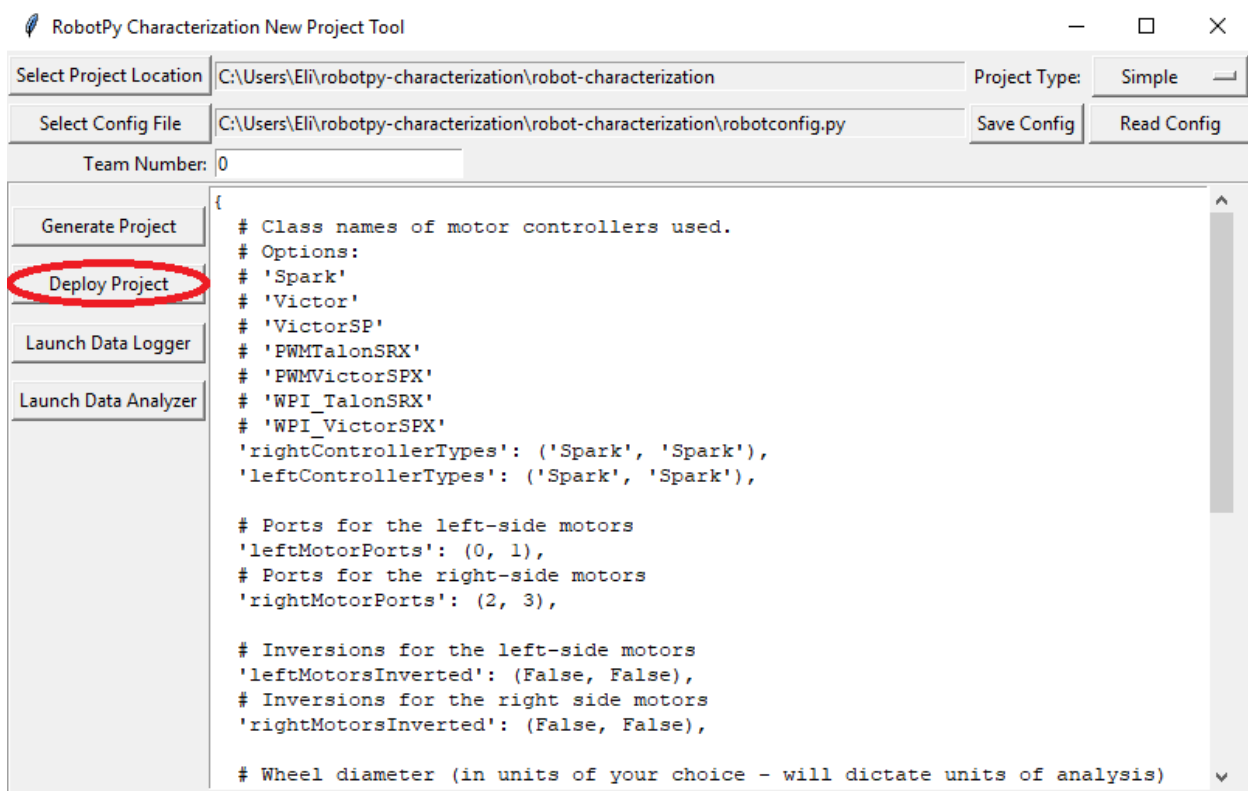
The generated robot code will be in Java, and will reflect the settings specified in your config file. Advanced users are free to modify the generated code to their liking, if the existing configuration options do not suffice.

## 16.3 Deploying a Project

Once a project has been generated, it is time to deploy it to the robot. This can be done in two ways.

### 16.3.1 Option 1: Using the Deploy Project Button

Pressing the Deploy Project button on the GUI will attempt to use GradleRIO to deploy the project to your robot. The GUI will always *assume* that the project is located in the characterization-project subfolder of the chosen project location.



Assuming a valid robot project is present at that location, a window should pop up displaying the Gradle output as the project builds and deploys.



## 16.3.2 Option 2: Deploying Manually

Since the generated project is a standard GradleRIO Java project, it can be deployed like any other. Users may open the generated project in their editor of choice and deploy as they normally would any other robot project. This can be convenient if customization of the generated code is required.

Now that the characterization code has been deployed, you'll need to run the characterization routine.

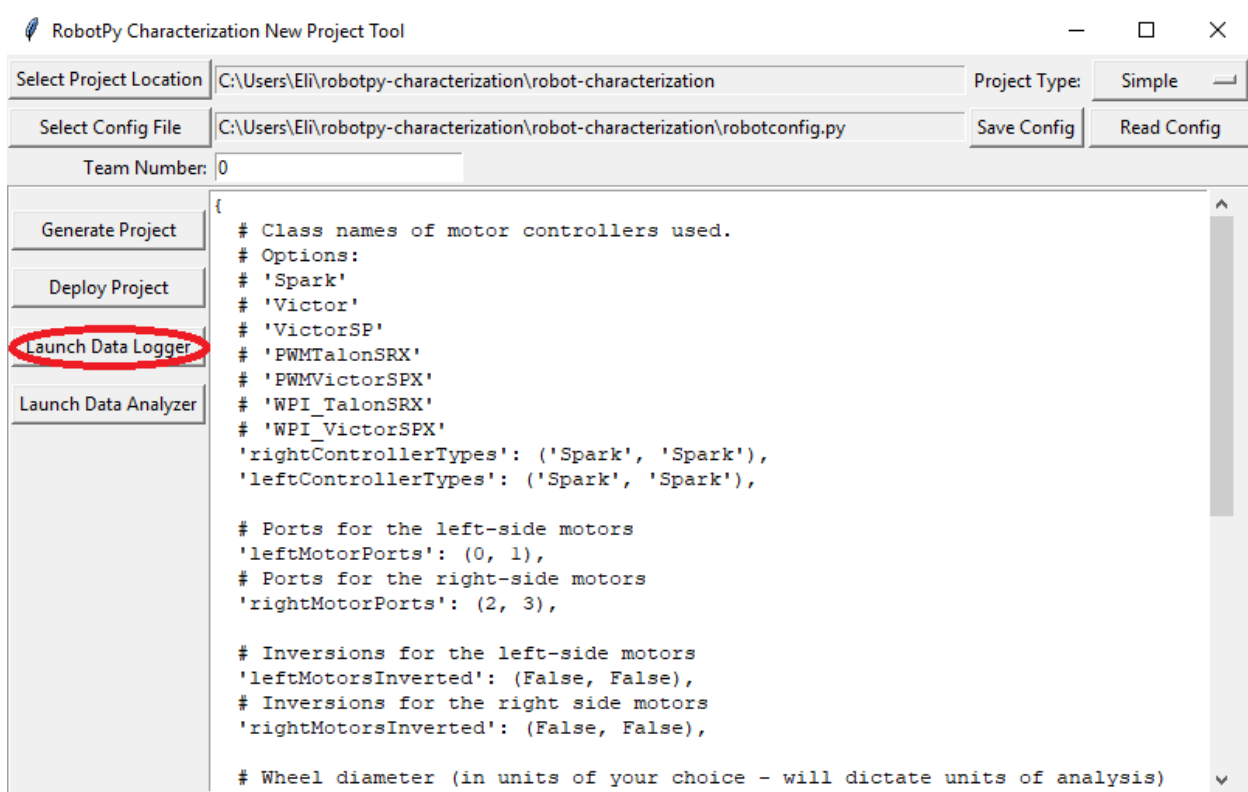
## 16.4 Running the Characterization Routine

Once the characterization code has been deployed, we can now run the characterization routine, and record the resulting data for analysis.

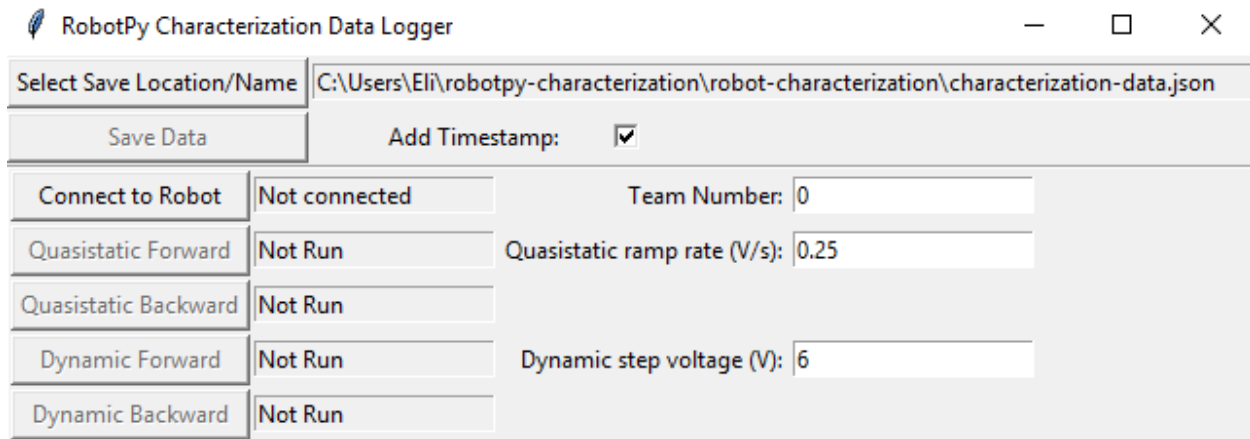
**Note:** Ensure you have sufficient space around the robot before running any characterization routine! The drive characterization requires at least 10' of space, ideally closer to 20'. The robot drive can not be accurately characterized while on blocks.

### 16.4.1 Launch the Data Logger

To launch the data logger, press the Launch Data Logger button.



This should open the data logger GUI.



RobotPy Characterization Data Logger

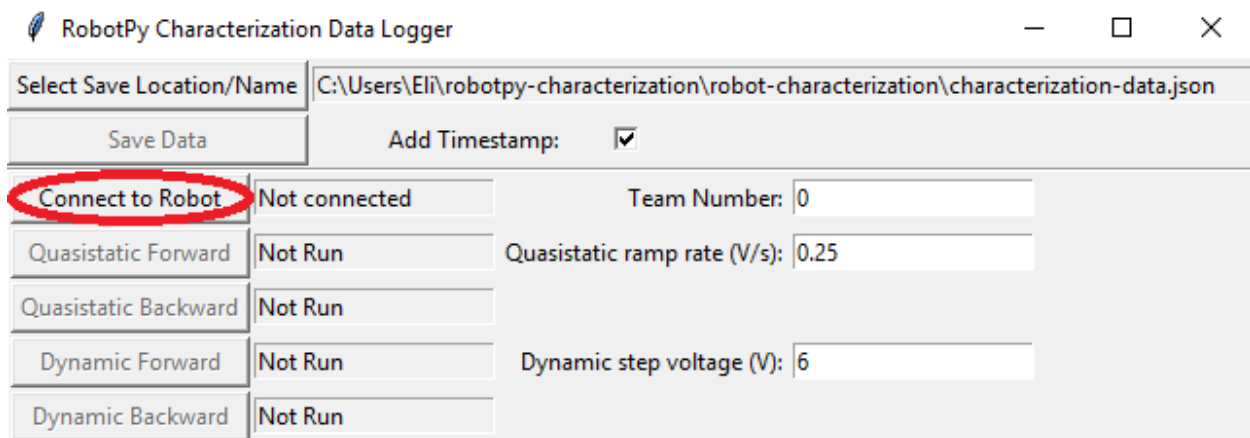
Select Save Location/Name: C:\Users\Eli\robotpy-characterization\robot-characterization\characterization-data.json

Save Data Add Timestamp: ☒

Connect to Robot	Not connected	Team Number: 0
Quasistatic Forward	Not Run	Quasistatic ramp rate (V/s): 0.25
Quasistatic Backward	Not Run	
Dynamic Forward	Not Run	Dynamic step voltage (V): 6
Dynamic Backward	Not Run	

### 16.4.2 Connect to the Robot

Next, we must connect to the robot. Press the **Connect to Robot** button. The status indicated next to the button should change to **Connecting...** while the tool attempts to connect to the robot's NetworkTables server.



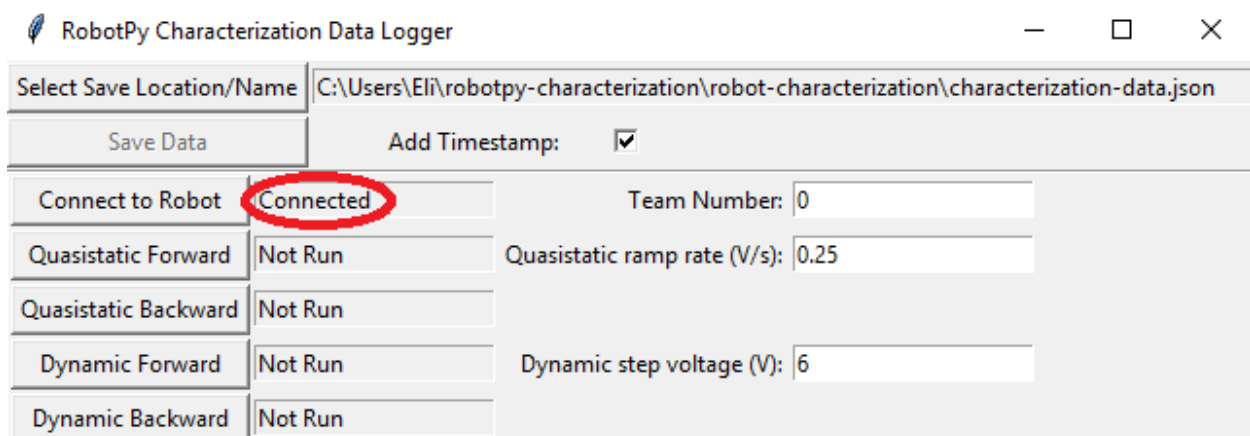
RobotPy Characterization Data Logger

Select Save Location/Name: C:\Users\Eli\robotpy-characterization\robot-characterization\characterization-data.json

Save Data Add Timestamp: ☒

<b>Connect to Robot</b>	Not connected	Team Number: 0
Quasistatic Forward	Not Run	Quasistatic ramp rate (V/s): 0.25
Quasistatic Backward	Not Run	
Dynamic Forward	Not Run	Dynamic step voltage (V): 6
Dynamic Backward	Not Run	

If the tool does not seem to be successfully connecting, try rebooting the robot. Eventually, the status should change to **Connected**, indicating the tool is successfully communicating with the robot.



RobotPy Characterization Data Logger

Select Save Location/Name: C:\Users\Eli\robotpy-characterization\robot-characterization\characterization-data.json

Save Data Add Timestamp: ☒

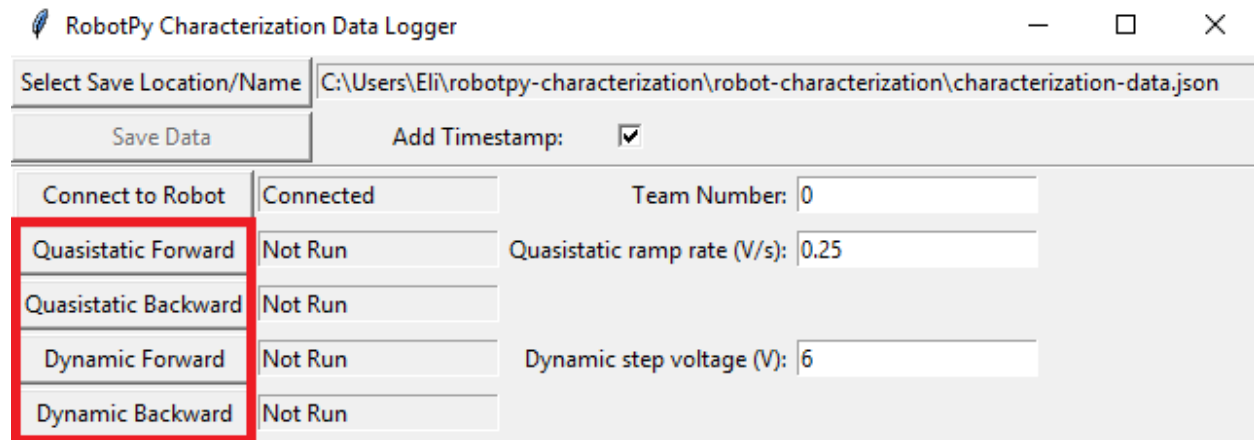
<b>Connected</b>	Connected	Team Number: 0
Quasistatic Forward	Not Run	Quasistatic ramp rate (V/s): 0.25
Quasistatic Backward	Not Run	
Dynamic Forward	Not Run	Dynamic step voltage (V): 6
Dynamic Backward	Not Run	

### 16.4.3 Running Tests

A standard motor characterization routine consists of two types of tests:

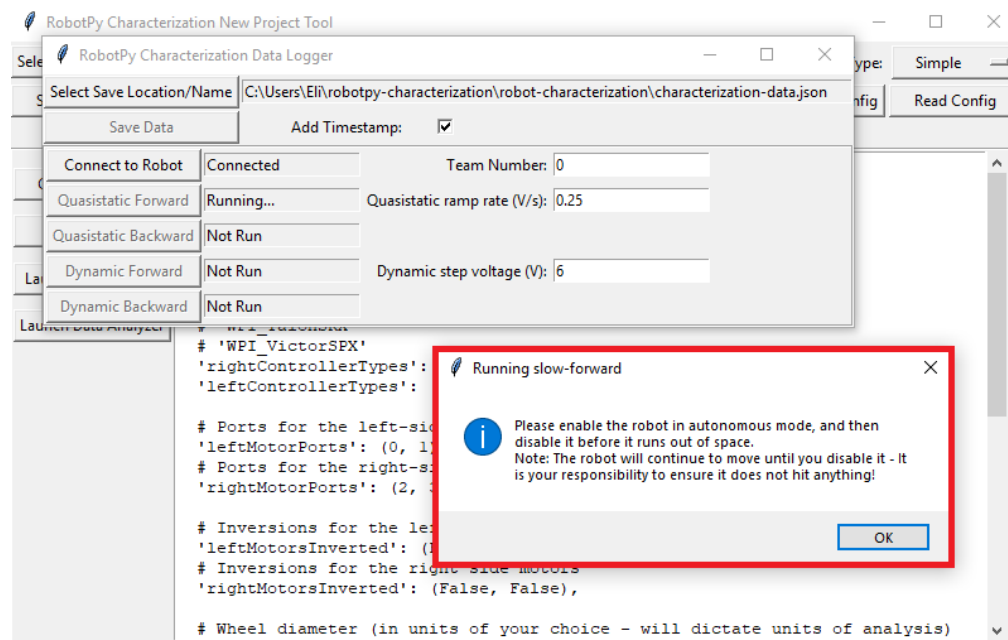
- **Quasistatic:** In this test, the mechanism is gradually sped-up such that the voltage corresponding to acceleration is negligible (hence, “as if static”).
- **Dynamic:** In this test, a constant ‘step voltage’ is given to the mechanism, so that the behavior while accelerating can be determined.

Each test type is run both forwards and backwards, for four tests in total, corresponding to the four buttons.



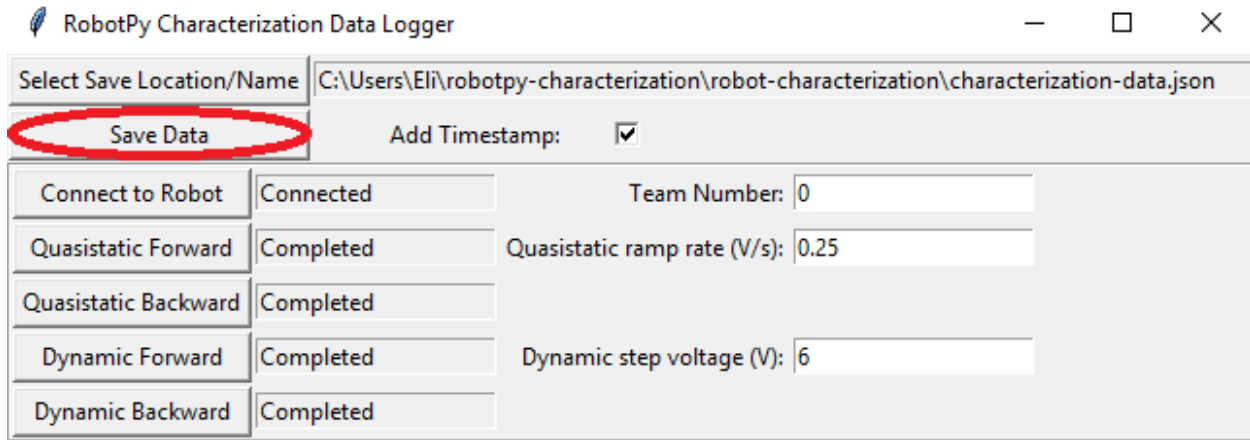
The tests can be run in any order, but running a “backwards” test directly after a “forwards” test is generally advisable (as it will more or less reset the mechanism to its original position).

Follow the instructions in the pop-up windows after pressing each test button.



The entire routine should look something like this:

After all four tests have been completed, the Save Data button will become activated.



RobotPy Characterization Data Logger

Select Save Location/Name: C:\Users\Eli\robotpy-characterization\robot-characterization\characterization-data.json

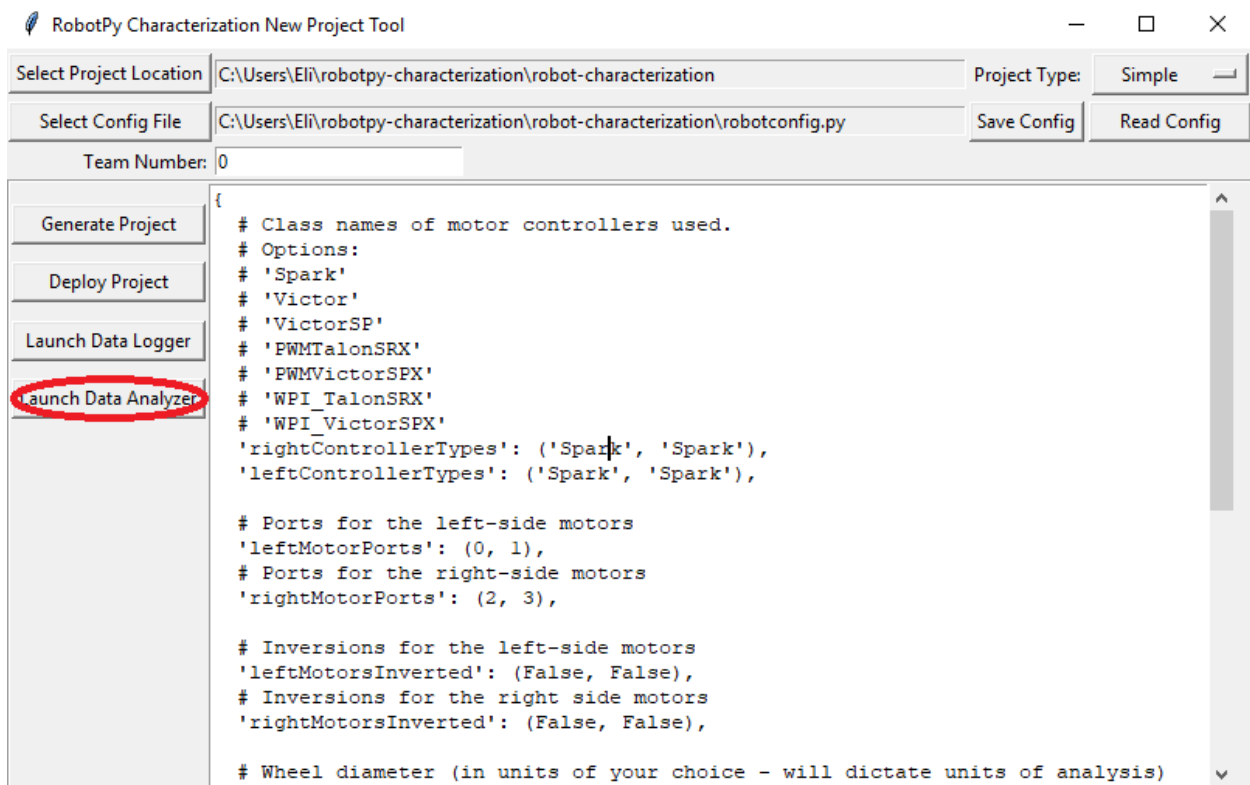
**Save Data** Add Timestamp: ☒

Connect to Robot	Connected	Team Number: 0
Quasistatic Forward	Completed	Quasistatic ramp rate (V/s): 0.25
Quasistatic Backward	Completed	
Dynamic Forward	Completed	Dynamic step voltage (V): 6
Dynamic Backward	Completed	

This will save the data as a JSON file with the specified location/name. A timestamp (%Y%m%d-%H%M) will be appended to the chosen filename if the Add Timestamp button is checked.

## 16.5 Analyzing Data

Once we have data from a characterization run, we can analyze it. To launch the data analyzer, click on the Launch Data Analyzer button.



RobotPy Characterization New Project Tool

Select Project Location: C:\Users\Eli\robotpy-characterization\robot-characterization Project Type: Simple

Select Config File: C:\Users\Eli\robotpy-characterization\robot-characterization\robotconfig.py Save Config Read Config

Team Number: 0

Generate Project Deploy Project Launch Data Logger **Launch Data Analyzer**

```
{
  # Class names of motor controllers used.
  # Options:
  # 'Spark'
  # 'Victor'
  # 'VictorSP'
  # 'PWMTalonSRX'
  # 'PWMVictorSPX'
  # 'WPI_TalonSRX'
  # 'WPI_VictorSPX'
  'rightControllerTypes': ('Spark', 'Spark'),
  'leftControllerTypes': ('Spark', 'Spark'),

  # Ports for the left-side motors
  'leftMotorPorts': (0, 1),
  # Ports for the right-side motors
  'rightMotorPorts': (2, 3),

  # Inversions for the left-side motors
  'leftMotorsInverted': (False, False),
  # Inversions for the right side motors
  'rightMotorsInverted': (False, False),

  # Wheel diameter (in units of your choice - will dictate units of analysis)
```

### 16.5.1 Loading your Data File

Now it's time to load the data file we saved from the logger tool. Click on Select Data File.

The screenshot shows the FRC Drive Characterization Tool window. At the top left, the 'Select Data File' button is circled in red. The window is divided into two main sections: 'Feedforward Analysis' on the left and 'Feedback Analysis' on the right. The 'Feedforward Analysis' section includes buttons for 'Analyze Data', 'Time-Domain Diagnostics', 'Voltage-Domain Diagnostics', and '3D Diagnostics'. It also has input fields for 'Accel Window Size' (8), 'Motion Threshold (units/s)' (0.2), 'kS' (0.0), 'kV' (0.0), 'kA' (0.0), 'r-squared' (0.0), and 'Track Width' (N/A). The 'Feedback Analysis' section includes a 'Gain Settings Preset' dropdown (Default), 'Controller Period (s)' (0.02), 'Max Controller Output' (12), 'Time-Normalized Controller' checkbox (checked), 'Controller Type' dropdown (Onboard), 'Post-Encoder Gearing' (1), 'Encoder EPR' (4096), 'Has Slave' checkbox (unchecked), 'Slave Update Period (s)' (0.01), 'Max Acceptable Position Error (units)' (0.1), 'Max Acceptable Velocity Error (units/s)' (0.2), 'Max Acceptable Control Effort (V)' (7), 'Loop Type' dropdown (Position), and input fields for 'kV' (0.0), 'kA' (0.0), 'kP' (0.0), and 'kD' (0.0). A 'Calculate Optimal Controller Gains' button is also present.

In the resulting file dialog, select the JSON file you want to analyze. If the file appears to be malformed, an error will be shown.

### 16.5.2 Running Feedforward Analysis

Once a data file has been selected, the Analyze Data button becomes available in the Feedforward Analysis frame. Click it.

The screenshot shows the FRC Drive Characterization Tool window after a data file has been selected. The 'Select Data File' button is no longer circled, and the 'Analyze Data' button in the 'Feedforward Analysis' section is now circled in red. The 'Select Data File' field now displays the path 'C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json'. The rest of the interface remains the same as in the previous screenshot.

By default, the analysis will be run by combining all the data in the test. For a finer-grained analysis, the analysis may be limited to a specific subset of data using the subset dropdown menu.



FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Feet Subset: **All Combined**

Wheel Diameter (units): .333

Feedforward Analysis	
Analyze Data	Accel Window Size: 8 kS: 0.829
Time-Domain Diagnostics	Motion Threshold (units/s): 0.2 kV: 3.04
Voltage-Domain Diagnostics	kA: 0.676
3D Diagnostics	r-squared: 0.998
	Track Width: 0.56341078

Feedback Analysis	
Gain Settings Preset: Default	Max Acceptable Position Error (units): 0.1
Controller Period (s): 0.02	Max Acceptable Velocity Error (units/s): 0.2
Max Controller Output: 12	Max Acceptable Control Effort (V): 7
Time-Normalized Controller: <input checked="" type="checkbox"/>	Loop Type: Position
Controller Type: Onboard	kV: 3.04
Post-Encoder Gearing: 1	kA: 0.676
Encoder EPR: 4096	Calculate Optimal Controller Gains
Has Slave: <input type="checkbox"/>	kP: 43.6
Slave Update Period (s): 0.01	kD: 20.2

The computed coefficients of the mechanism characterization will then be filled in, along with a goodness-of-fit measure (r-squared).

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Feet Subset: All Combined

Wheel Diameter (units): .333

Feedforward Analysis	
Analyze Data	Accel Window Size: 8 kS: 0.829
Time-Domain Diagnostics	Motion Threshold (units/s): 0.2 kV: 3.04
Voltage-Domain Diagnostics	kA: 0.676
3D Diagnostics	r-squared: 0.998
	Track Width: 0.56341078

Feedback Analysis	
Gain Settings Preset: Default	Max Acceptable Position Error (units): 0.1
Controller Period (s): 0.02	Max Acceptable Velocity Error (units/s): 0.2
Max Controller Output: 12	Max Acceptable Control Effort (V): 7
Time-Normalized Controller: <input checked="" type="checkbox"/>	Loop Type: Position
Controller Type: Onboard	kV: 3.04
Post-Encoder Gearing: 1	kA: 0.676
Encoder EPR: 4096	Calculate Optimal Controller Gains
Has Slave: <input type="checkbox"/>	kP: 43.6
Slave Update Period (s): 0.01	kD: 20.2

## 16.6 Viewing Diagnostics

The first diagnostic to look at is the r-squared - it should be somewhere north of ~.9. If it is significantly lower than this, there is likely a problem with your characterization data.

To investigate further, you can generate a number of diagnostic plots with the buttons on the left-hand side:

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Feet Subset: All Combined

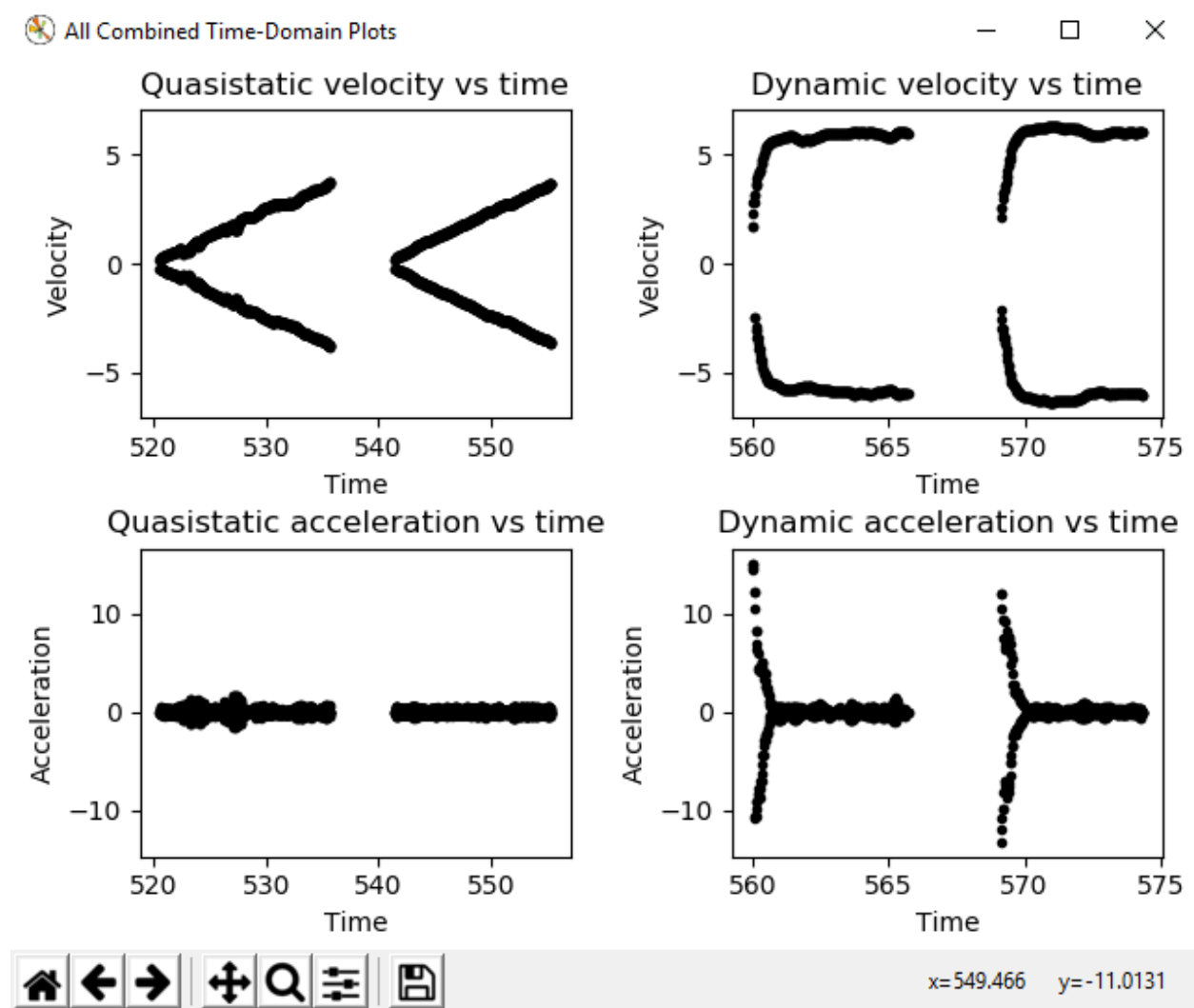
Wheel Diameter (units): .333

Feedforward Analysis	
Analyze Data	Accel Window Size: 8 kS: 0.829
Time-Domain Diagnostics	Motion Threshold (units/s): 0.2 kV: 3.04
Voltage-Domain Diagnostics	kA: 0.676
3D Diagnostics	r-squared: 0.998
	Track Width: 0.56341078

Feedback Analysis	
Gain Settings Preset: Default	Max Acceptable Position Error (units): 0.1
Controller Period (s): 0.02	Max Acceptable Velocity Error (units/s): 0.2
Max Controller Output: 12	Max Acceptable Control Effort (V): 7
Time-Normalized Controller: <input checked="" type="checkbox"/>	Loop Type: Position
Controller Type: Onboard	kV: 3.04
Post-Encoder Gearing: 1	kA: 0.676
Encoder EPR: 4096	Calculate Optimal Controller Gains
Has Slave: <input type="checkbox"/>	kP: 43.6
Slave Update Period (s): 0.01	kD: 20.2

### 16.6.1 Time-Domain Diagnostics

The Time-Domain Diagnostics plots display velocity and acceleration versus time over the course of the analyzed tests. For a typical drive characterization, these should look something like this (other mechanisms will be highly similar):



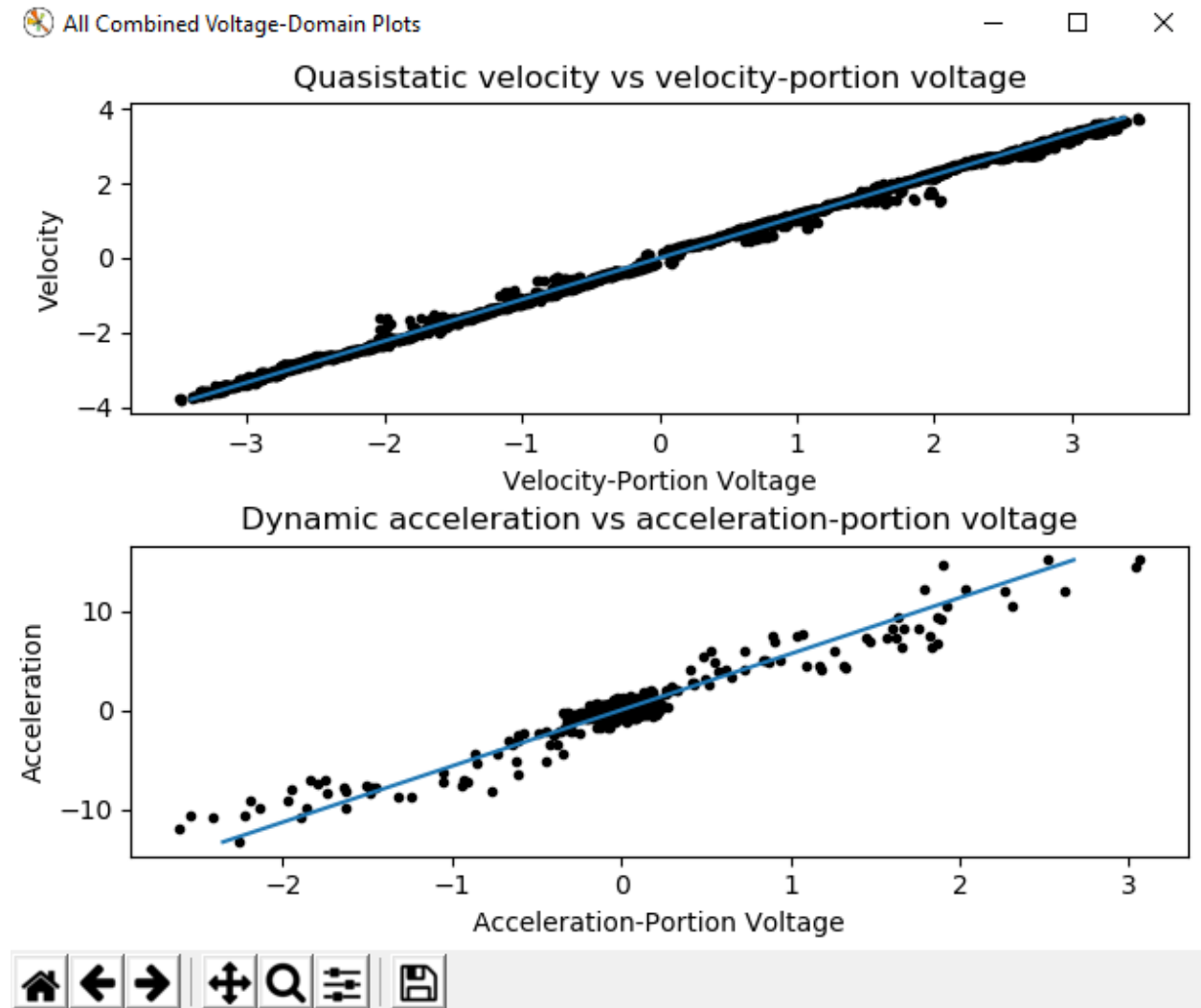
The vertical “mirroring” visible here is normal, and is simply the result of the left- and right-side encoders having different signs - this does not cause any trouble for the characterization tool.

The quasistatic test ought to have nearly linear velocity, and nearly-zero acceleration (hence “quasistatic”). The dynamic test ought to have velocity that asymptotically approaches a steady-state speed (the shape of the curve should be exponential, in fact), and acceleration that, accordingly, rapidly falls to zero (also exponentially, as the derivative of an exponential function is also an exponential function).

Deviation from this behavior is a sign of an [error](#), either in your robot setup, analysis settings, or your test procedure.

## 16.6.2 Voltage-Domain Diagnostics

The Voltage-Domain Diagnostics button plots velocity and acceleration versus voltage. Velocity is plotted for the quasistatic test, and acceleration is plotted for the dynamic test. For a typical drive characterization, the plots should resemble this (again, other mechanisms will be similar)



Both plots should be linear, however the dynamic plot will almost certainly have substantially more noise. The noise on the dynamic plot may be reduced by increasing the Accel Window Size setting.

FRC Drive Characterization Tool

Select Data File:  Units:  Subset:

Wheel Diameter (units):

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: <input type="text" value="8"/>	kS: <input type="text" value="0.829"/>	Gain Settings Preset: <input type="text" value="Default"/>
Time-Domain Diagnostics	Motion Threshold (units/s): <input type="text" value="0.2"/>	kV: <input type="text" value="3.04"/>	Max Acceptable Position Error (units): <input type="text" value="0.1"/>
Voltage-Domain Diagnostics		kA: <input type="text" value="0.676"/>	Max Acceptable Velocity Error (units/s): <input type="text" value="0.2"/>
3D Diagnostics		r-squared: <input type="text" value="0.998"/>	Max Acceptable Control Effort (V): <input type="text" value="7"/>
	Track Width: <input type="text" value="0.563410786"/>		Time-Normalized Controller: <input checked="" type="checkbox"/>
		Controller Type: <input type="text" value="Onboard"/>	Loop Type: <input type="text" value="Position"/>
		Post-Encoder Gearing: <input type="text" value="1"/>	kV: <input type="text" value="3.04"/>
		Encoder EPR: <input type="text" value="4096"/>	kA: <input type="text" value="0.676"/>
		Has Slave: <input type="checkbox"/>	<input type="button" value="Calculate Optimal Controller Gains"/>
		Slave Update Period (s): <input type="text" value="0.01"/>	kP: <input type="text" value="43.6"/>
			kD: <input type="text" value="20.2"/>

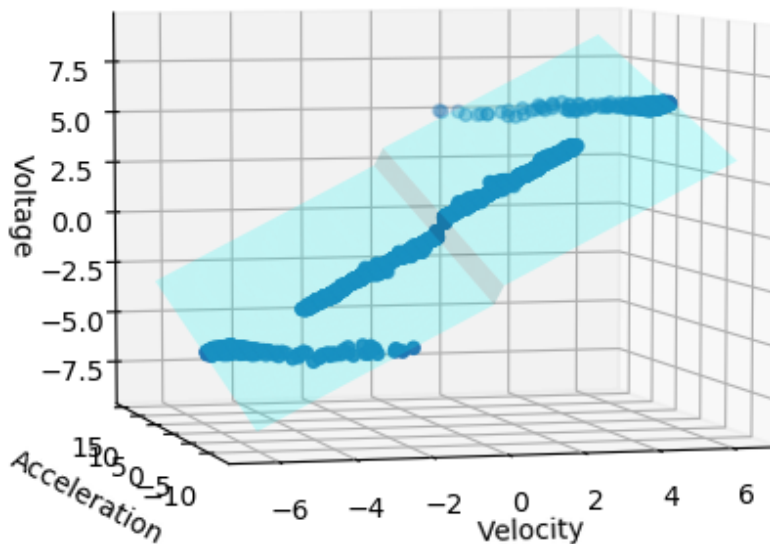
However, if your robot or mechanism has low mass compared to the motor power, this may “eat” what little meaningful acceleration data you have (however, in these cases kA will tend towards zero and can usually be ignored, anyway).

**Note:** The x-axis corresponds to velocity-portion voltage and acceleration-portion voltage, respectively - as the governing voltage-balance equations are multi-dimensional, plots against raw voltage are not as useful as one might expect.

### 16.6.3 3D Diagnostics

The 3D Diagnostics button will generate a 3d plot of voltage over the entire velocity-acceleration plane (this may be an adjusted voltage to remove the nonlinearity in mechanisms with nonlinear equations, such as arms).

Voltage vs velocity and acceleration



This plot is interactive, and may be rotated by clicking-and-dragging. The quasistatic and dynamic tests should both be clearly visible as streaks of data, and the best fit-plane should pass through all the data points. The data from both the quasistatic and dynamic tests should appear as straight lines (the reason for this is left as an exercise for the reader).

The discontinuity corresponds to  $k_S$ , which always opposes the direction of motion and thus changes direction as the plot crosses the 0 velocity mark.

#### 16.6.4 Diagnostics Plots for Common Failure Modes

When something has gone wrong with the characterization, the diagnostic plots provide crucial clues as to *what* has gone wrong. This section describes some common failures encountered while running the characterization tool, the identifying features of their diagnostic plots, and the steps that can be taken to fix them.

##### Improperly Set Motion Threshold

One of the most-common errors is an inappropriate value for the motion threshold.

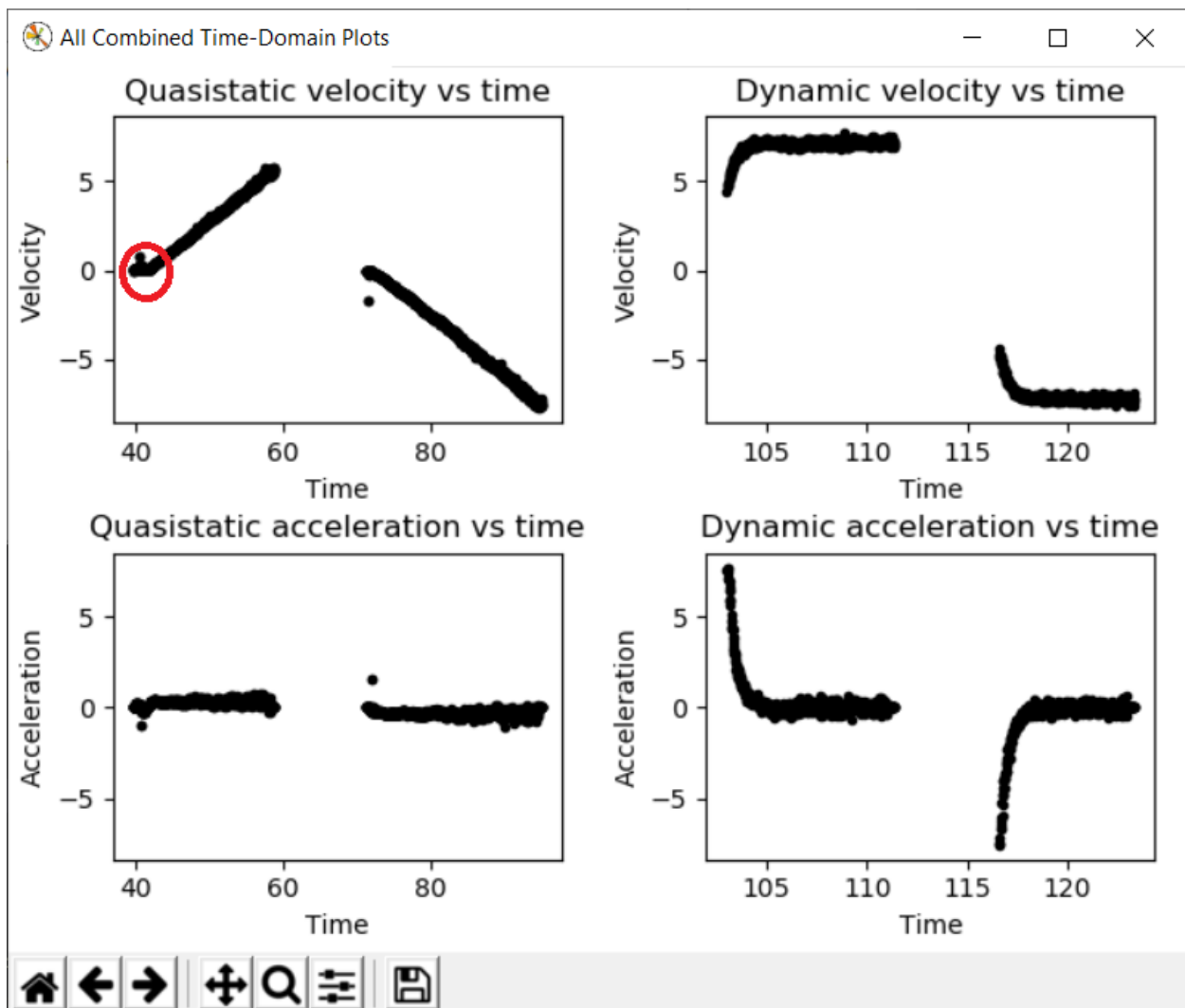
FRC Drive Characterization Tool

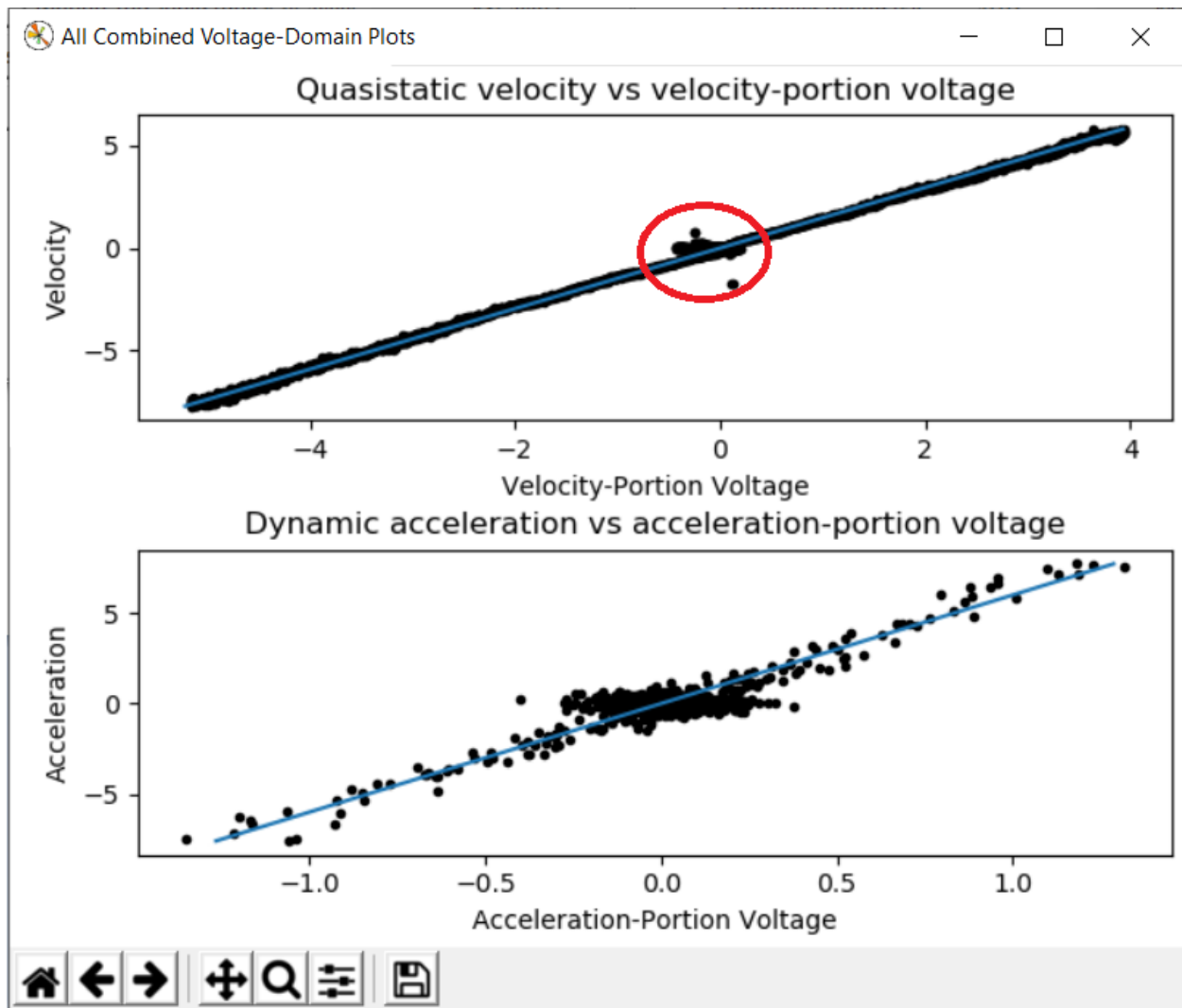
Select Data File:  Units:  Subset:

Wheel Diameter (units):

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: <input type="text" value="8"/>	Gain Settings Preset: <input type="text" value="Default"/>	Max Acceptable Position Error (units): <input type="text" value="0.1"/>
Time-Domain Diagnostics	Motion Threshold (units/s): <input type="text" value="0.2"/>	Controller Period (s): <input type="text" value="0.02"/>	Max Acceptable Velocity Error (units/s): <input type="text" value="0.2"/>
Voltage-Domain Diagnostics	kS: <input type="text" value="0.829"/>	Max Controller Output: <input type="text" value="12"/>	Max Acceptable Control Effort (V): <input type="text" value="7"/>
3D Diagnostics	kV: <input type="text" value="3.04"/>	Time-Normalized Controller: <input checked="" type="checkbox"/>	Loop Type: <input type="text" value="Position"/>
	kA: <input type="text" value="0.676"/>	Controller Type: <input type="text" value="Onboard"/>	kV: <input type="text" value="3.04"/>
	r-squared: <input type="text" value="0.998"/>	Post-Encoder Gearing: <input type="text" value="1"/>	kA: <input type="text" value="0.676"/>
	Track Width: <input type="text" value="0.563410786"/>	Encoder EPR: <input type="text" value="4096"/>	<input type="button" value="Calculate Optimal Controller Gains"/>
		Has Slave: <input type="checkbox"/>	kP: <input type="text" value="43.6"/>
		Slave Update Period (s): <input type="text" value="0.01"/>	kD: <input type="text" value="20.2"/>

### Motion Threshold Too Low

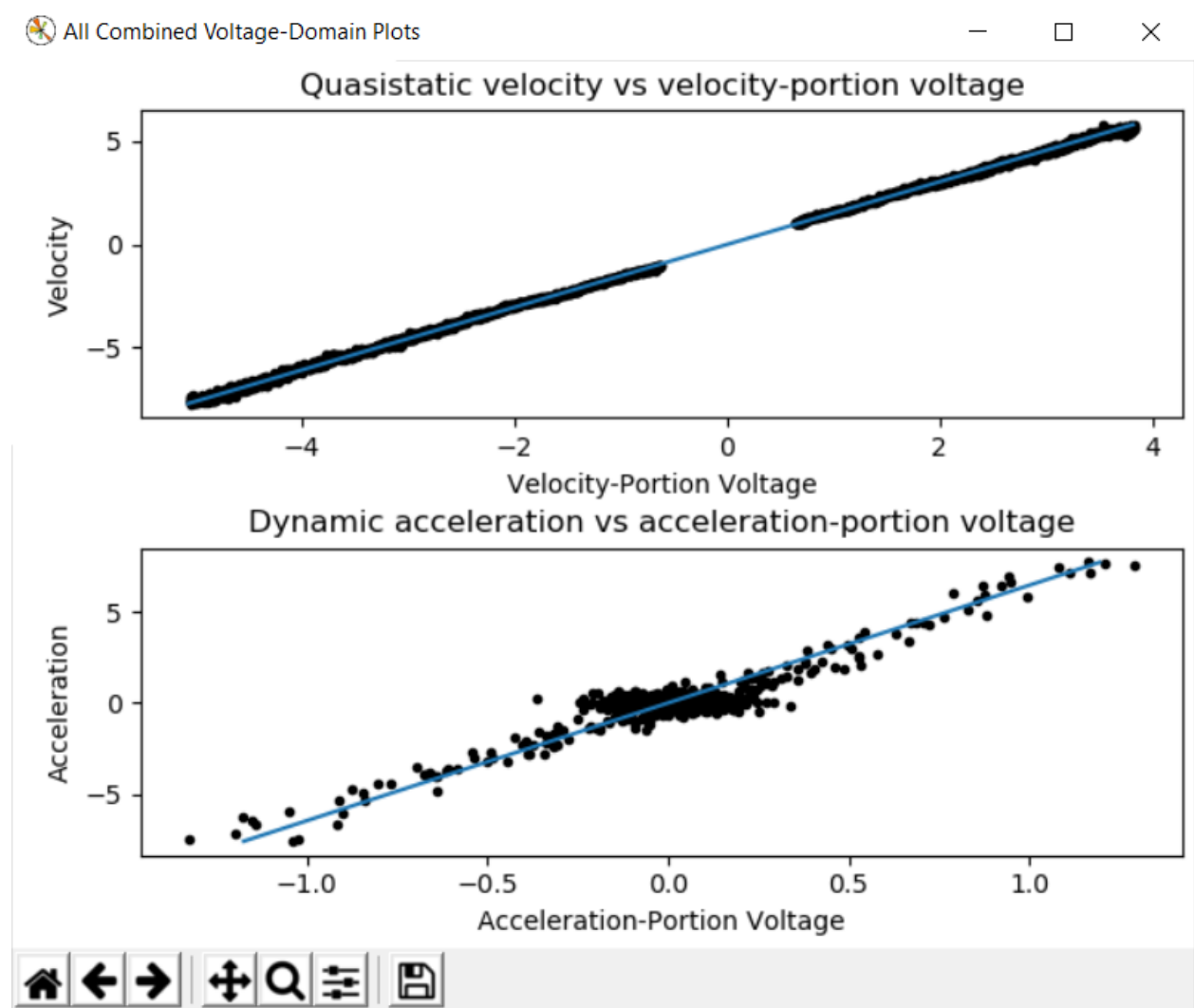




The presence of a “leading tail” (emphasized by added red circle) on the time-domain and voltage-domain plots indicates that the Motion Threshold setting is too low, and thus data points from before the robot begins to move are being included.

To solve this, increase the setting and re-analyze the data.

## Motion Threshold Too High

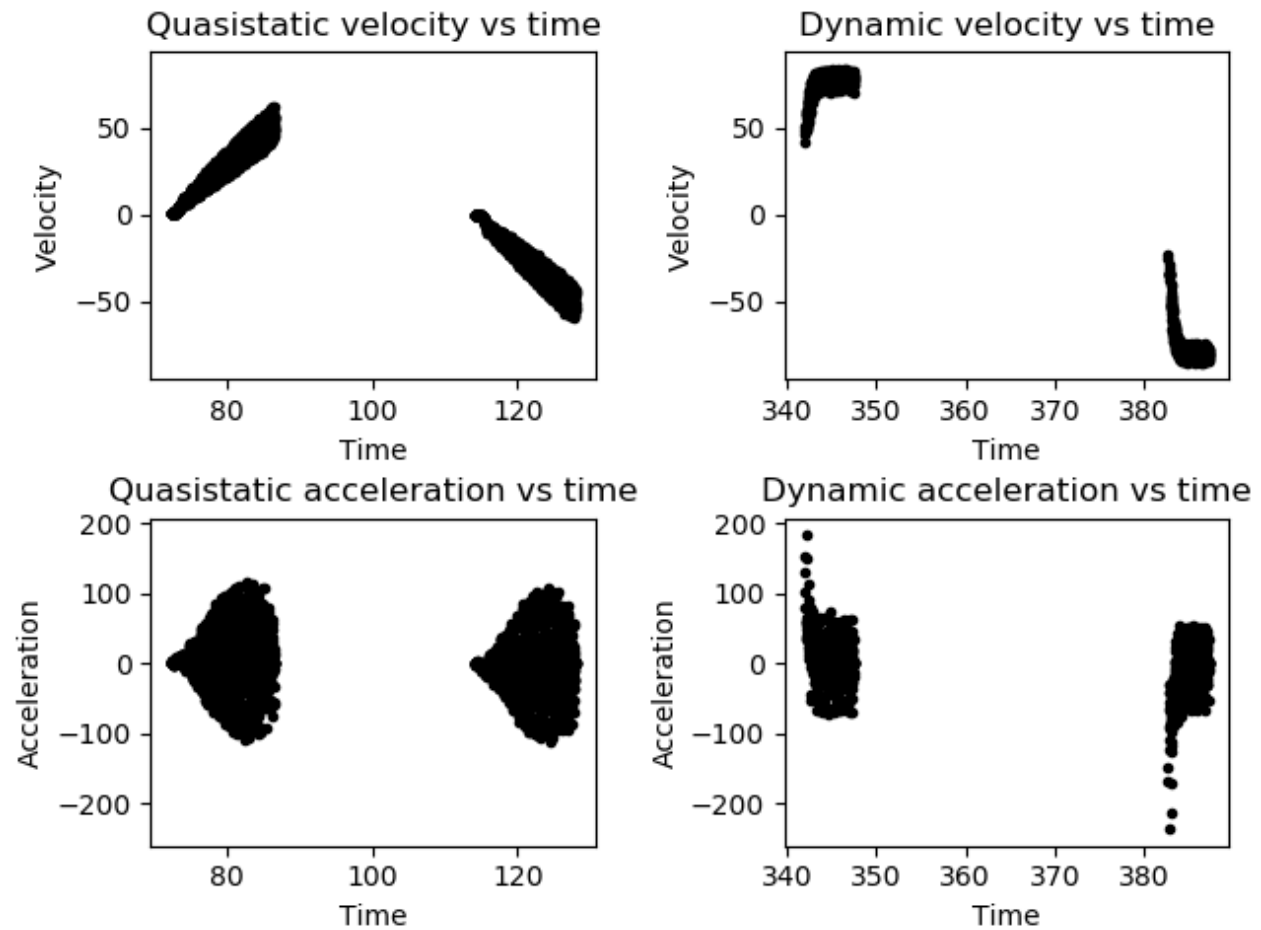


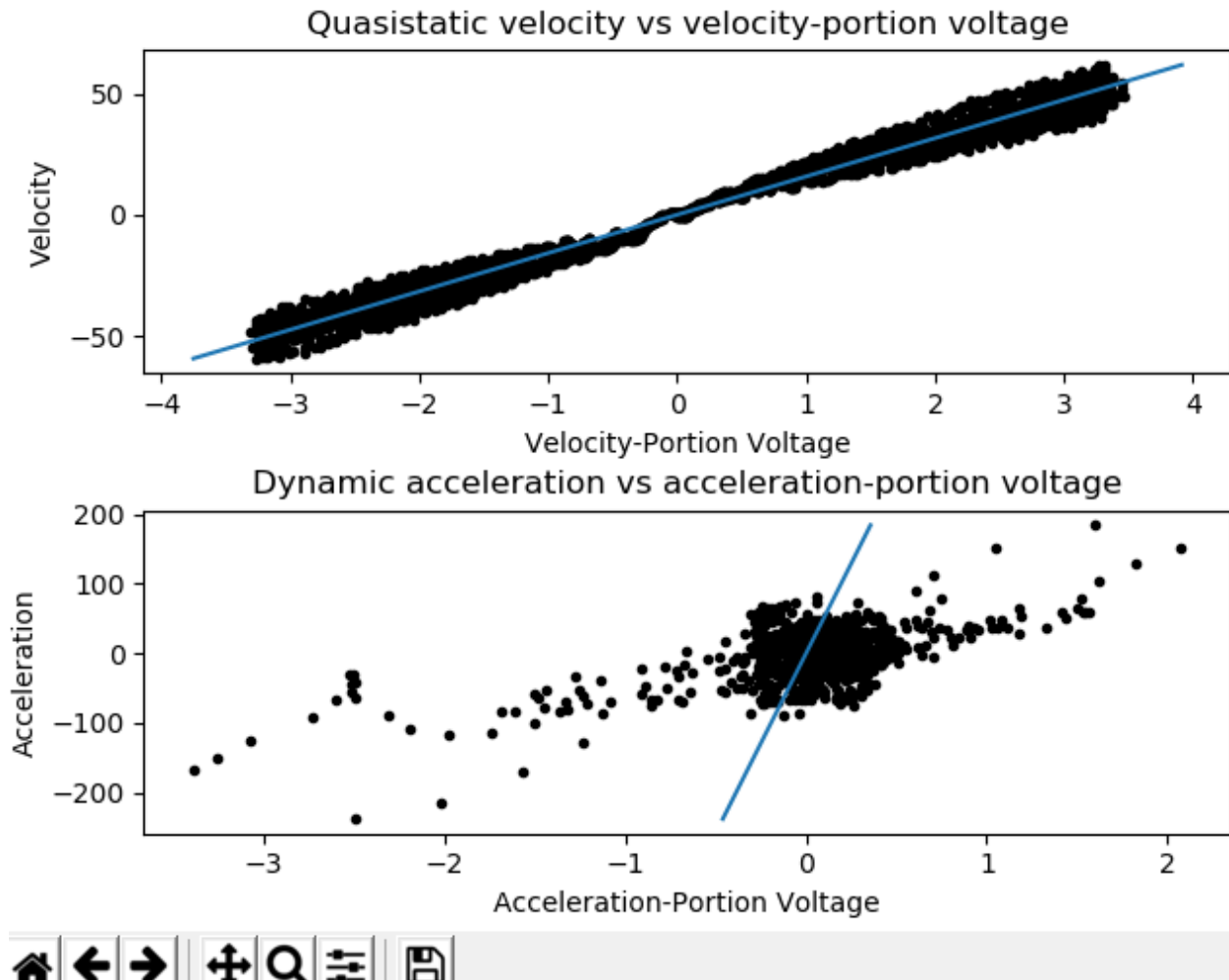
While not nearly as problematic as a too-low threshold, a motion threshold that is too high will result in a large “gap” in the voltage domain quasistatic plot.

To solve this, decrease the setting and re-analyze the data.



## Magnetic Encoders Velocity Noise





Magnetic encoders such as the [CTRE Mag Encoder](#) and the [AndyMark magnetic encoder](#) are extremely popular in FRC. However, a particular noise pattern has been observed when these encoders are used on robot drives, whose particular cause is not yet known. This noise pattern is uniquely distinguished by significant velocity noise proportional to motor velocity, and is particularly common on the kit-of-parts [toughbox mini](#) gearboxes.

Characterization constants can sometimes be accurately determined even from data polluted this noise by increasing the accel window size setting. However, this sort of encoder noise is problematic for robot code much the same way it is problematic for the characterization tool. As the root cause of the noise is not known, it is recommended to try a different encoder setup if this is observed, either by moving the encoders to a different shaft or replacing them with a different type of encoder.

## 16.7 Feedback Analysis

**Important:** These gains are, in effect, “educated guesses” - they are not guaranteed to be perfect, and should be viewed as a “starting point” for further tuning.

**Warning:** The feedback gain calculation assumes that there is no mechanical backlash, sensor noise, or phase lag in the sensor measurement. While these are reasonable assumptions in many situations, none of them are strictly true in practice. In particular, many “smart motor controllers” (such as the Talon SRX, Talon FX, and SparkMax) have default settings that apply substantial *low-pass filtering* to their encoder velocity measurements, which introduces a significant amount of phase lag. This can cause the calculated gains for velocity loops to be unstable. To rectify this, either decrease the amount of filtering through the controller’s API, or reduce the magnitude of the PID gains - it has been found that shrinking gains by about a factor of 10 works well for most default filtering settings.

Once the feedforward coefficients have been computed, the controls on the Feedback Analysis pane become available.

The screenshot shows the FRC Drive Characterization Tool interface. The Feedback Analysis pane is highlighted with a red box. It contains the following settings:

- Gain Settings Preset: Default
- Controller Period (s): 0.02
- Max Controller Output: 12
- Time-Normalized Controller: ☒
- Controller Type: Onboard
- Post-Encoder Gearing: 1
- Encoder EPR: 4096
- Has Slave: ☐
- Slave Update Period (s): 0.01
- Max Acceptable Position Error (units): 0.1
- Max Acceptable Velocity Error (units/s): 0.2
- Max Acceptable Control Effort (V): 7
- Loop Type: Position
- kV: 3.04
- kA: 0.676
- kP: 43.6
- kD: 20.2

The Calculate Optimal Controller Gains button is located at the bottom right of the Feedback Analysis pane.

These can be used to calculate optimal feedback gains for a PD or P controller for your mechanism (via [LQR](#)).

## 16.7.1 Set Units

Before using the Feedback Analysis pane, it is crucial that you set the Units settings to match the units of your data.

The screenshot shows the FRC Drive Characterization Tool interface. The Units dropdown menu is highlighted with a red circle and set to Feet. The Feedback Analysis pane is also visible, showing the same settings as in the previous screenshot.

Additionally, if your choice of units requires a physical measurement (i.e. it is non-rotational), it is also important to specify the relevant mechanism dimension used for conversion.

### 16.7.2 Enter Controller Parameters

**Note:** The “Spark Max” preset assumes that the user has configured the controller to operate in the units of analysis with the Spark Max API’s position/velocity scaling factor feature.

The calculated feedforward gains are *dimensioned quantities*. Unfortunately, not much attention is often paid to the units of PID gains in FRC controls, and so the various typical options for PID controller implementations differ in their unit conventions (which are often not made clear to the user).

To specify the correct settings for your PID controller, use the following options.

- **Gain Settings Preset:** This drop-down menu will auto-populate the remaining fields with likely settings for one of a number of common FRC controller setups. Note that some settings, such as post-encoder gearing, PPR, and the presense of a slave motor must still be manually specified (as the analyzer has no way of knowing these without user input), and that others may vary from the given defaults depending on user setup.
- **Controller Period:** This is the execution period of the control loop, in seconds. The default RIO loop rate is 50Hz, corresponding to a period of 0.02s. The onboard controllers on most “smart controllers” run at 1Khz, or a period of 0.001s.
- **Max Controller Output:** This is the maximum value of the controller output, with respect to the PID calculation. Most controllers calculate outputs with a maximum value of 1, but Talon controllers have a maximum output of 1023.

- **Time-Normalized Controller:** This specifies whether the PID calculation is normalized to the period of execution, which affects the scaling of the D gain.
- **Controller Type:** This specifies whether the controller is an onboard RIO loop, or is running on a smart motor controller such as a Talon or a SPARK Max.
- **Post-Encoder Gearing:** This specifies the gearing between the encoder and the mechanism itself. This is necessary for control loops that do not allow user-specified unit scaling in their PID computations (e.g. those running on Talons). This will be disabled if not relevant.
- **Encoder EPR:** This specifies the edges-per-revolution (not cycles per revolution) of the encoder used, which is needed in the same cases as Post-Encoder Gearing.
- **Has Slave:** Whether there is a motor controller slaved to the controller running the control loop, if the control loop is being run on a peripheral device. This changes the effective loop period.
- **Slave Update Period:** The rate at which the slave (if present) is updated. By default, this is 100Hz (every 0.01s) for Talons and Sparks, but can be changed.

### 16.7.3 Specify Optimality Criteria

Finally, the user must specify what will be considered an “optimal” controller. This takes the form of desired tolerances for the system error and control effort - note that it is *not* guaranteed that the system will obey these tolerances at all times.

The screenshot shows the FRC Drive Characterization Tool interface. The 'Feedback Analysis' section is active, and a red box highlights the following fields:

- Max Acceptable Position Error (units): 0.1
- Max Acceptable Velocity Error (units/s): 0.2
- Max Acceptable Control Effort (V): 7

Other visible fields include:

- Wheel Diameter (units): .333
- Gain Settings Preset: Default
- Controller Period (s): 0.02
- Max Controller Output: 12
- Time-Normalized Controller: ☒
- Controller Type: Onboard
- Post-Encoder Gearing: 1
- Encoder EPR: 4096
- Has Slave: ☐
- Slave Update Period (s): 0.01
- Feedforward Analysis: Accel Window Size: 8, kS: 0.829, kV: 3.04, kA: 0.676, r-squared: 0.998, Track Width: 0.56341078
- Calculate Optimal Controller Gains button

As a rule, smaller values for the Max Acceptable Error and larger values for the Max Acceptable Control Effort will result in larger gains - this will result in larger control efforts, which can grant better setpoint-tracking but may cause more violent behavior and greater wear on components.

The Max Acceptable Control Effort should never exceed 12V, as that corresponds to full battery voltage, and ideally should be somewhat lower than this.

### 16.7.4 Select Loop Type (Drive Only)

It is typical to control drives with both position and velocity PIDs, depending on application. Either can be selected using the drop-down Loop Type menu.

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Feet Subset: All Combined

Wheel Diameter (units): 0.333

**Feedforward Analysis**

Analyze Data Accel Window Size: 8 kS: 0.829

Time-Domain Diagnostics Motion Threshold (units/s): 0.2 kV: 3.04

Voltage-Domain Diagnostics kA: 0.676

3D Diagnostics r-squared: 0.998

Track Width: 0.56341078

**Feedback Analysis**

Gain Settings Preset: Default Max Acceptable Position Error (units): 0.1

Controller Period (s): 0.02 Max Acceptable Velocity Error (units/s): 0.2

Max Controller Output: 12 Max Acceptable Control Effort (V): 7

Time-Normalized Controller: ☒ **Loop Type: Position**

Controller Type: Onboard kV: 3.04

Post-Encoder Gearing: 1 kA: 0.676

Encoder EPR: 4096 Calculate Optimal Controller Gains

Has Slave: ☐ kP: 43.6

Slave Update Period (s): 0.01 kD: 20.2

### 16.7.5 Enter Known Velocity/Acceleration

**Note:** Sometimes, with an exceptionally light mechanism/robot and/or exceptionally-noisy data, it is possible for the kA value to be exceedingly small (or even slightly negative). In this case, the user should set kA to zero. The computed feedback gains in this case may also be zero - this is because such a mechanism should not require feedback to accurately track the setpoint under the assumptions of LQR. These assumptions may not be perfectly accurate, and users may need to add feedback regardless - in this case, the loop must be tuned manually.

If one wishes to use the Feedback Analysis pane without running a full analysis on a set of data, or otherwise view the effect of modifying the kV and kA values, this can be done here.

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Feet Subset: All Combined

Wheel Diameter (units): 0.333

**Feedforward Analysis**

Analyze Data Accel Window Size: 8 kS: 0.829

Time-Domain Diagnostics Motion Threshold (units/s): 0.2 kV: 3.04

Voltage-Domain Diagnostics kA: 0.676

3D Diagnostics r-squared: 0.998

Track Width: 0.56341078

**Feedback Analysis**

Gain Settings Preset: Default Max Acceptable Position Error (units): 0.1

Controller Period (s): 0.02 Max Acceptable Velocity Error (units/s): 0.2

Max Controller Output: 12 Max Acceptable Control Effort (V): 7

Time-Normalized Controller: ☒ Loop Type: Position

Controller Type: Onboard kV: 3.04

Post-Encoder Gearing: 1 kA: 0.676

Encoder EPR: 4096 Calculate Optimal Controller Gains

Has Slave: ☐ kP: 43.6

Slave Update Period (s): 0.01 kD: 20.2

### 16.7.6 Calculate Gains

Finally, press the Calculate Optimal Controller Gains to determine the feedback gains.

FRC Drive Characterization Tool

Select Data File
C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json
Units:
Feet
Subset:
All Combined

Wheel Diameter (units): .333

Analyze Data

Time-Domain Diagnostics

Voltage-Domain Diagnostics

3D Diagnostics

Feedforward Analysis

Accel Window Size: 8

Motion Threshold (units/s): 0.2

kS: 0.829

kV: 3.04

kA: 0.676

r-squared: 0.998

Track Width: 0.56341078

Gain Settings Preset: Default

Controller Period (s): 0.02

Max Controller Output: 12

Time-Normalized Controller: ☒

Controller Type: Onboard

Post-Encoder Gearing: 1

Encoder EPR: 4096

Has Slave: ☐

Slave Update Period (s): 0.01

Feedback Analysis

Max Acceptable Position Error (units): 0.1

Max Acceptable Velocity Error (units/s): 0.2

Max Acceptable Control Effort (V): 7

Loop Type: Position

kV: 3.04

kA: 0.676

Calculate Optimal Controller Gains

kP: 43.6

kD: 20.2

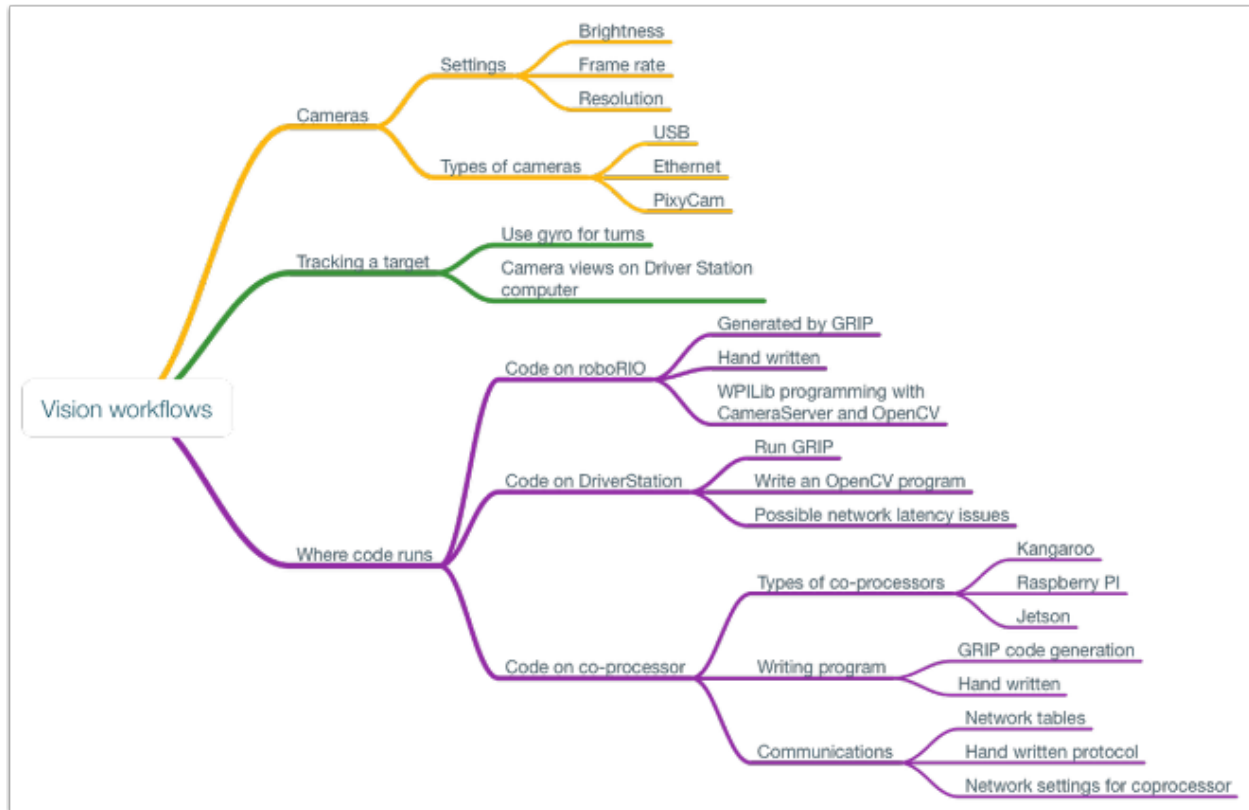
## **17.1 Vision Introduction**

### **17.1.1 Strategies for Vision Programming**

Using computer vision is a great way of making your robot be responsive to the elements on the field and make it much more autonomous. Often in FRC games there are bonus points for autonomously shooting balls or other game pieces into goals or navigating to locations on the field. Computer vision is a great way of solving many of these problems. And if you have autonomous code that can do the challenge, then it can be used during the teleop period as well to help the human drivers.

There are many options for choosing the components for vision processing and where the vision program should run. WPILib and associated tools support a number of options and give teams a lot of flexibility to decide what to do. This article will attempt to give you some insight into many of the choices and tradeoffs that are available.

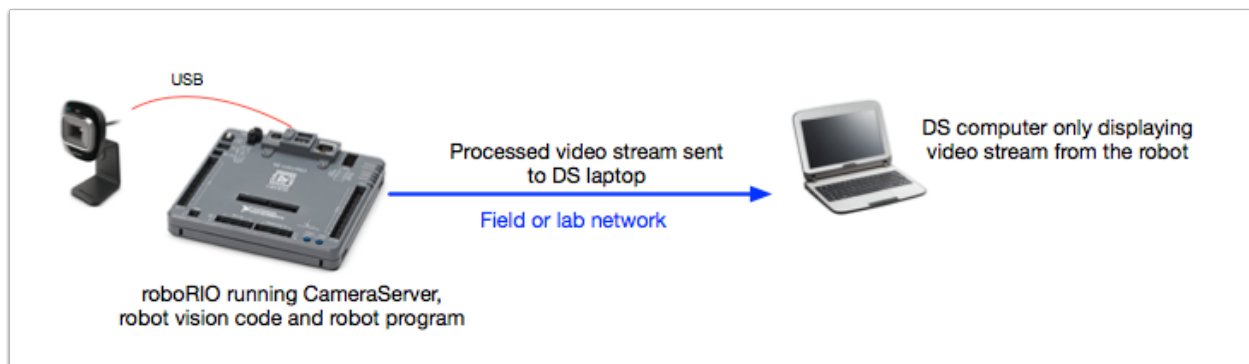




## OpenCV Computer Vision Library

**OpenCV** is an open source computer vision library that is widely used throughout academia and industry. It has support from hardware manufactures providing GPU accelerated processing, it has bindings for a number of languages including C++, Java, and Python. It is also well documented with many web sites, books, videos, and training courses so there are lots of resources available to help learn how to use it. The C++ and Java versions of WPILib include the OpenCV libraries, there is support in the library for capturing, processing and viewing video, and tools to help you create your vision algorithms. For more information about OpenCV see <https://opencv.org>.

## Vision Code on roboRIO

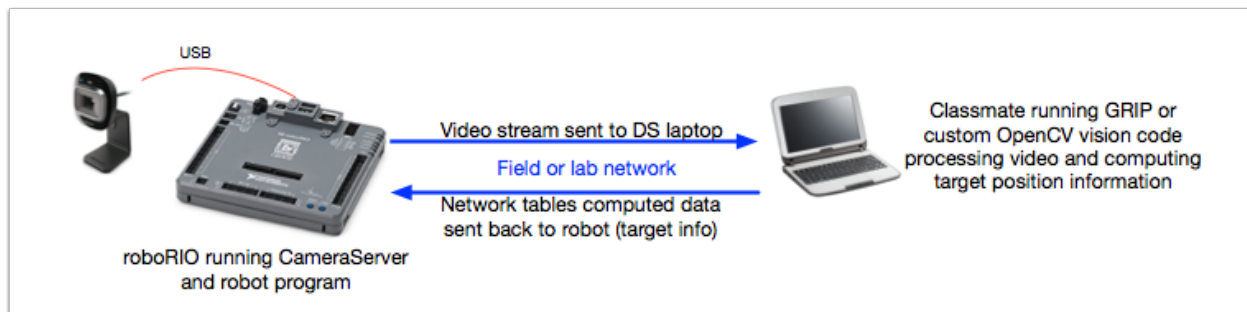


Vision code can be embedded into the main robot program on the roboRIO. Building and running the vision code is straightforward because it is built and deployed along with the robot program. The vision code can be written by hand or generated by GRIP in either C++ or Java. The disadvantage of this approach is that having vision code running on the same processor as the robot program can cause performance issues. This is something you will have to evaluate depending on the requirements for your robot and vision program.

In this approach, the vision code simply produces results that the robot code directly uses. Be careful about synchronization issues when writing robot code that is getting values from a vision thread. The GRIP generated code and the VisionRunner class in WPILib make this easier.

Using functions provided by the CameraServer class, the video stream can be sent to dashboards such as Shuffleboard so operators can see what the camera sees. In addition, annotations can be added to the images using OpenCV commands so targets or other interesting objects can be identified in the dashboard view.

### Vision Code on DS Computer

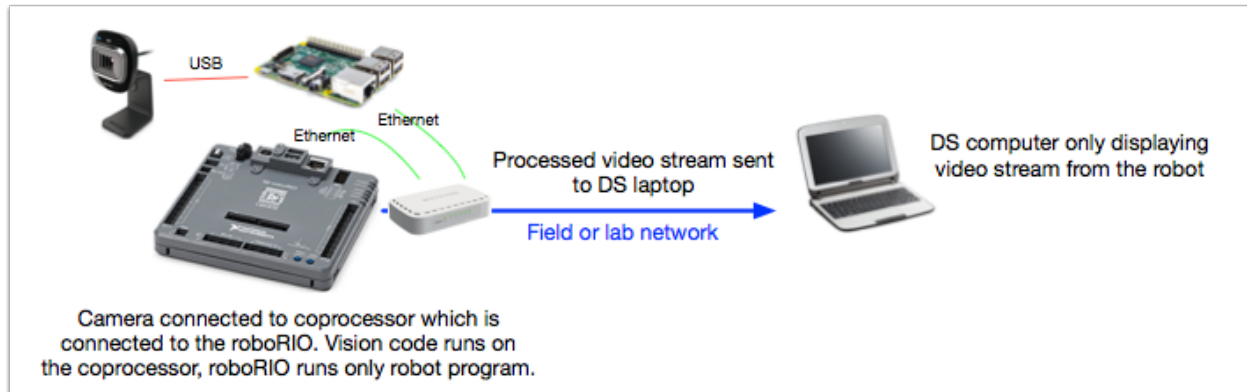


When vision code is running on the DS computer, the video is streamed back to the Driver Station laptop for processing. Even the older Classmate laptops are substantially faster at vision processing than the roboRIO. GRIP can be run on the Driver Station laptop directly with the results sent back to the robot using NetworkTables. Alternatively you can write your own vision program using a language of your choosing. Python makes a good choice since there is a native NetworkTables implementation and the OpenCV bindings are very good.

After the images are processed, the key values such as the target position, distance or anything else you need can be sent back to the robot with NetworkTables. This approach generally has higher latency, as delay is added due to the images needing to be sent to the laptop. Bandwidth limitations also limit the maximum resolution and FPS of the images used for processing.

The video stream can be displayed on Shuffleboard or in GRIP.

### Vision Code on Coprocessor



Coprocessors such as the Raspberry Pi are ideal for supporting vision code (see [Using the Raspberry Pi for FRC](#)). The advantage is that they can run full speed and not interfere with the robot program. In this case, the camera is probably connected to the coprocessor or (in the case of Ethernet cameras) an Ethernet switch on the robot. The program can be written in any language; Python is a good choice because of its simple bindings to OpenCV and NetworkTables. Some teams have used high performance vision coprocessors such as the Nvidia Jetson for fastest speed and highest resolution, although this approach generally requires advanced Linux and programming knowledge.

This approach takes a bit more programming expertise as well as a small amount of additional weight, but otherwise it brings the best of both worlds compared to the other two approaches, as coprocessors are much faster than the roboRIO and the image processing can be performed with minimal latency or bandwidth use.

Data can be sent from the vision program on the coprocessor to the robot using NetworkTables or a private protocol over a network or serial connection.

### Camera Options

There are a number of camera options supported by WPILib. Cameras have a number of parameters that affect operation; for example, frame rate and image resolution affect the quality of the received images, but when set too high impact processing time and, if sent to the driver station, may exceed the available bandwidth on the field.

The CameraServer class in C++ and Java is used to interface with cameras connected to the robot. It retrieve frames for local processing through a Source object and sends the stream to your driver station for viewing or processing there.

Details on using cameras with WPILib are detailed in [Using the CameraServer on the roboRIO](#).

### 17.1.2 Read and Process Video: CameraServer Class

#### Concepts

The cameras typically used in FRC (commodity USB and Ethernet cameras such as the Axis camera) offer relatively limited modes of operation. In general, they provide only a single image output (typically in an RGB compressed format such as JPG) at a single resolution and

frame rate. USB cameras are particularly limited as only one application may access the camera at a time.

CameraServer supports multiple cameras. It handles details such as automatically reconnecting when a camera is disconnected, and also makes images from the camera available to multiple “clients” (e.g. both your robot code and the dashboard can connect to the camera simultaneously).

## Camera Names

Each camera in CameraServer must be uniquely named. This is also the name that appears for the camera in the Dashboard. Some variants of the CameraServer `startAutomaticCapture()` and `addAxisCamera()` functions will automatically name the camera (e.g. “USB Camera 0” or “Axis Camera”), or you can give the camera a more descriptive name (e.g. “Intake Cam”). The only requirement is that each camera have a unique name.

## USB Camera Notes

### CPU Usage

The CameraServer is designed to minimize CPU usage by only performing compression and decompression operations when required and automatically disabling streaming when no clients are connected.

To minimize CPU usage, the dashboard resolution should be set to the same resolution as the camera; this allows the CameraServer to not decompress and recompress the image, instead, it can simply forward the JPEG image received from the camera directly to the dashboard. It’s important to note that changing the resolution on the dashboard does *not* change the camera resolution; changing the camera resolution may be done by calling `setResolution()` on the camera object.

## USB Bandwidth

The roboRIO can only transmit and receive so much data at a time over its USB interfaces. Camera images can require a lot of data, and so it is relatively easy to run into this limit. The most common cause of a USB bandwidth error is selecting a non-JPEG video mode or running too high of a resolution, particularly when multiple cameras are connected.

## Architecture

The CameraServer consists of two layers, the high level WPILib **CameraServer class** and the low level **cscore library**.

### CameraServer Class

The CameraServer class (part of WPILib) provides a high level interface for adding cameras to your robot code. It also is responsible for publishing information about the cameras and camera servers to NetworkTables so that Driver Station dashboards such as the LabVIEW

Dashboard and Shuffleboard can list the cameras and determine where their streams are located. It uses a singleton pattern to maintain a database of all created cameras and servers.

Some key functions in CameraServer are:

- `startAutomaticCapture()`: Add a USB camera (e.g. Microsoft LifeCam) and starts a server for it so it can be viewed from the dashboard.
- `addAxisCamera()`: Add an Axis camera. Even if you aren't processing images from the Axis camera in your robot code, you may want to use this function so that the Axis camera appears in the Dashboard's drop down list of cameras. It also starts a server so the Axis stream can still be viewed when your driver station is connected to the roboRIO via USB (useful at competition if you have both the Axis camera and roboRIO connected to the two robot radio Ethernet ports).
- `getVideo()`: Get OpenCV access to a camera. This allows you to get images from the camera for image processing on the roboRIO (in your robot code).
- `putVideo()`: Start a server that you can feed OpenCV images to. This allows you to pass custom processed and/or annotated images to the dashboard.

### cscore Library

The cscore library provides the lower level implementation to:

- Get images from USB and HTTP (e.g. Axis) cameras
- Change camera settings (e.g. contrast and brightness)
- Change camera video modes (pixel format, resolution and frame rate)
- Act as a web server and serve images as a standard MJPEG stream
- Convert images to/from OpenCV Mat objects for image processing

### Sources and Sinks

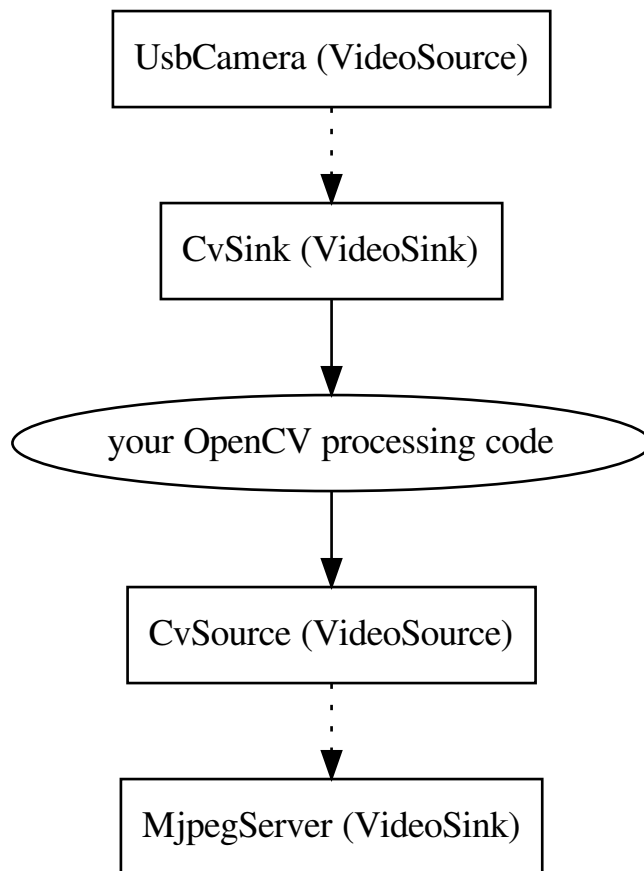
The basic architecture of the cscore library is similar to that of MJPGStreamer, with functionality split between sources and sinks. There can be multiple sources and multiple sinks created and operating simultaneously.

An object that generates images is a source and an object that accepts/consumes images is a sink. The generate/consume is from the perspective of the library. Thus cameras are sources (they generate images). The MJPEG web server is a sink because it accepts images from within the program (even though it may be forwarding those images on to a web browser or dashboard). Sources may be connected to multiple sinks, but sinks can be connected to one and only one source. When a sink is connected to a source, the cscore library takes care of passing each image from the source to the sink.

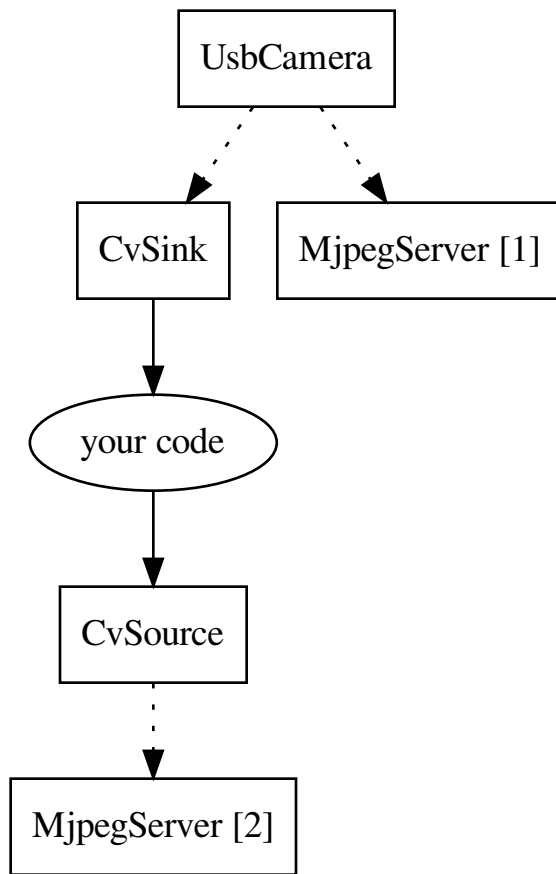
- **Sources** obtain individual frames (such as provided by a USB camera) and fire an event when a new frame is available. If no sinks are listening to a particular source, the library may pause or disconnect from a source to save processor and I/O resources. The library autonomously handles camera disconnects/reconnects by simply pausing and resuming firing of events (e.g. a disconnect results in no new frames, not an error).
- **Sinks** listen to a particular source's event, grab the latest image, and forward it to its destination in the appropriate format. Similarly to sources, if a particular sink is inactive

(e.g. no client is connected to a configured MJPEG over HTTP server), the library may disable parts of its processing to save processor resources.

User code (such as that used in a FRC robot program) can act as either a source (providing processed frames as if it were a camera) or as a sink (receiving a frame for processing) via OpenCV source and sink objects. Thus an image processing pipeline that gets images from a camera and serves the processed images out looks like the below graph:



Because sources can have multiple sinks connected, the pipeline may branch. For example, the original camera image can also be served by connecting the UsbCamera source to a second MjpegServer sink in addition to the CvSink, resulting in the below graph:



When a new image is captured by the camera, both the CvSink and the MjpegServer [1] receive it.

The above graph is what the following CameraServer snippet creates:

Java

```
import edu.wpi.first.cameraserver.CameraServer;
import edu.wpi.first.cscore.CvSink;
import edu.wpi.first.cscore.CvSource;

// Creates UsbCamera and MjpegServer [1] and connects them
CameraServer.getInstance().startAutomaticCapture();

// Creates the CvSink and connects it to the UsbCamera
CvSink cvSink = CameraServer.getInstance().getVideo();

// Creates the CvSource and MjpegServer [2] and connects them
CvSource outputStream = CameraServer.getInstance().putVideo("Blur", 640, 480);
```

C++

```
#include "cameraserver/CameraServer.h"

// Creates UsbCamera and MjpegServer [1] and connects them
frc::CameraServer::GetInstance().StartAutomaticCapture();

// Creates the CvSink and connects it to the UsbCamera
cs::CvSink cvSink = frc::CameraServer::GetInstance().GetVideo();

// Creates the CvSource and MjpegServer [2] and connects them
cs::CvSource outputStream = frc::CameraServer::GetInstance().PutVideo("Blur", 640, 480);
```

The CameraServer implementation effectively does the following at the cscore level (for explanation purposes). CameraServer takes care of many of the details such as creating unique names for all cscore objects and automatically selecting port numbers. CameraServer also keeps a singleton registry of created objects so they aren't destroyed if they go out of scope.

Java

```
import edu.wpi.cscore.CvSink;
import edu.wpi.cscore.CvSource;
import edu.wpi.cscore.MjpegServer;
import edu.wpi.cscore.UsbCamera;

// Creates UsbCamera and MjpegServer [1] and connects them
UsbCamera usbCamera = new UsbCamera("USB Camera 0", 0);
MjpegServer mjpegServer1 = new MjpegServer("serve_USB Camera 0", 1181);
mjpegServer1.setSource(usbCamera);

// Creates the CvSink and connects it to the UsbCamera
CvSink cvSink = new CvSink("opencv_USB Camera 0");
cvSink.setSource(usbCamera);

// Creates the CvSource and MjpegServer [2] and connects them
CvSource outputStream = new CvSource("Blur", PixelFormat.kMJPEG, 640, 480, 30);
MjpegServer mjpegServer2 = new MjpegServer("serve_Blur", 1182);
mjpegServer2.setSource(outputStream);
```

C++

```
#include "cscore_oo.h"

// Creates UsbCamera and MjpegServer [1] and connects them
cs::UsbCamera usbCamera("USB Camera 0", 0);
cs::MjpegServer mjpegServer1("serve_USB Camera 0", 1181);
mjpegServer1.SetSource(usbCamera);

// Creates the CvSink and connects it to the UsbCamera
cs::CvSink cvSink("opencv_USB Camera 0");
cvSink.SetSource(usbCamera);

// Creates the CvSource and MjpegServer [2] and connects them
cs::CvSource outputStream("Blur", cs::PixelFormat::kJPEG, 640, 480, 30);
cs::MjpegServer mjpegServer2("serve_Blur", 1182);
mjpegServer2.SetSource(outputStream);
```



## Reference Counting

All cscore objects are internally reference counted. Connecting a sink to a source increments the source's reference count, so it's only strictly necessary to keep the sink in scope. The CameraServer class keeps a registry of all objects created with CameraServer functions, so sources and sinks created in that way effectively never go out of scope (unless explicitly removed).

### 17.1.3 2017 Vision Examples

#### LabVIEW

The 2017 LabVIEW Vision Example is included with the other LabVIEW examples. From the Splash screen, click Support->Find FRC Examples or from any other LabVIEW window, click Help->Find Examples and locate the Vision folder to find the 2017 Vision Example. The example images are bundled with the example.

#### C++/Java

We have provided a GRIP project and the description below, as well as the example images, bundled into a ZIP that [can be found on TeamForge](#).

See [Using Generated Code in a Robot Program](#) for details about integrating GRIP generated code in your robot program.

The code generated by the included GRIP project will find OpenCV contours for green particles in images like the ones included in the Vision Images folder of this ZIP. From there you may wish to further process these contours to assess if they are the target. To do this:

1. Use the boundingRect method to draw bounding rectangles around the contours
2. The LabVIEW example code calculates 5 separate ratios for the target. Each of these ratios should nominally equal 1.0. To do this, it sorts the contours by size, then starting with the largest, calculates these values for every possible pair of contours that may be the target, and stops if it finds a target or returns the best pair it found.

In the formulas below, each letter refers to a coordinate of the bounding rect (H = Height, L = Left, T = Top, B = Bottom, W = Width) and the numeric subscript refers to the contour number (1 is the largest contour, 2 is the second largest, etc).

- Top height should be 40% of total height (4 in / 10 in):

$$\text{Group Height} = \frac{H_1}{0.4(B_2 - T_1)}$$

- Top of bottom stripe to top of top stripe should be 60% of total height (6 in / 10 in):

$$d\text{Top} = \frac{T_2 - T_1}{0.6(B_2 - T_1)}$$

- The distance between the left edge of contour 1 and the left edge of contour 2 should be small relative to the width of the 1st contour; then we add 1 to make the ratio centered on 1:

$$L\text{Edge} = \frac{L_1 - L_2}{W_1} + 1$$

- The widths of both contours should be about the same:

$$\text{Width ratio} = \frac{W_1}{W_2}$$

- The larger stripe should be twice as tall as the smaller one

$$\text{Height ratio} = \frac{H_1}{2H_2}$$

Each of these ratios is then turned into a 0-100 score by calculating:

$$100 - (100 \cdot \text{abs}(1 - \text{Val}))$$

3. To determine distance, measure pixels from top of top bounding box to bottom of bottom bounding box:

$$\text{distance} = \frac{\text{Target height in ft.}(10/12) \cdot Y\text{Res}}{2 \cdot \text{PixelHeight} \cdot \tan(\text{viewAngle of camera})}$$

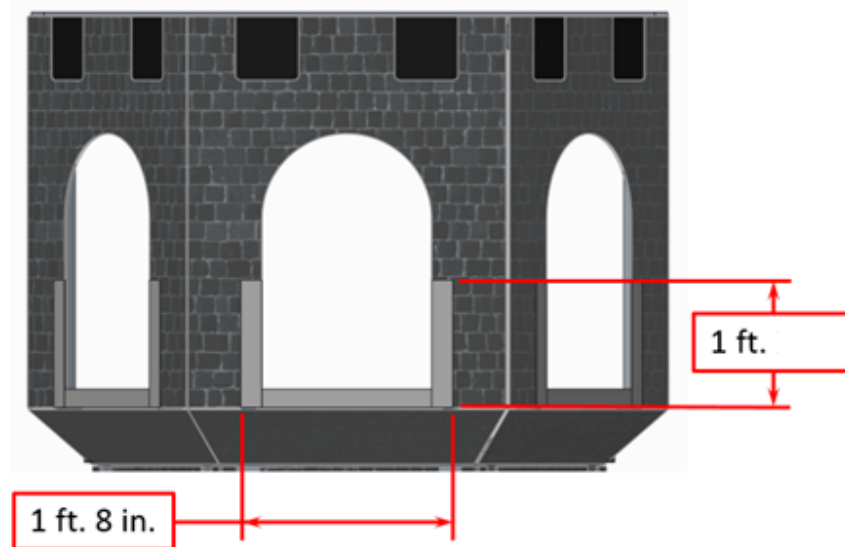
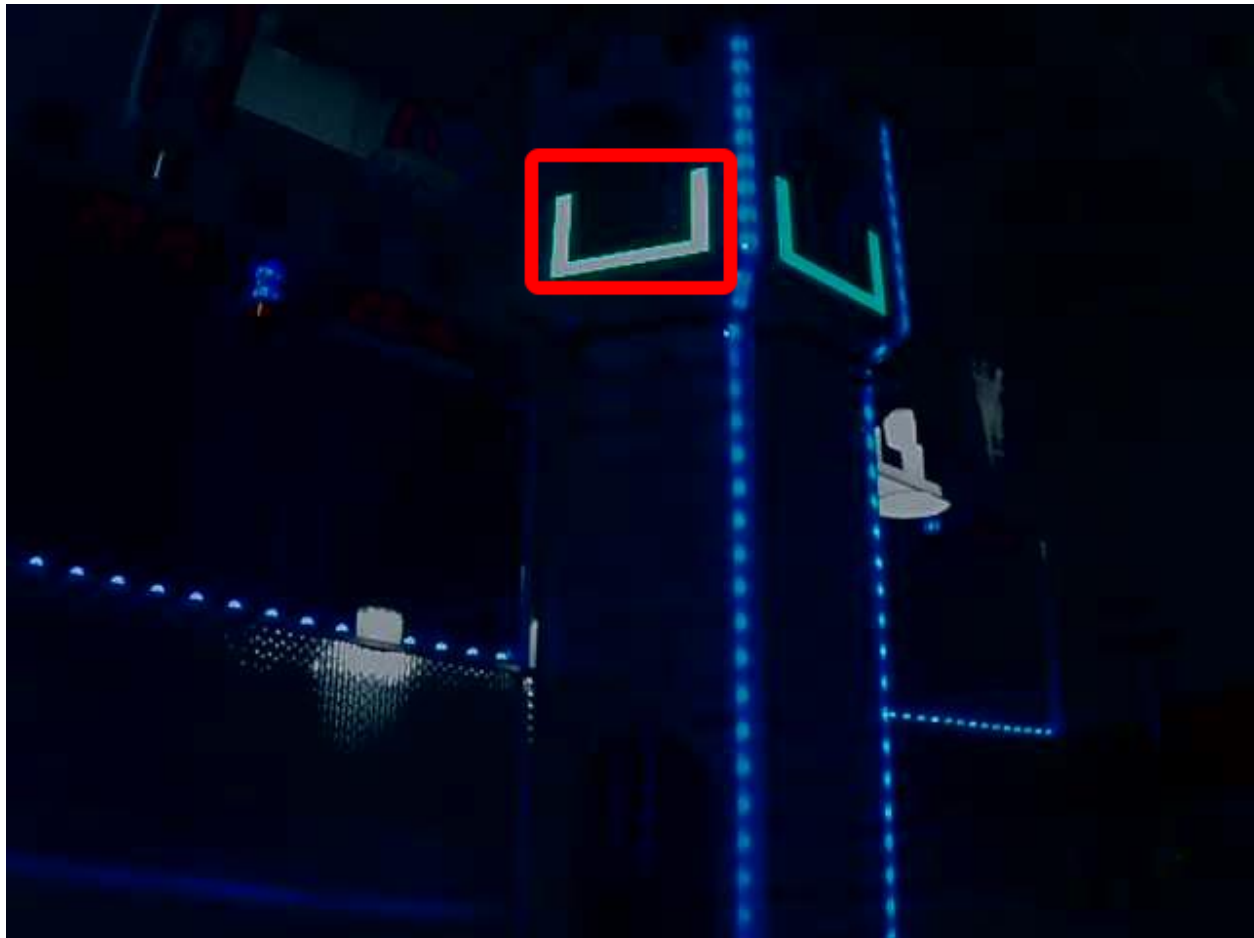
The LabVIEW example uses height as the edges of the round target are the most prone to noise in detection (as the angle points further from the camera the color looks less green). The downside of this is that the pixel height of the target in the image is affected by perspective distortion from the angle of the camera. Possible fixes include:

- Try using width instead
- Empirically measure height at various distances and create a lookup table or regression function
- Mount the camera to a servo, center the target vertically in the image and use servo angle for distance calculation (you'll have to work out the proper trig yourself or find a math teacher to help!)
- Correct for the perspective distortion using OpenCV. To do this you will need to [calibrate your camera with OpenCV](#). This will result in a distortion matrix and camera matrix. You will take these two matrices and use them with the `undistortPoints` function to map the points you want to measure for the distance calculation to the "correct" coordinates (this is much less CPU intensive than undistorting the whole image)

#### 17.1.4 Target Info and Retroreflection

Many FRC games have retroreflective tape attached to field elements to aid in vision processing. This document describes the Vision Targets from the 2016 FRC game and the visual properties of the material making up the targets. Note that for official dimensions and drawings of all field components, please see the Official Field Drawings.

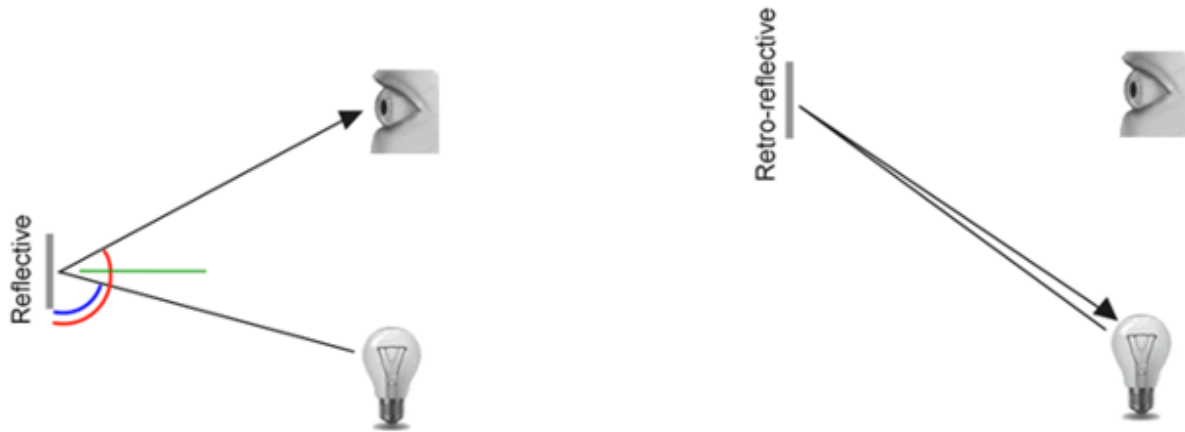
## Targets



Each 2016 vision target consists of a 1' 8" wide, 1' tall U-shape made of 2" wide retroreflective material (3M 8830 Silver Marking Film). The targets are located immediately adjacent to the bottom of each high goal. When properly lit, the retroreflective tape produces a bright and/or

color-saturated marker.

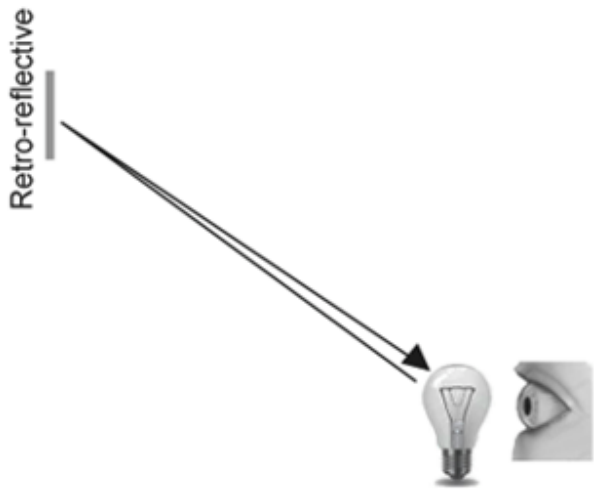
### Retroreflectivity vs. Reflectivity



Highly reflective materials are generally mirrored so that light “bounces off” at a supplementary angle. As shown above-left, the blue and red angles sum to 180 degrees. An equivalent explanation is that the light reflects about the surface normal the green line drawn perpendicular to the surface. Notice that a light pointed at the surface will return to the light source only if the blue angle is  $\sim 90$  degrees.

Retro-reflective materials are not mirrored, but it will typically have either shiny facets across the surface, or it will have a pearl-like appearance. Not all faceted or pearl-like materials are retro-reflective, however. Retro-reflective materials return the majority of light back to the light source, and they do this for a wide range of angles between the surface and the light source, not just the 90 degree case. Retro-reflective materials accomplish this using small prisms, such as found on a bicycle or roadside reflector, or by using small spheres with the appropriate index of refraction that accomplish multiple internal reflections. In nature, the eyes of some animals, including house cats, also exhibit the retro-reflective effect typically referred to as night-shine. The [Wikipedia article on retroreflectors](#) goes into more detail on how retro-reflection is accomplished.

## Examples of Retroreflection



This material should be relatively familiar as it is often used to enhance nighttime visibility of road signs, bicycles, and pedestrians.

Initially, retro-reflection may not seem like a useful property for nighttime safety, but when the light and eye are near one another, as shown below, the reflected light returns to the eye, and the material shines brightly even at large distances. Due to the small angle between the driver's eyes and vehicle headlights, retro-reflective materials can greatly increase visibility of distant objects during nighttime driving.

## Demonstration

To further explore retro-reflective material properties:

1. Place a piece of the material on a wall or vertical surface
2. Stand 10-20 feet away, and shine a small flashlight at the material.
3. Start with the light held at your belly button, and raise it slowly until it is between your eyes. As the light nears your eyes, the intensity of the returned light will increase rapidly.
4. Alter the angle by moving to other locations in the room and repeating. The bright reflection should occur over a wide range of viewing angles, but the angle from light source to eye is key and must be quite small.

Experiment with different light sources. The material is hundreds of times more reflective than white paint; so dim light sources will work fine. For example, a red bicycle safety light will demonstrate that the color of the light source determines the color of the reflected light. If possible, position several team members at different locations, each with their own light source. This will show that the effects are largely independent, and the material can simultaneously appear different colors to various team members. This also demonstrates that the material is largely immune to environmental lighting. The light returning to the viewer is almost entirely determined by a light source they control or one directly behind them. Using the flashlight, identify other retro-reflective articles already in your environment: on clothing, backpacks, shoes, etc.

## Lighting



We have seen that the retro-reflective tape will not shine unless a light source is directed at it, and the light source must pass very near the camera lens or the observer's eyes. While there are a number of ways to accomplish this, a very useful type of light source to investigate is the ring flash, or ring light, shown above. It places the light source directly on or around the camera lens and provides very even lighting. Because of their bright output and small size, LEDs are particularly useful for constructing this type of device.

As shown above, inexpensive circular arrangements of LEDs are available in a variety of colors and sizes and are easy to attach to the Axis cameras. While not designed for diffuse even lighting, they work quite well for causing retro-reflective tape to shine. A small green LED ring is available through FIRST Choice. Other similar LED rings are available from suppliers such as SuperBrightLEDs.

## Sample Images

Sample images are located with the code examples for each language (packaged with LabVIEW, and in a separate ZIP in the same location as the C++/Java samples).

### 17.1.5 Identifying and Processing the Targets

Once an image is captured, the next step is to identify Vision Target(s) in the image. This document will walk through one approach to identifying the 2016 targets. Note that the images used in this section were taken with the camera intentionally set to underexpose the images, producing very dark images with the exception of the lit targets, see the section on Camera Settings for details.

### Additional Options

This document walks through the approach used by the example code provided in LabVIEW (for PC or roboRIO), C++ and Java. In addition to these options teams should be aware of the following alternatives that allow for vision processing on the Driver Station PC or an on-board PC:

1. [RoboRealm](#)
2. SmartDashboard Camera Extension (programmed in Java, works with any robot language)
3. [GRIP](#)

### Original Image

The image shown below is the starting image for the example described here. The image was taken using the green ring light available in *FIRST*® Choice combined with an additional ring light of a different size.



## What is HSL/HSV?

The Hue or tone of the color is commonly seen on the artist's color wheel and contains the colors of the rainbow Red, Orange, Yellow, Green, Blue, Indigo, and Violet. The hue is specified using a radial angle on the wheel, but in imaging the circle typically contains only 256 units, starting with red at zero, cycling through the rainbow, and wrapping back to red at the upper end. Saturation of a color specifies amount of color, or the ratio of the hue color to a shade of gray. Higher ratio means more colorful, less gray. Zero saturation has no hue and is completely gray. Luminance or Value indicates the shade of gray that the hue is blended with. Black is 0 and white is 255.

The example code uses the HSV color space to specify the color of the target. The primary reason is that it readily allows for using the brightness of the targets relative to the rest of the image as a filtering criteria by using the Value (HSV) or Luminance (HSL) component. Another reason to use the HSV color system is that the thresholding operation used in the example runs more efficiently on the roboRIO when done in the HSV color space.

## Masking

In this initial step, pixel values are compared to constant color or brightness values to create a binary mask shown below in yellow. This single step eliminates most of the pixels that are not part of a target's retro-reflective tape. Color based masking works well provided the color is relatively saturated, bright, and consistent. Color inequalities are generally more accurate when specified using the HSL (Hue, Saturation, and Luminance) or HSV (Hue, Saturation, and Value) color space than the RGB (Red, Green, and Blue) space. This is especially true when the color range is quite large in one or more dimension.

Notice that in addition to the target, other bright parts of the image (overhead light and tower lighting) are also caught by the masking step.





### Particle Analysis

After the masking operation, a particle report operation is used to examine the area, bounding rectangle, and equivalent rectangle for the particles. These are used to compute several scored terms to help pick the shapes that are most rectangular. Each test described below generates a score (0-100) which is then compared to pre-defined score limits to decide if the particle is a target or not.

### Coverage Area

The Area score is calculated by comparing the area of the particle compared to the area of the bounding box drawn around the particle. The area of the retroreflective strips is 80 square inches. The area of the rectangle that contains the target is 240 square inches. This means that the ideal ratio between area and bounding box area is  $1/3$ . Area ratios close to  $1/3$  will produce a score near 100, as the ratio diverges from  $1/3$  the score will approach 0.

### Aspect Ratio

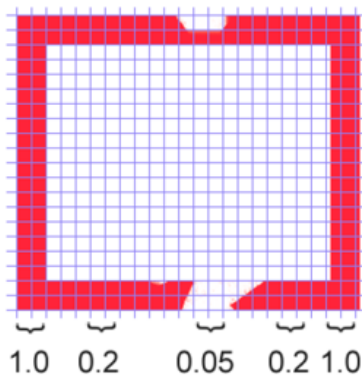
The aspect ratio score is based on (Particle Width / Particle Height). The width and height of the particle are determined using something called the “equivalent rectangle”. The equivalent rectangle is the rectangle with side lengths  $x$  and  $y$  where  $2x + 2y$  equals the particle perimeter and  $x \cdot y$  equals the particle area. The equivalent rectangle is used for the aspect ratio calculation as it is less affected by skewing of the rectangle than using the bounding box. When using the bounding box rectangle for aspect ratio, as the rectangle is skewed the height increases and the width decreases.

The target is 20” wide by 12” tall, for a ratio of 1.6. The detected aspect ratio is compared to this ideal ratio. The aspect ratio score is normalized to return 100 when the ratio matches the target ratio and drops linearly as the ratio varies below or above.

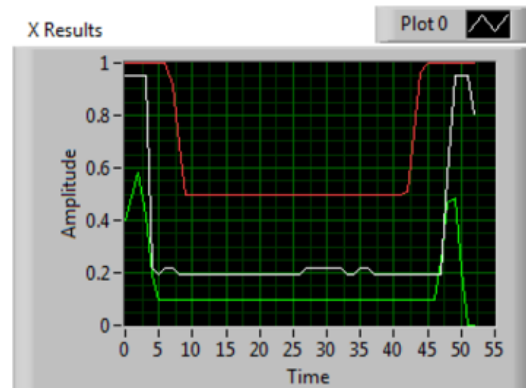
### Moment

The moment measurement calculates the particles moment of inertia about it’s center of mass. This measurement provides a representation of the pixel distribution in the particle. The ideal score for this test is  $\sim 0.28$ . See: [Moment of Inertia](#)

## X/Y Profiles



Column averages for a particle rectangle.



White line is the average, red is upper limit, and green is lower limit..

The edge score describes whether the particle matches the appropriate profile in both the X and Y directions. As shown, it is calculated using the row and column averages across the bounding box extracted from the original image and comparing that to a profile mask. The score ranges from 0 to 100 based on the number of values within the row or column averages that are between the upper and lower limit values.

## Measurements

If a particle scores well enough to be considered a target, it makes sense to calculate some real-world measurements such as position and distance. The example code includes these basic measurements, so let's look at the math involved to better understand it.

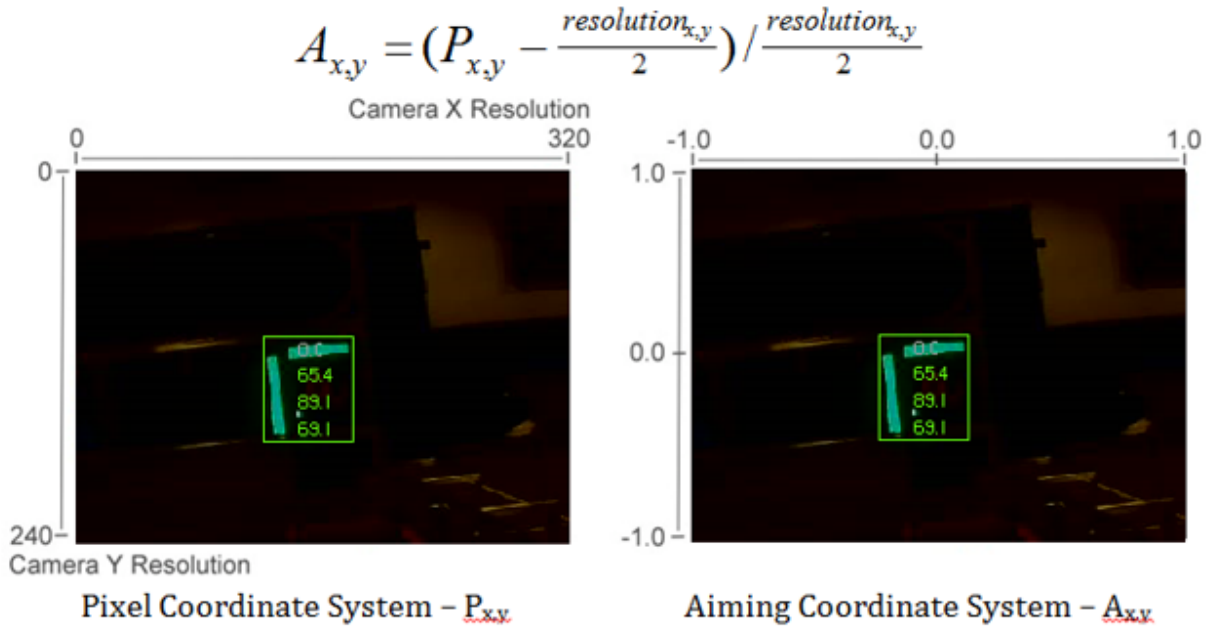
## Position

The target position is well described by both the particle and the bounding box, but all coordinates are in pixels with 0,0 being at the top left of the screen and the right and bottom edges determined by the camera resolution. This is a useful system for pixel math, but not nearly as useful for driving a robot; so let's change it to something that may be more useful.

To convert a point from the pixel system to the aiming system, we can use the formula shown below.

The resulting coordinates are close to what you may want, but the Y axis is inverted. This could be corrected by multiplying the point by [1,-1] (Note: this is not done in the sample code). This coordinate system is useful because it has a centered origin and the scale is similar to joystick outputs and RobotDrive inputs.

$$A_{x,y} = \left( P_{x,y} - \frac{\text{resolution}_{x,y}}{2} \right) / \frac{\text{resolution}_{x,y}}{2}$$

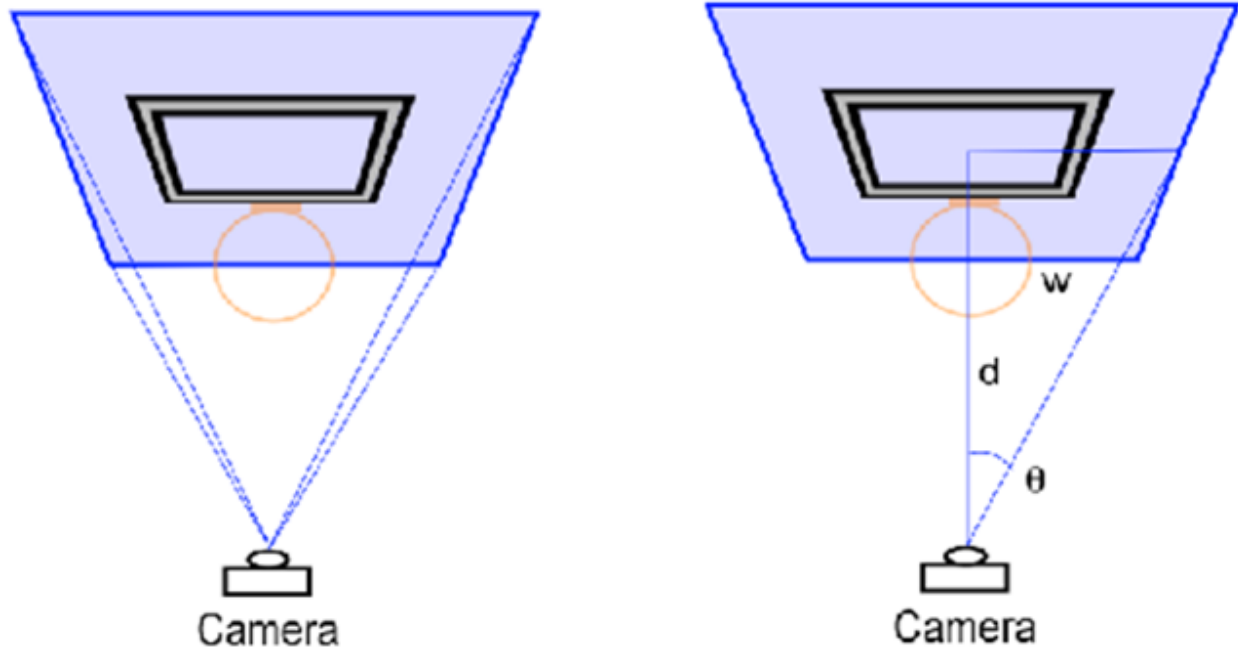


## Distance

The target distance is computed with knowledge about the target size and the camera optics. The approach uses information about the camera lens view angle and the width of the camera field of view. Shown below-left, a given camera takes in light within the blue pyramid extending from the focal point of the lens. Unless the lens is modified, the view angle is constant and equal to  $2\Theta$ . As shown to the right, the values are related through the trigonometric relationship of:

$$\tan \theta = \frac{w}{d}$$

The datasheets for the cameras can be found at the following links: [Axis 206](#), [Axis M1011](#), [Axis M1013](#), [LifeCam HD-3000](#). These give rough horizontal view angles for the lenses. Remember that this is for entire field of view, and is therefore  $2\theta$ . The 2016 code uses the vertical field-of-view and it is therefore highly recommend to perform calibration (as described in the next article) to determine the appropriate view angle for your camera (empirically determined values for each camera type are included in the code as a reference).



### Distance Continued

The next step is to use the information we have about the target to find the width of the field of view the blue rectangle shown above. This is possible because we know the target rectangle size in both pixels and feet, and we know the FOV rectangle width in pixels. We can use the relationships of:

$$\frac{T_{\text{ft}}}{T_{\text{pixel}}} = \frac{FOV_{\text{ft}}}{FOV_{\text{pixel}}}$$

and

$$FOV_{\text{ft}} = 2w = 2d \tan \theta$$

to create an equation to solve for  $d$ , the distance from the target:

$$d = \frac{T_{\text{ft}} \cdot FOV_{\text{pixel}}}{2T_{\text{pixel}} \tan \theta}$$

Notice that the datasheets give approximate view angle information. When testing, it was found that the calculated distance to the target tended to be a bit short. Using a tape measure to measure the distance and treating the angle as the unknown it was found that view angles of  $41.7^\circ$  for the 206,  $37.4^\circ$  for the M1011, and  $49^\circ$  for the M1013 gave better results. Information on performing your own distance calibration is included in the next article.

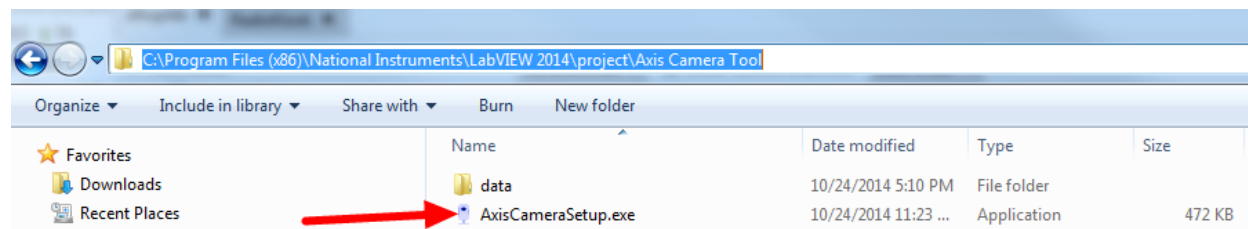
### 17.1.6 Configuring an Axis Camera

**Note:** Three different Axis camera models are supported by the FRC software, the Axis 206, Axis M1011 and Axis M1013. This document provides instructions on how to configure one of these cameras for FRC use. To follow the instructions in this document, you must have installed the NI FRC Game Tools and Configured your radio

### Connect the camera

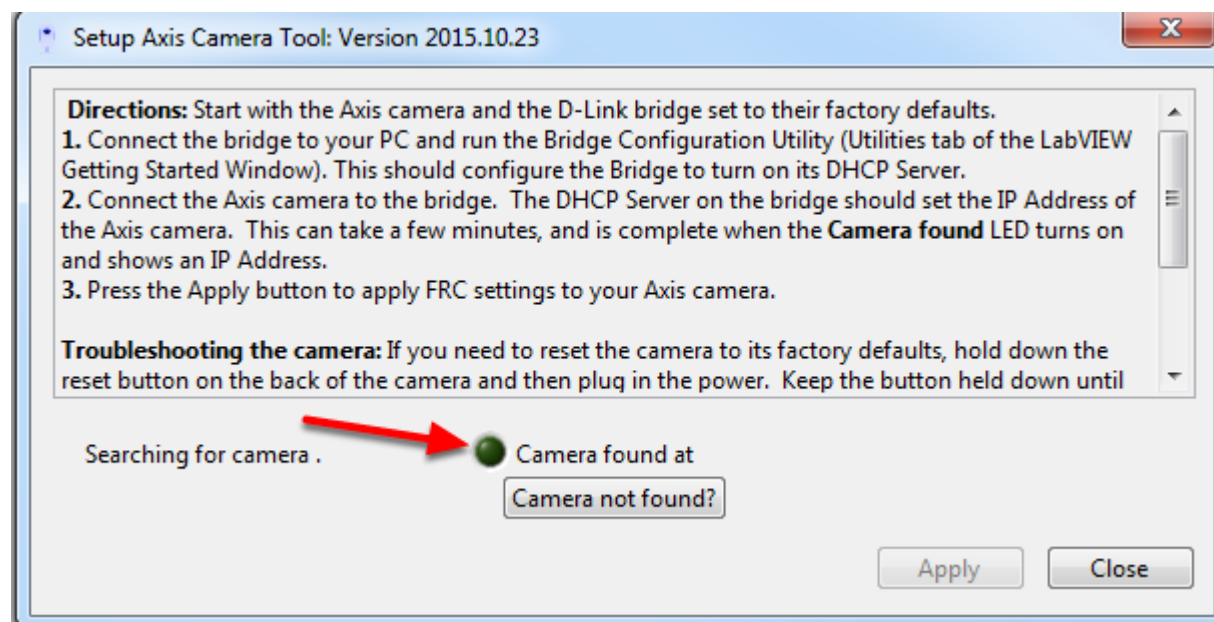
Connect the Axis camera to the radio using an Ethernet cable. Connect your computer to the radio using an Ethernet cable or via a wireless connection.

### Axis Camera Setup Tool



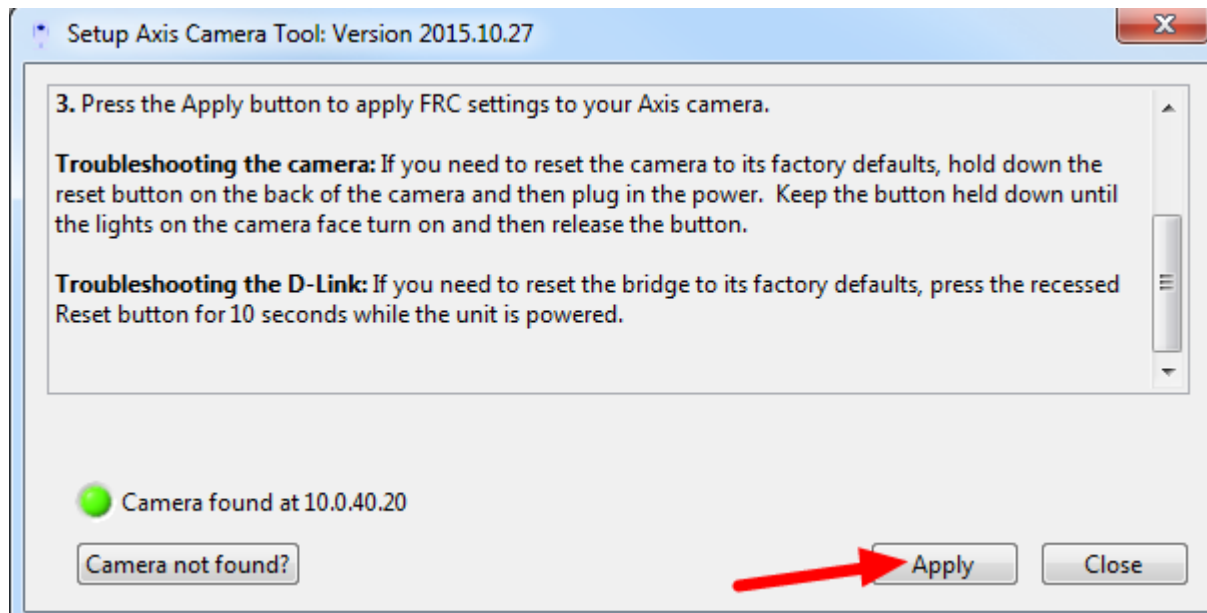
Browse to C:\Program Files (x86)\National Instruments\LabVIEW 2019\project\Axis Camera Tool and double-click on AxisCameraSetup.exe to start the Axis Camera Setup Tool.

### Tool Overview



The camera should be automatically detected and the green indicator light should be lit. If it is not, make sure the camera is powered on (the ring on the camera face should be green) and connected to your computer. If the indicator remains off follow the instructions in the tool textbox next to Troubleshooting the camera to reset the camera. You can also use the "Camera not found?" button to check the IP address of your computer, one of the addresses listed should be of the form 10.TE.AM.XX where TEAM is your 4 digit team number.

## Setup the Camera



To configure the camera, press Apply. This will configure many of the necessary/recommended settings for using the camera for FRC. Currently the tool does not properly configure the DNS name of the camera in many cases.

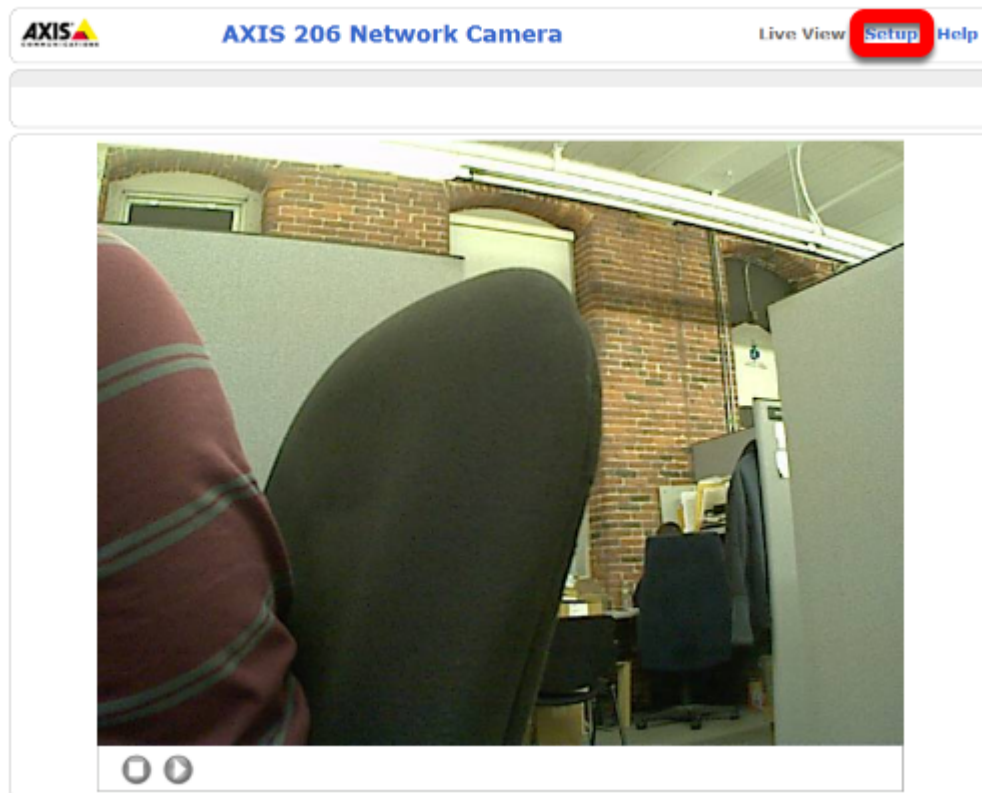
## Camera Webpage

A screenshot of the Axis Communications 'Configure Root Password' webpage. The page has the Axis logo at the top left and a row of flags at the top right. The main heading is 'Configure Root Password'. Below it, there are three input fields: 'User name:' with 'root' entered, 'Password:', and 'Confirm password:'. An 'OK' button is to the right of the password fields. At the bottom, there is a paragraph of text: 'The password for the pre-configured administrator root must be changed before the product can be used.' and another paragraph: 'If the password for root is lost, the product must be reset to the factory default settings, by pressing the button located in the product's casing. Please see the user documentation for more information.'

To set the network settings, open a web browser and enter the address shown next to Camera found at in the tool (in the example above this is 10.0.40.20) in the address bar and press enter.

You should see a Configure Root Password page, set this password to whatever you would like, but admin is recommended.

### Setup Page



Click Setup to go to the setup page.

## Configure Basic Network Settings

**AXIS 206 Network Camera** Live View | Setup | Help

**Basic TCP/IP Settings** ?

**Network Settings**

View current network settings: View

**IP Address Configuration**

2 ☒ Obtain IP address via DHCP

☐ Use the following IP address:

IP address:  Test

Subnet mask:

Default router:

**Services**

☒ Enable ARP/Ping setting of IP Address

Options for notification of IP address change Settings...

AXIS Internet Dynamic DNS Service Settings...

3 Save Reset

**Left Sidebar:**

- Basic Configuration
- Video & Image
- Live View Config
- System Options
  - Users
  - Date & Time
  - Network
    - 1 **Basic**
    - Advanced
    - QoS
    - SMTP (email)
    - UPnP
    - Bonjour
    - LED settings
    - Maintenance
  - Support
  - Advanced
- Language
- About

To configure the network settings of the camera, click the arrow to expand the System Options pane, then click the arrow to expand Network, then expand TCP/IP and select Basic. Set the camera to obtain an IP address via DHCP by selecting the bubble. Alternately, you may choose to set a static IP in the range 10.TE.AM.3 to 10.TE.AM.19. This is outside the range handed out by the radio (home use) or FMS system (event use) so you will avoid any IP conflicts.

Click Save.



## Configure Advanced Network Settings

**AXIS 206 Network Camera** [Live View](#) | [Setup](#) | [Help](#)

**Advanced TCP/IP Settings**

**DNS Configuration**

☒ Obtain DNS server address via DHCP [View](#)

☐ Use the following DNS server address:

Domain name:  (use ; to separate names)

Primary DNS server:

Secondary DNS server:

**NTP Configuration**

☒ Obtain NTP server address via DHCP [View](#)

☐ Use the following NTP server address:

Network address:  (host name or IP address)

**Host Name Configuration**

☒ Use the host name:

☐ Obtain host name via DHCP [View](#)

☐ Enable dynamic DNS updates

Register DNS name:  (Axisproduct.example.com)

TTL:

**Link-Local Address**

☒ Auto-Configure Link-Local Address [View](#)

**HTTP**

HTTP port:

**NAT traversal (port mapping)**

NAT traversal is disabled. [Enable](#)

☐ Use manually selected NAT router:  (LAN IP address)

Alternative HTTP port:  \*

\* If left blank, a port number will be set automatically upon enable.

**FTP**

☒ Enable FTP server

**Network Traffic**

Connection type:

[Save](#) [Reset](#)

Next click Advanced under TCP/IP. Set the Host Name Configuration to “Use the host name:” and set the value to axis - camera as shown. If you plan to use multiple cameras on your robot, select a unique host name for each. You will need to modify the dashboard and/or robot code to work with the additional cameras and unique host names.

Click Save.

## Manual Camera Configuration

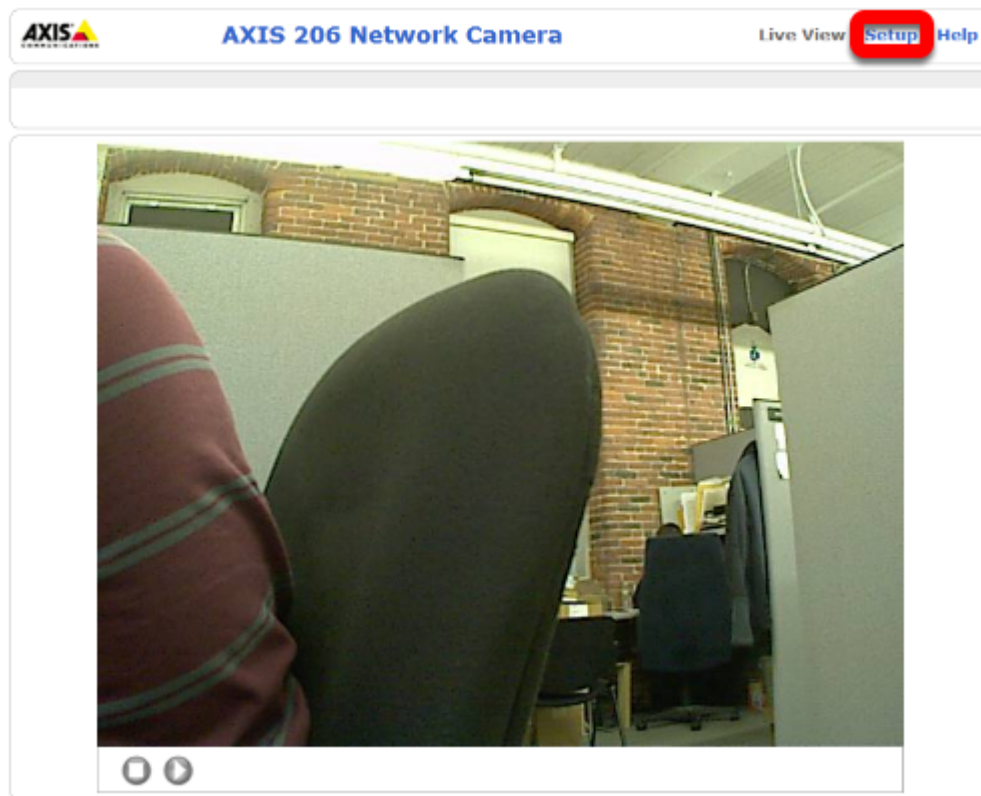


The screenshot shows the 'Configure Root Password' web interface for an Axis Communications device. At the top left is the Axis Communications logo. To the right of the logo is a row of eight small flags representing different countries: USA, South Korea, Japan, Italy, France, Spain, Germany, and China. The main heading is 'Configure Root Password' in blue. Below the heading are three input fields: 'User name:' with the text 'root' entered, 'Password:', and 'Confirm password:'. To the right of the 'Confirm password:' field is an 'OK' button. Below the input fields is a horizontal line, followed by two paragraphs of text. The first paragraph states: 'The password for the pre-configured administrator root must be changed before the product can be used.' The second paragraph states: 'If the password for root is lost, the product must be reset to the factory default settings, by pressing the button located in the product's casing. Please see the user documentation for more information.'

It is recommended to use the Setup Axis Camera Tool to configure the Axis Camera. If you need to configure the camera manually, connect the camera directly to the computer, configure your computer to have a static IP of 192.168.0.5, then open a web browser and enter 192.168.0.90 in the address bar and press enter. You should see a Configure Root Password page, set this password to whatever you would like, but admin is recommended.

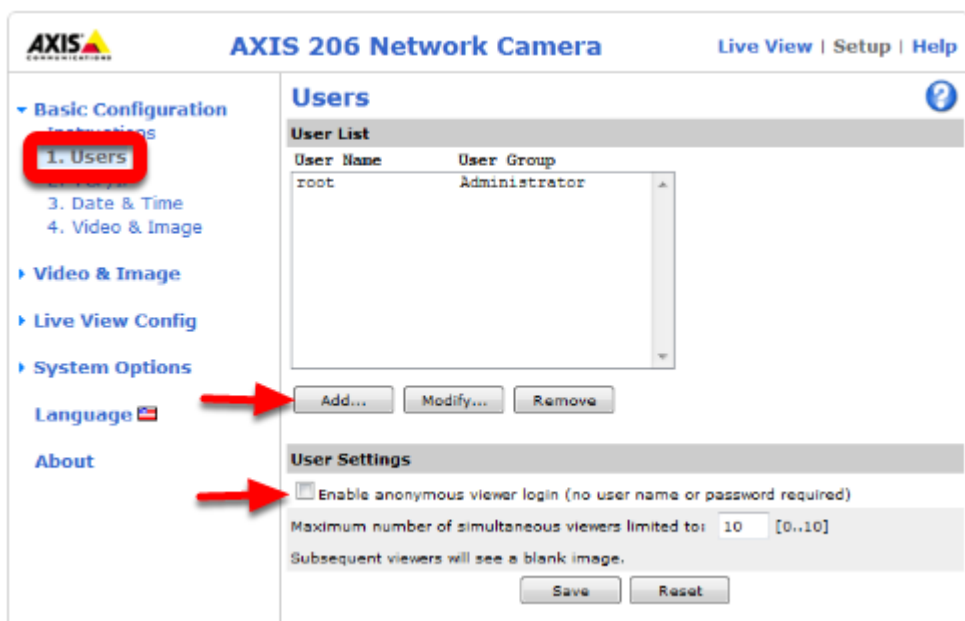
If you do not see the camera webpage come up, you may need to reset the camera to factory defaults. To do this, remove power from the camera, hold the reset button while applying power to the camera and continue holding it until the lights on the camera face turn on, then release the reset button and wait for the lights to turn green. The camera is now reset to factory settings and should be accessible via the 192.168.0.90 address.

## Manual - Setup Page



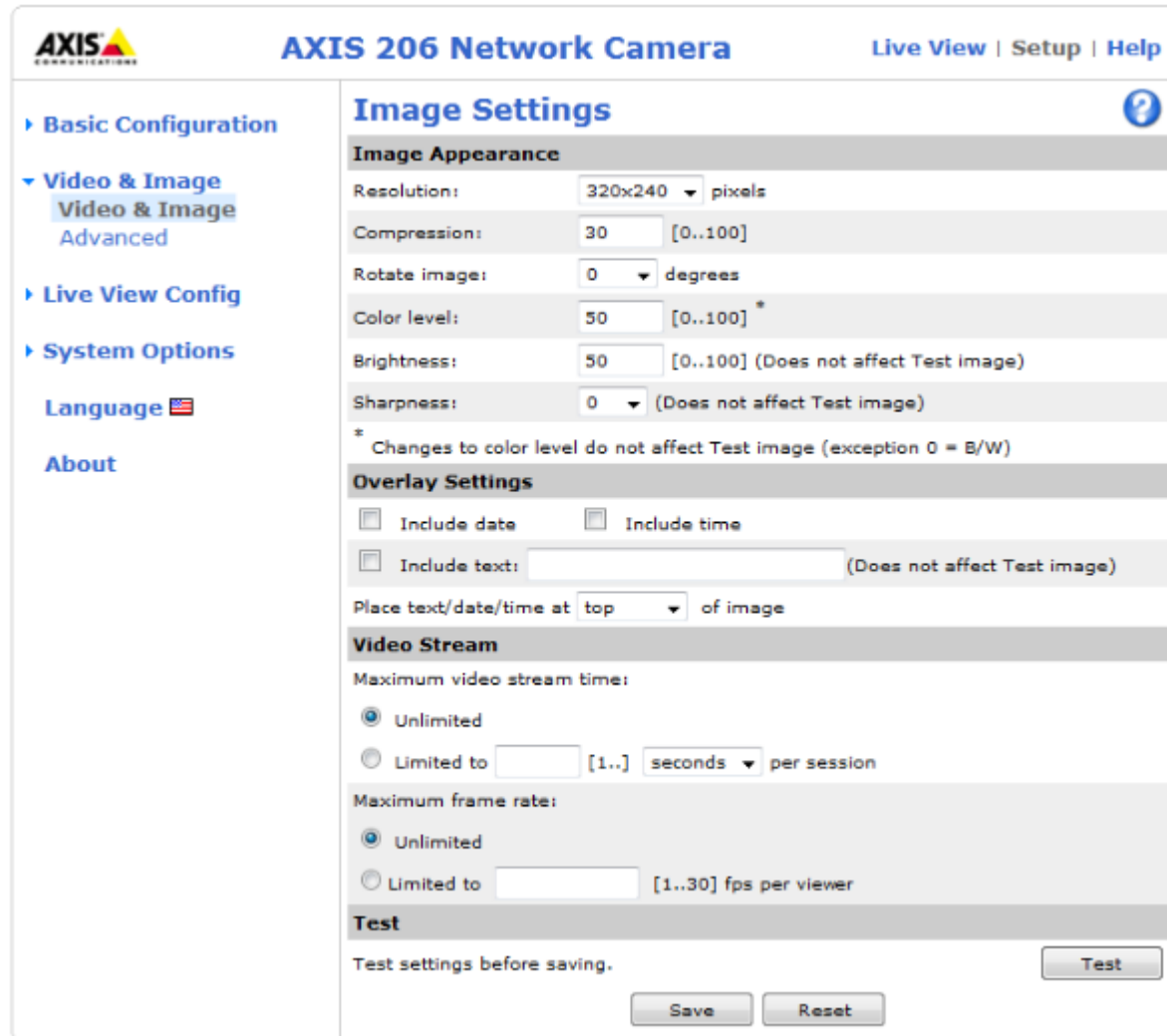
Click Setup to go to the setup page.

## Manual - Configure Users



On the left side click Users to open the users page. Click Add then enter the Username FRC Password FRC and click the Administrator bubble, then click OK. If using the SmartDashboard, check the Enable anonymous viewer login box. Then click Save.

## Manual - Configure Image Settings



The screenshot shows the web interface for an AXIS 206 Network Camera. The left sidebar contains navigation links: Basic Configuration, Video & Image (selected), Live View Config, System Options, Language, and About. The main content area is titled 'Image Settings' and includes a help icon. It is divided into three sections: Image Appearance, Overlay Settings, and Video Stream. The Image Appearance section has fields for Resolution (320x240 pixels), Compression (30), Rotate image (0 degrees), Color level (50), Brightness (50), and Sharpness (0). The Overlay Settings section has checkboxes for Include date, Include time, and Include text, along with a dropdown to place text/date/time at the top of the image. The Video Stream section has radio buttons for Maximum video stream time (Unlimited or Limited to a specified number of seconds per session) and Maximum frame rate (Unlimited or Limited to a specified number of fps per viewer). At the bottom, there is a 'Test' button and 'Save' and 'Reset' buttons.

**AXIS 206 Network Camera** Live View | Setup | Help

**Image Settings** ?

**Image Appearance**

Resolution: 320x240 pixels

Compression: 30 [0..100]

Rotate image: 0 degrees

Color level: 50 [0..100] \*

Brightness: 50 [0..100] (Does not affect Test image)

Sharpness: 0 (Does not affect Test image)

\* Changes to color level do not affect Test image (exception 0 = B/W)

**Overlay Settings**

☐ Include date ☐ Include time

☐ Include text: (Does not affect Test image)

Place text/date/time at: top of image

**Video Stream**

Maximum video stream time:

☒ Unlimited

☐ Limited to [1..] seconds per session

Maximum frame rate:

☒ Unlimited

☐ Limited to [1..30] fps per viewer

**Test**

Test settings before saving. Test

Save Reset

Click Video & Image on the left side to open the image settings page. Set the Resolution and Compression to the desired values (recommended 320x240, 30). To limit the framerate to under 30 FPS, select the Limited to bubble under Maximum frame rate and enter the desired rate in the box. Color, Brightness and Sharpness may also be set on this screen if desired. Click Save when finished.

## Manual - Configure Basic Network Settings

**AXIS 206 Network Camera** Live View | Setup | Help

**Basic TCP/IP Settings** ?

**Network Settings**

View current network settings: View

**IP Address Configuration**

2 ☒ Obtain IP address via DHCP

☐ Use the following IP address:

IP address:  Test

Subnet mask:

Default router:

**Services**

☒ Enable ARP/Ping setting of IP Address

Options for notification of IP address change Settings...

AXIS Internet Dynamic DNS Service Settings...

3 Save Reset

**Left Sidebar:**

- Basic Configuration
- Video & Image
- Live View Config
- System Options
  - Users
  - Date & Time
  - Network
    - 1 **Basic**
    - Advanced
    - QoS
    - SMTP (email)
    - UPnP
    - Bonjour
    - LED settings
    - Maintenance
  - Support
  - Advanced
- Language
- About

To configure the network settings of the camera, click the arrow to expand the System Options pane, then click the arrow to expand Network, then expand TCP/IP and select Basic. Set the camera to obtain an IP address via DHCP by selecting the bubble. Alternately, you may choose to set a static IP in the range 10.TE.AM.3 to 10.TE.AM.19. This is outside the range handed out by the radio (home use) or FMS system (event use) so you will avoid any IP conflicts.

Click Save.

## Manual - Configure Advanced Network Settings

**AXIS 206 Network Camera** Live View | Setup | Help

**Advanced TCP/IP Settings**

**DNS Configuration**

☒ Obtain DNS server address via DHCP View

☐ Use the following DNS server address:

Domain name:  (use ; to separate names)

Primary DNS server:

Secondary DNS server:

**NTP Configuration**

☒ Obtain NTP server address via DHCP View

☐ Use the following NTP server address:

Network address:  (host name or IP address)

**Host Name Configuration**

☒ Obtain host name via DHCP View

☒ Use the host name:

☐ Enable dynamic DNS updates

Register DNS name:  (Axisproduct.example.com)

TTL:

**Link-Local Address**

☒ Auto-Configure Link-Local Address View

**HTTP**

HTTP port:

**NAT traversal (port mapping)**

NAT traversal is disabled. Enable

☐ Use manually selected NAT router:  (LAN IP address)

Alternative HTTP port:  \*

\* If left blank, a port number will be set automatically upon enable.

**FTP**

☒ Enable FTP server

**Network Traffic**

Connection type:

Save Reset

Next click Advanced under TCP/IP. Set the Host Name Configuration to “Use the host name:” and set the value to axis - camera as shown. If you plan to use multiple cameras on your robot, select a unique host name for each. You will need to modify the dashboard and/or robot code to work with the additional cameras and unique host names.

Click Save.

### 17.1.7 Using the Microsoft Lifecam HD-3000

The Microsoft Lifecam HD-3000 is a USB webcam that was tested with the roboRIO as part of the Beta testing and software development effort. While other USB webcams may work with the roboRIO, this camera has been tested to be compatible with the provided software.

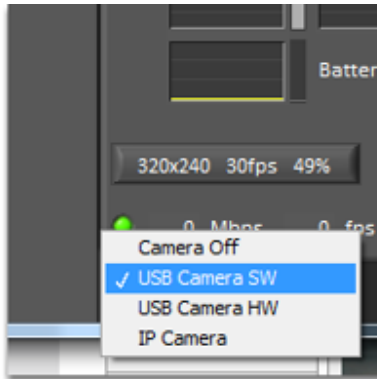
#### Connecting the Camera to the roboRIO



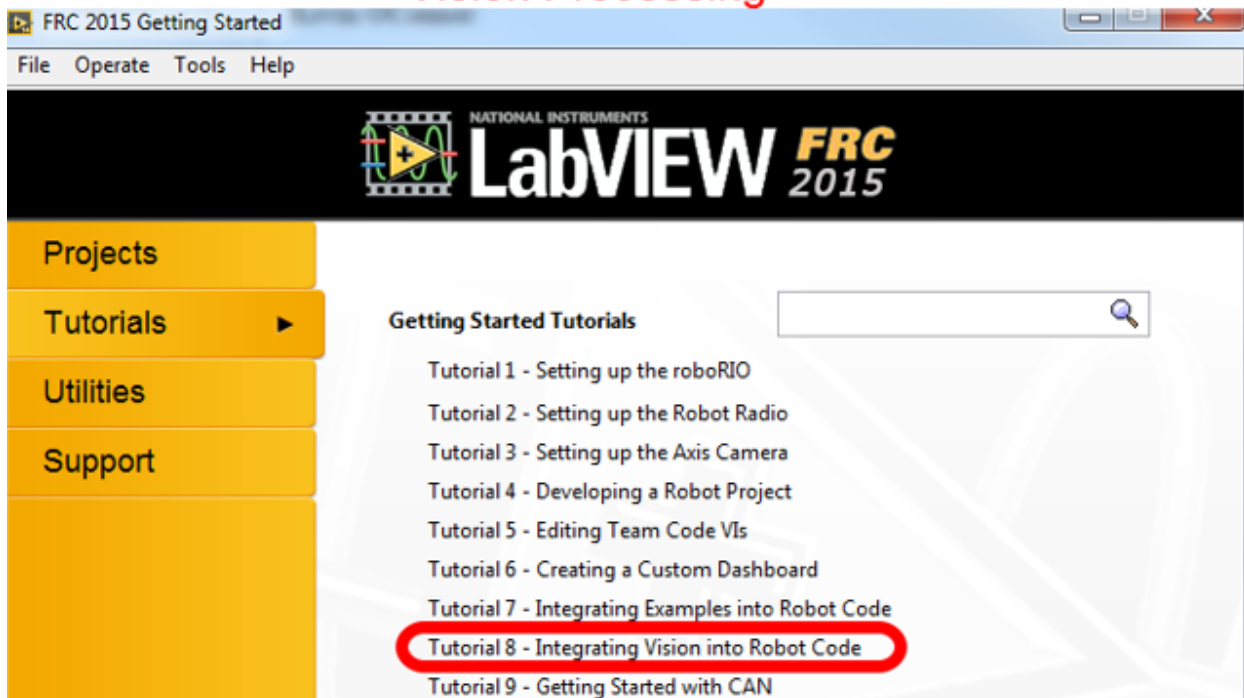
The camera can be connected to either of the roboRIO USB ports.

## Using the Camera - LabVIEW

Dashboard  
Stream



Vision Processing



To stream the camera back to the Dashboard using LabVIEW, no additional code is necessary. Simply select USB HW (image compression done by the camera, fewer options but lower roboRIO CPU usage) or USB SW (image compressed by roboRIO, more options, but higher roboRIO CPU usage) and the image should begin streaming back.

**Note:** The camera should be plugged in before your LabVIEW code starts running to work properly. If you just plugged in the camera, rebooting the roboRIO is a quick way to make sure it is recognized properly.

The default LabVIEW templates and the image processing examples are already set up for the USB camera if you want to do image processing. On the LabVIEW splash screen, click Tutorials, then click Tutorial 8 for more information about integrating Vision processing in



your LabVIEW code.

### Using the Camera - C++/Java

To stream the camera back to the Dashboard using C++ or Java robot code, you will need to add some code to your robot project. See [Using the CameraServer on the roboRIO](#) for instructions on using the CameraServer class to automatically stream images back to the Dashboard.

#### 17.1.8 Camera Settings

It is very difficult to achieve good image processing results without good images. With a light mounted near the camera lens, you should be able to use the provided examples, the LabVIEW Dashboard or Shuffleboard, NI Vision Assistant or a web browser to view camera images and experiment with camera settings.

## Changing Camera Settings

- Basic Setup **M1013**
- Video
  - Video Stream
  - Stream Profiles
  - Camera Settings**
  - Overlay Image
  - Privacy Mask
- Live View Config
- Detectors
- Events
- Recordings
- System Options
- About

### Camera Settings

**View Area**

☐ Enable View Area

**Image Appearance**

Color level:  50 [0..100]

Brightness:  50 [0..100]

Sharpness:  50 [0..100]

Contrast:  50 [0..100]

**White Balance**

White balance: Fixed Outdoor 1

**Exposure Settings**

Exposure value:  50 [0..100]

Enable Backlight compensation: ☐

Exposure priority: Default

**View Image Settings**

- Basic Configuration **206**
- Video & Image **M1011**
  - Video & Image**
  - Advanced
- Live View Config
- System Options
- Language
- About

### Image Settings

**Image Appearance**

Resolution: 640x480 pixels

Compression: 30 [0..100]

Rotate image: 0 degrees

Color level: 50 [0..100] \*

Brightness: 50 [0..100] (Does not affect Test image)

Sharpness: 0 (Does not affect Test image)

\* Changes to color level do not affect Test image (exception 0 = B/W)

**Overlay Settings**

☐ Include date ☐ Include time

☐ Include text: (Does not affect Test image)

Place text/date/time at top of image

**Video Stream**

To change the camera settings on any of the supported Axis cameras (206, M1011, M1013), browse to the camera's webpage by entering its address (usually 10.TE.AM.11) in a web browser. Click Setup near the top right corner of the page. On the M1013, the settings listed below are split between the Video Stream page and the Camera Settings page, both listed under the Video section.

### Focus

The Axis M1011 has a fixed-focus lens and no adjustment is needed. The Axis 206 camera has a black bezel around the lens that rotates to move the lens in and out and adjust focus. The Axis M103 has a silver and black bezel assembly around the lens to adjust the focus. Ensure that the images you are processing are relatively sharp and focused for the distances needed on your robot.

## Compression



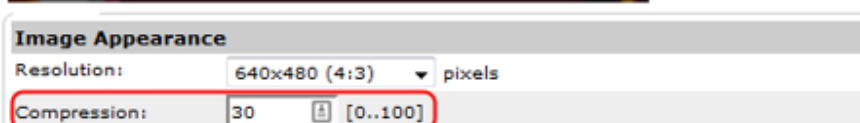
320x240 Color Image:  
Compression set to 0. Image file size is 20,715 bytes.  
High quality, but large in size. May be slower to compress and decompress - which impacts frame rate.



320x240 Color Image:  
Compression set to 30. Image file size is 6,450 bytes. Good quality, relatively small in size. Some image artifacts are present on edges.



320x240 Color Image:  
Compression set to 100. Image file size is 2,222 bytes. Poor quality for processing. Notice blocky artifacts and rough edges.



The Axis camera returns images in BMP, JPEG, or MJPEG format. BMP images are quite large and take more time to transmit to the cRIO and laptop. Therefore the WPILib implementations typically use MJPEG (motion JPEG). The compression setting ranges from 0 to 100, with 0 being very high quality images with very little compression, and 100 being very low quality images with very high compression. The camera default is 30, and it is a good compromise, with few artifacts that will degrade image processing.

---

**Note:** Teams are advised to consider how the compression setting on the camera affects bandwidth if performing processing on the Driver Station computer, see the FMS Whitepaper for more details.

---

### Resolution

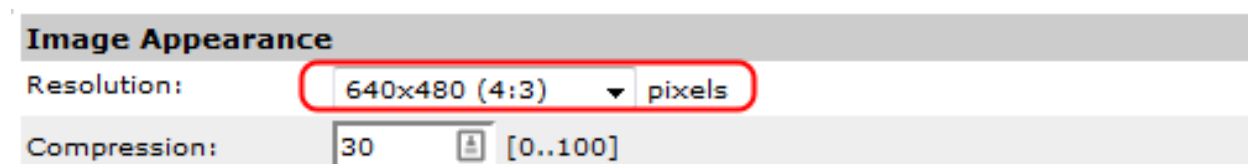


Image sizes shared by the supported cameras are 160x120, 320x240, and 640x480. The M1011 and 1013 have additional sizes, but they aren't built into WPILib. The largest image size has four times as many pixels that are one-fourth the size of the middle size image. The large image has sixteen times as many pixels as the small image.

The tape used on the target is 4 inches wide, and for good processing, you will want that 4 inch feature to be at least two pixels wide. Using the distance equations above, we can see that a medium size image should be fine up to the point where the field of view is around 640 inches, a little over 53 feet, which is nearly double the width of the FRC field. This occurs at around 60 feet away, longer than the length of the field. The small image size should be usable for processing to a distance of about 30 feet or a little over mid-field.

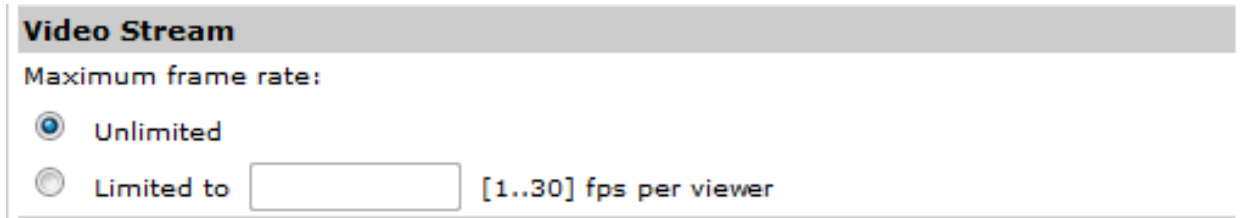
Image size also impacts the time to decode and to process. Smaller images will be roughly four times faster than the next size up. If the robot or target is moving, it is quite important to minimize image processing time since this will add to the delay between the target location and perceived location. If both robot and target are stationary, processing time is typically less important.

---

**Note:** When requesting images using LabVIEW (either the Dashboard or Robot Code), the resolution and Frame Rate settings of the camera will be ignored. The LabVIEW code specifies the framerate and resolution as part of the stream request (this does not change the settings stored in the camera, it overrides that setting for the specific stream). The SmartDashboard and robot code in C++ or Java will use the resolution and framerate stored in the camera.

---

## Frame Rate



**Video Stream**

Maximum frame rate:

☒ Unlimited

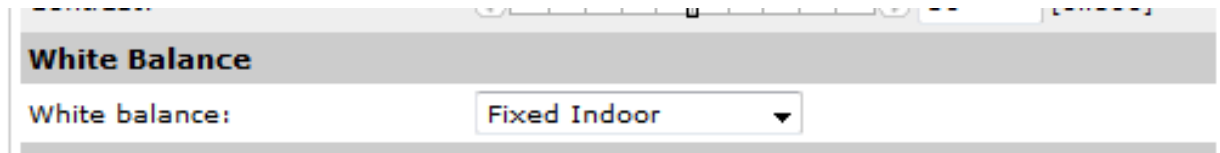
☐ Limited to  [1..30] fps per viewer

The Axis Cameras have a max framerate of 30 frames per second. If desired, a limit can be set lower to reduce bandwidth consumption.

## Color Enable

The Axis cameras typically return color images, but are capable of disabling color and returning a monochrome or grayscale image. The resulting image is a bit smaller in file size, and considerably quicker to decode. If processing is carried out only on the brightness or luminance of the image, and the color of the ring light is not used, this may be a useful technique for increasing the frame rate or lowering the CPU usage.

## White Balance



**White Balance**

White balance: Fixed Indoor ▼

If the color of the light shine is being used to identify the marker, be sure to control the camera settings that affect the image coloring. The most important setting is white balance. It controls how the camera blends the component colors of the sensor in order to produce an image that matches the color processing of the human brain. The camera has five or six named presets, an auto setting that constantly adapts to the environment, and a hold setting – for custom calibration.

The easiest approach is to use a named preset, one that maintains the saturation of the target and doesn't introduce problems by tinting neutral objects with the color of the light source.

To custom-calibrate the white balance, place a known neutral object in front of the camera. A sheet of white paper is a reasonable object to start with. Set the white balance setting to auto, wait for the camera to update its filters (ten seconds or so), and switch the white balance to hold.

## Exposure

**Image Appearance** M1013

Color level:  50 [0..100]

**Brightness:**  0 [0..100]

Sharpness:  50 [0..100]

Contrast:  50 [0..100]

**White Balance**

White balance: Fixed Indoor

**Exposure Settings**

**Exposure value:**  0 [0..100]

Enable Backlight compensation: ☐

Exposure priority: Motion

---

**Lighting Conditions** 206/M1011

White balance: Automatic

**Exposure control:** Automatic

**Low Light Behavior**

**Exposure priority:** None

The brightness or exposure of the image also has an impact on the colors being reported. The issue is that as overall brightness increases, color saturation will start to drop. Let's look at an example to see how this occurs. A saturated red object placed in front of the camera will return an RGB measurement high in red and low in the other two e.g. (220, 20, 30). As overall white lighting increases, the RGB value increases to (240, 40, 50), then (255, 80, 90), then (255, 120, 130), and then (255, 160, 170). Once the red component is maximized, additional light can only increase the blue and green, and acts to dilute the measured color and lower the saturation. If the point is to identify the red object, it is useful to adjust the exposure to avoid diluting your principal color. The desired image will look somewhat dark except for the colored shine.

There are two approaches to control camera exposure times. One is to allow the camera to compute the exposure settings automatically, based on its sensors, and then adjust the camera's brightness setting to a small number to lower the exposure time. The brightness setting acts similar to the exposure compensation setting on SLR cameras. The other approach is to calibrate the camera to use a custom exposure setting. To do this on a 206 or M1011, change the exposure setting to auto, expose the camera to bright lights so that it computes a short exposure, and then change the exposure setting to hold. Both approaches will result in an overall dark image with bright saturated target colors that stand out from the background and are easier to mask.

The M1013 exposure settings look a little different. The Enable Backlight compensation op-

tion is similar to the Auto exposure settings of the M1011 and 206 and you will usually want to un-check this box. Adjust the Brightness and Exposure value sliders until your image looks as desired. The Exposure Priority should generally be set to Motion. This will prioritize framerate over image quality. Note that even with these settings the M1013 camera still performs some auto exposure compensation so it is recommended to check calibration frequently to minimize any impact lighting changes may have on image processing. See [Calibration](#) for more details.

### **17.1.9 Calibration**

While many of the numbers for the Vision Processing code can be determined theoretically, there are a few parameters that are typically best to measure empirically then enter back into the code (a process typically known as calibration). This article will show how to perform calibration for the Color (masking), and View Angle (distance) using the NI Vision Assistant. If you are using C++ or Java and have not yet installed the NI Vision Assistant, see the article [Installing NI Vision Assistant](#).



## Enable Snapshots

**AXIS M1013 Network Camera** Live View | Setup | Help

**Live View Layout**

**Stream Profile**

Stream profile: Motion JPEG

☒ Show stream profile selection

**Default Viewer**

Windows Internet Explorer: AMC (ActiveX)

Other Browsers: Server push

**Note:** QuickTime is only used with H.264. Motion JPEG will be shown with AMC in Windows Internet Explorer and with server push in other browsers.

**Viewer Settings**

☒ Show viewer toolbar

☒ Enable H.264 decoder installation

☒ Show crosshair in PTZ joystick mode\*

☐ Use PTZ joystick mode as default\*

☐ Enable recording button

\* Not applicable to AMC (ActiveX).

**Action Buttons**

☐ Show manual trigger button

☒ Show snapshot button

**User Defined Links**

☐ Show custom link 1 Use as: ☒ cgi link ☐ web link  
Name: Custom link 1 URL: http://

☐ Show custom link 2 Use as: ☒ cgi link ☐ web link  
Name: Custom link 2 URL: http://

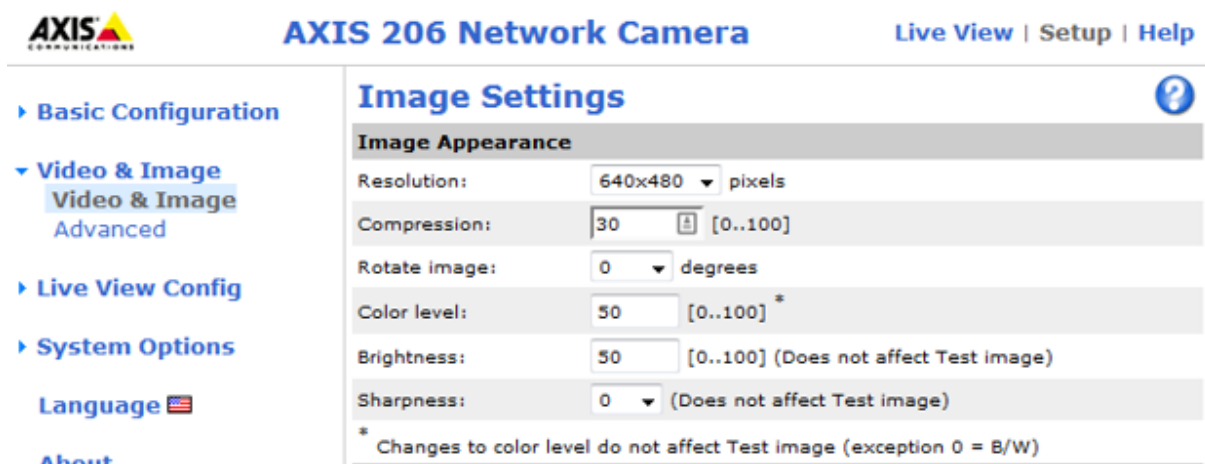
☐ Show custom link 3 Use as: ☒ cgi link ☐ web link  
Name: Custom link 3 URL: http://

☐ Show custom link 4 Use as: ☒ cgi link ☐ web link  
Name: Custom link 4 URL: http://

Save Reset

To capture snapshots from the Axis camera, you must first enable the Snapshot button. Open a web-browser and browse to camera's address (10.TE.AM.11), enter the Username/Password combo FRC/FRC if prompted, then click Setup->Live View Config->Layout. Click on the checkbox to Show snapshot button then click Save.

## Check Camera Settings



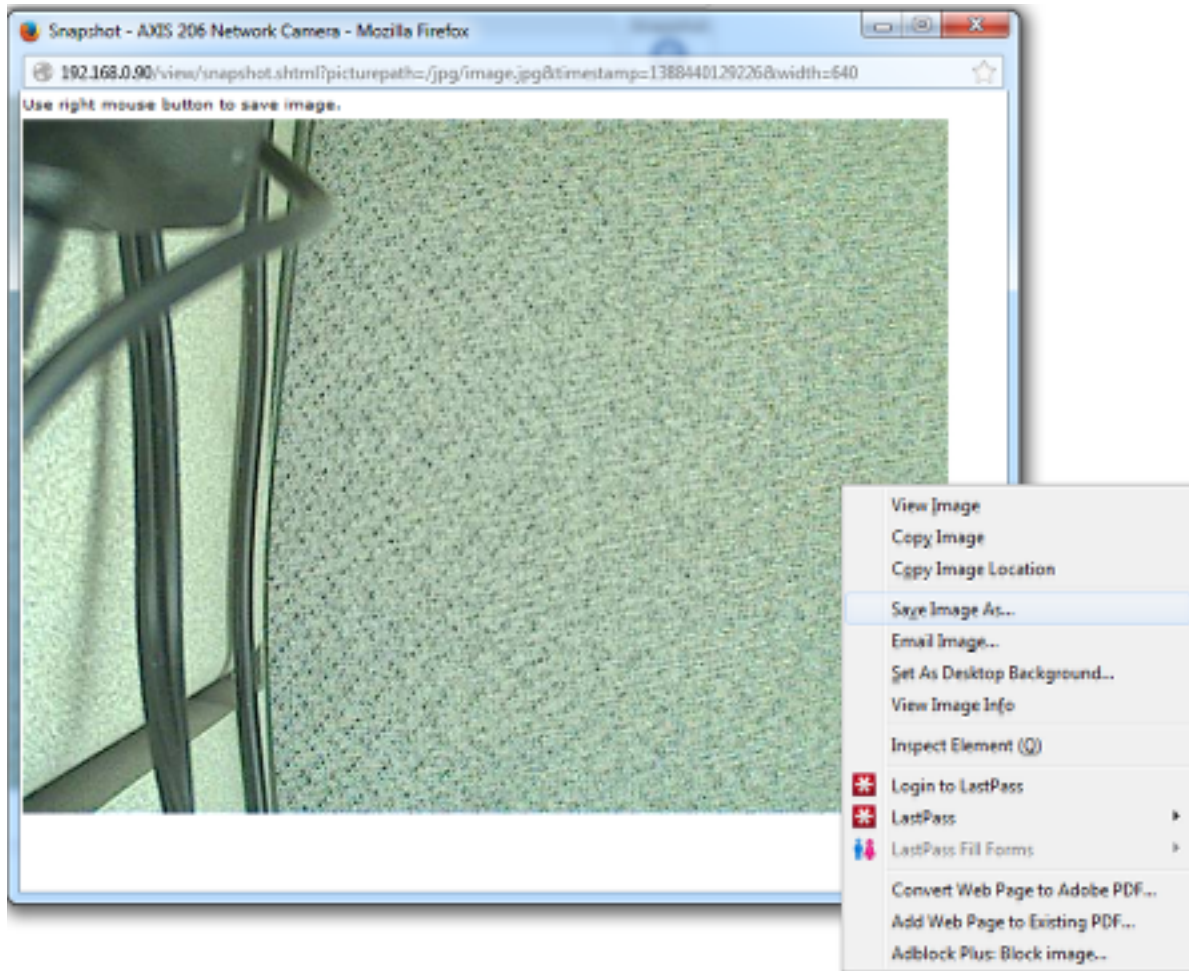
The screenshot shows the web interface for an AXIS 206 Network Camera. The top navigation bar includes the AXIS logo, the camera model name, and links for Live View, Setup, and Help. A left sidebar contains a menu with options: Basic Configuration, Video & Image (selected), Live View Config, System Options, Language, and About. The main content area is titled 'Image Settings' and features a sub-section 'Image Appearance'. This section contains several configuration fields: Resolution (640x480 pixels), Compression (30), Rotate image (0 degrees), Color level (50), Brightness (50), and Sharpness (0). Each field has a text input, a dropdown menu, and a range indicator. A note at the bottom states: '\* Changes to color level do not affect Test image (exception 0 = B/W)'.

Setting	Value	Range/Unit
Resolution	640x480	pixels
Compression	30	[0..100]
Rotate image	0	degrees
Color level	50	[0..100] *
Brightness	50	[0..100] (Does not affect Test image)
Sharpness	0	(Does not affect Test image)

\* Changes to color level do not affect Test image (exception 0 = B/W)

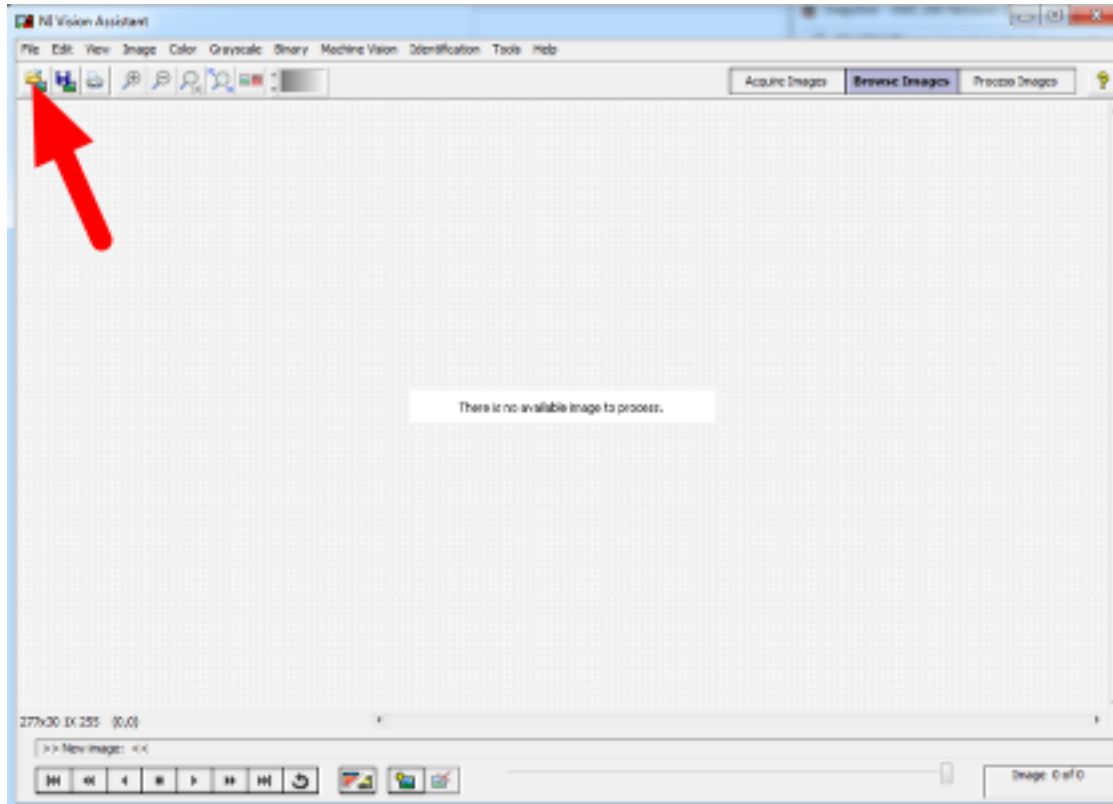
Depending on how you are capturing the image stream in your program, it may be possible to stream a different resolution, framerate and/or compression than what is saved in the camera and used in the Live View. Before performing any calibration it is recommended you verify that the settings in the camera match the settings in your code. To check the settings in the camera, click on the Video and Image header on the left side of the screen, then click Video and Image.

### Capture Images



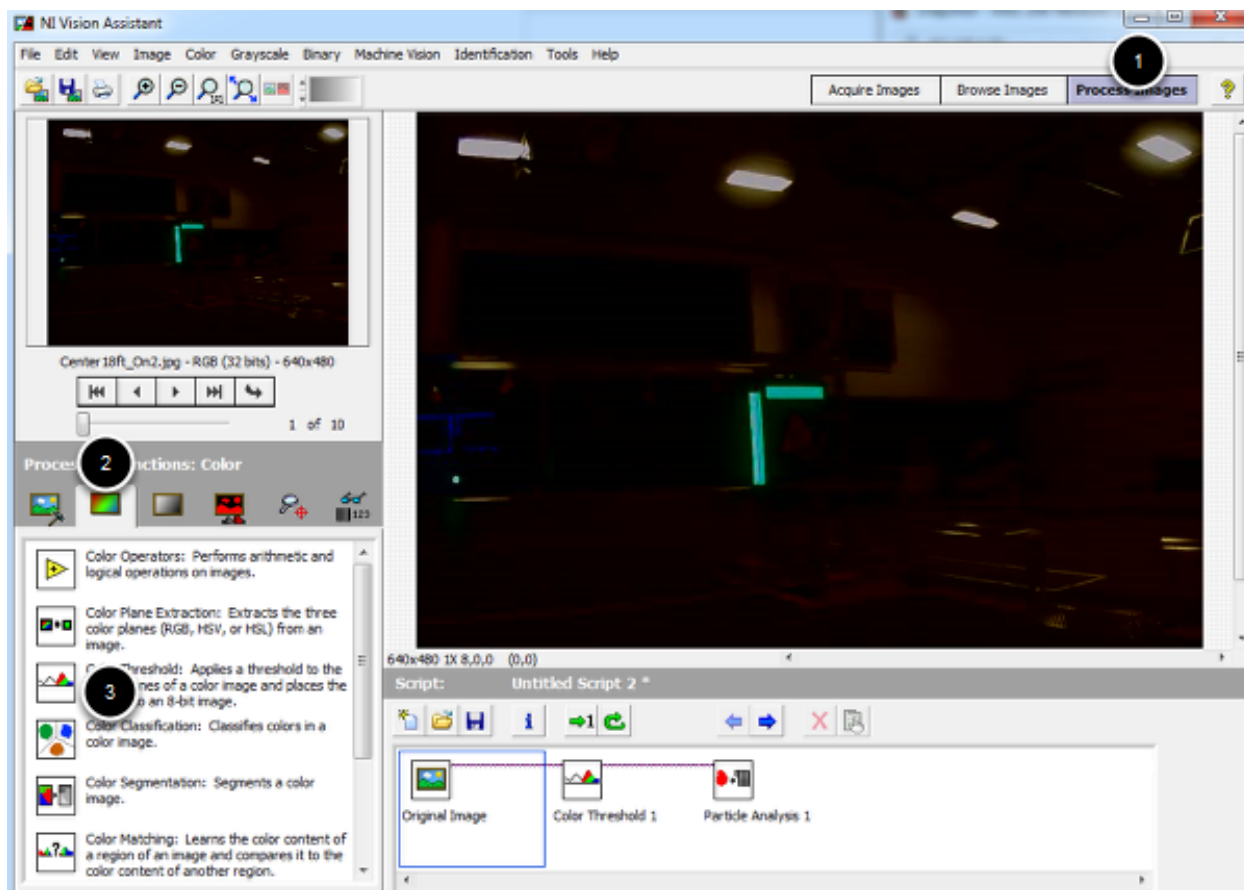
Click the Live View button to return to the Live View page and you should now see a Snapshot button. Clicking this button opens a pop-up window with a static image capture. Right-click on this image, select Save Image as and select your desired location and file name, then save the image.

## Load Image(s) in Vision Assistant



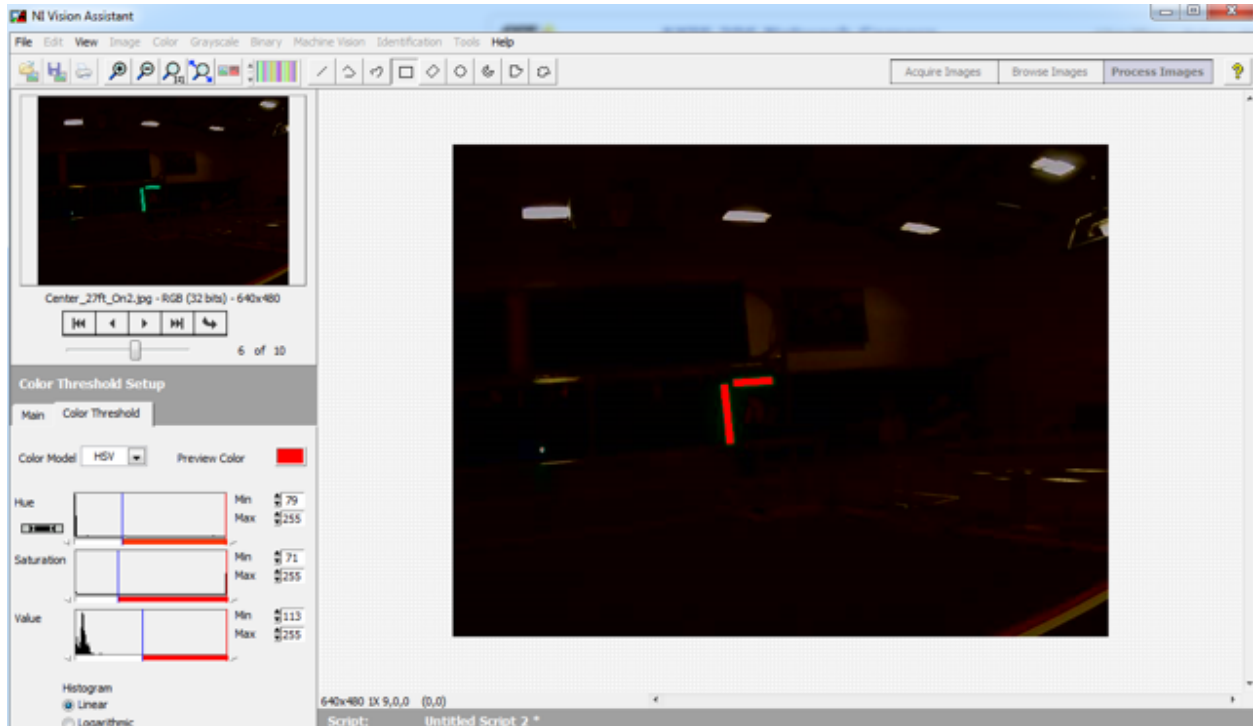
Open the NI Vision Assistant and select the Browse Images option. Select the Open Images icon in the top left of the Toolbar, then locate your images. Repeat as necessary to load all desired images.

### Color Threshold



Click Process Images in the top right, then select the color tab on the bottom right and click the Color Threshold icon.

## HSV Calibration



Change the Color Model dropdown to HSV. Next tune the window on each of the three values to cover as much of the target as possible while filtering everything else. If using a green light, you may want to use the values in the sample code as a starting point. If you have multiple images you can use the controls in the top left to cycle through them. Use the center two arrow controls or the slider to change the preview image in the top left window, then click the right-most arrow to make it the active image. When you are happy with the values you have selected, note down the ranges for the Hue, Saturation and Value. You will need to enter these into the appropriate place in the vision code. Click OK to finish adding the step to the script.

You may wish to take some new sample images using the time for camera calibration at your event to verify or tweak your ranges slightly based on the venue lighting conditions.

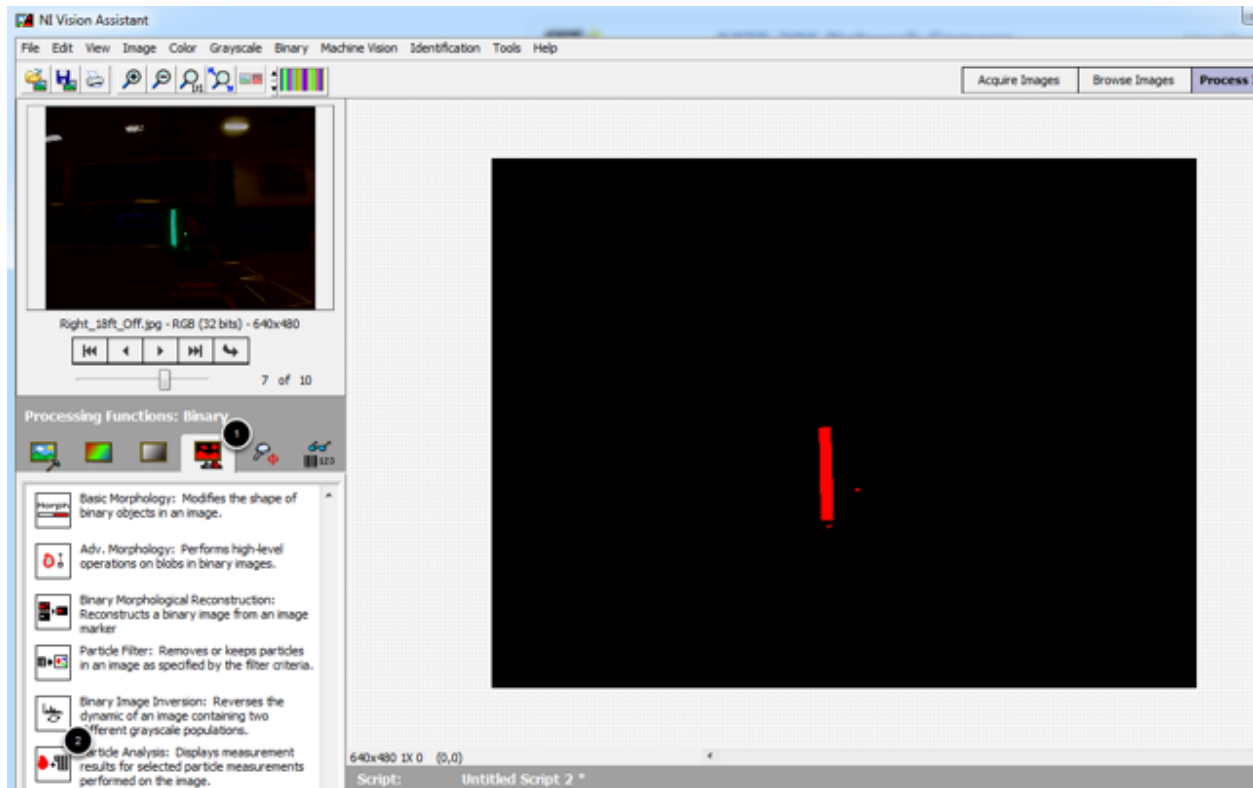
## View Angle/Distance Calibration

While a theoretical view angle for each camera model can be found in the datasheet, empirical testing has found that these numbers may be a bit off even for the horizontal view angle. Given that this year's code uses the vertical field-of-view it is best to perform your own calibration for your camera (though empirical values for each camera type are included in the code as a reference). To do this set up an equation where the view angle,  $\theta$ , is the only unknown. To do this, utilize a target of known size at a known distance, leaving the view angle as the only unknown. Let's take our equation from the previous article,  $d = T_{ft} \cdot \frac{FOV_{pixel}}{T_{pixel} \tan \theta}$ , and re-arrange it to solve for  $\theta$ :

$$\tan \theta = T_{ft} \cdot \frac{FOV_{pixel}}{T_{pixel} \cdot d}$$

$$\theta = \arctan \left( T_{ft} \cdot \frac{FOV_{\text{pixel}}}{T_{\text{pixel}} \cdot d} \right)$$

## Taking Measurements

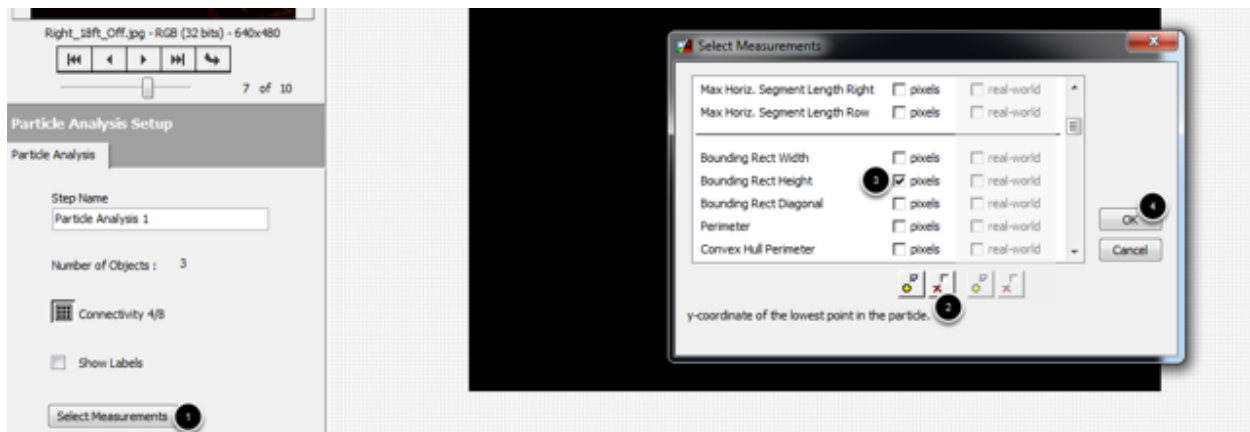


One way to take the required measurements is to use the same images of the retro-reflective tape that were used for the color calibration above. We can use Vision Assistant to provide the height of the detected blob in pixels. By measuring the real-world distance between the camera and the target, we now have all of the variables to solve our equation for the view angle.

To measure the particles in the image, click the Binary tab, then click the Particle Analysis icon.

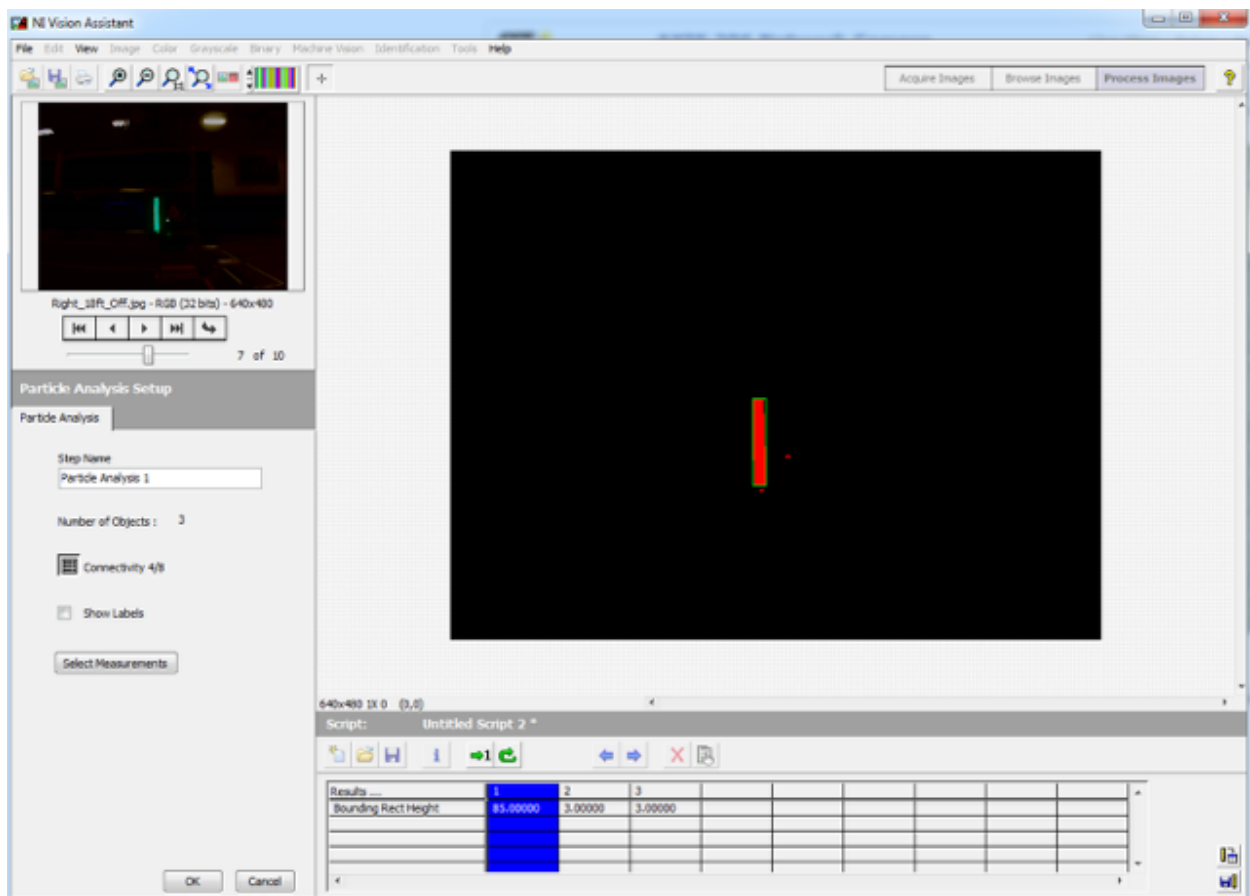


## Selecting Measurements



Click on the Select Measurements button. In this case, we are only interested in the bounding box height. Click on the button with the X to deselect all measurements, then locate the Bounding Rect Height measurement and check the box. Click OK to save.

## Measuring the Particle



The measurements for each particle will now be displayed in the window at the bottom of the



screen. If your image has multiple particles, you can click in each box to have Vision Assistant highlight the particle so you can make sure you have the right one. This article will show the calculation using a single image, but you may wish to perform the calculation on multiple images from multiple distances and use a technique such as averaging or least squares fit to determine the appropriate value for the View angle. You can use the same arrow controls described in the color section above to change the active image.

### Calculation

As seen in the previous step, the particle representing the 32in tall vertical target in this example measured 85 pixels tall in a 640x480 image. The image shown was taken from (very roughly) 18 ft. away. Plugging these numbers into the equation from above....

$$\theta = \arctan \left( 2.66 \cdot \frac{480}{2 \cdot 85 \cdot 18} \right) = 22.65^\circ$$

Depending on what you use to calculate the arctangent, your answer may be in radians, make sure to convert back to degrees if entering directly into the sample code as the view angle.

---

**Note:** The code uses View Angle and we just calculated  $\theta$ . Make sure to multiply  $\theta$  by 2 if replacing the constants in the code. Multiplying our result by 2 yields  $45.3^\circ$ . This image is from a M1013 camera, so our value is a bit off from the previously measured 29.1 but given that the 18ft. was a very rough measurement this shows that we are in the ballpark and likely performed the calculation correctly.

---

### 17.1.10 Axis M1013 Camera Compatibility

The Axis M1011 camera has been discontinued and superseded by the Axis M1013 camera. This document details the differences between the two cameras when used with WPILib and the provided sample vision programs.

#### Optical Differences

The Axis M1013 camera has a few major optical differences from the M1011 camera:

1. The M1013 is an adjustable focus camera. Make sure to focus your M1013 camera by turning the grey and black lens housing to make sure you have a clear image at your desired viewing distance.
2. The M1013 has a wider view angle ( $67^\circ$ ) compared to the M1011 ( $47^\circ$ ). This means that for a feature of a fixed size, the image of that feature will span a smaller number of pixels

#### Using the M1013 with WPILib

The M1013 camera has been tested with all of the available WPILib parameters and the following performance exceptions were noted:

1. The M1013 does not support the 160x120 resolution. Requesting a stream of this resolution will result in no images being returned or displayed.

2. The M1013 does not appear to work with the Color Enable parameter exposed by WPILib. Regardless of the setting of this parameter a full color image was returned.

All other WPILib camera parameters worked as expected. If any issues not noted here are discovered, please file a bug report on GitHub.

### 17.1.11 Using the Axis Camera at Single Network Events

The convention for using the Axis camera uses mDNS with the camera name set to `axis-camera.local`. At home, this works fine as there is only one camera on the network. At official events, this works fine as each team is on their own VLAN and therefore doesn't have visibility to another team's camera. However, at an off-season event using a single network, this will cause an issue where all teams will connect to whichever team's camera "wins" the mDNS resolution and becomes `axis-camera`. The other cameras will see that the name is taken and use an alternative name. This article describes how to modify the Dashboard and/or robot code to use a different mDNS name to separate the camera streams.

#### Changing the Camera mDNS Name

To change the mDNS name in the camera, follow the instructions in [Configuring an Axis Camera](#), but substitute the new name such as `axis-cameraTEAM` where TEAM is your team number.

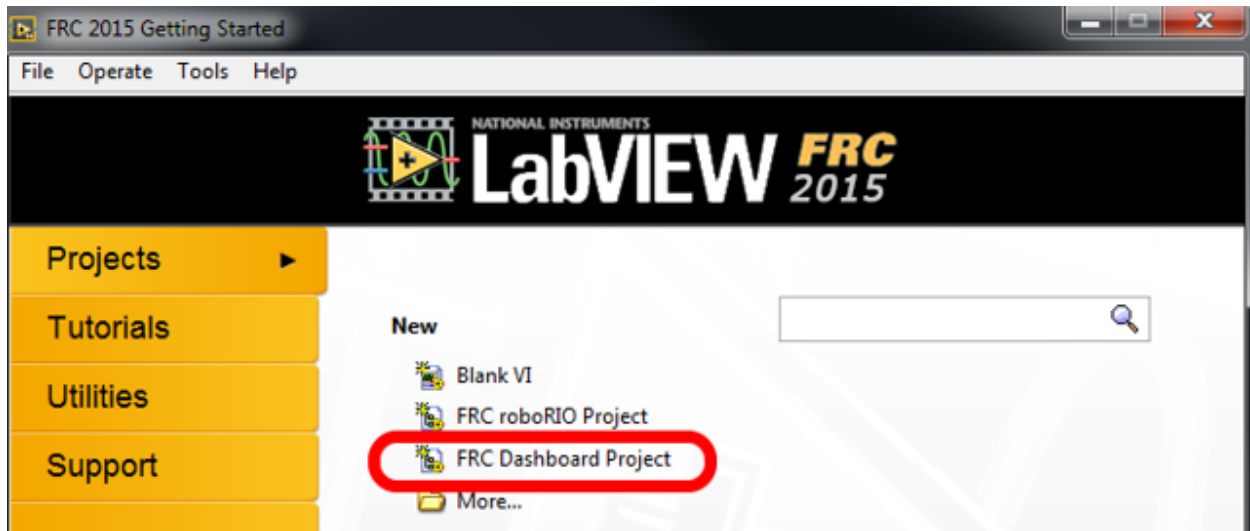
#### Viewing the Camera on the DS PC - Browser or SmartDashboard

If you are using a web-browser or SmartDashboard (which accepts mDNS names for the Simple Camera Viewer widget), updating to use the new mDNS name is simple. Simply change the URL in the browser or the address in the Simple Camera Viewer widget properties to the new mDNS name and you are all set.

#### Viewing the Camera on the DS PC - LabVIEW Dashboard

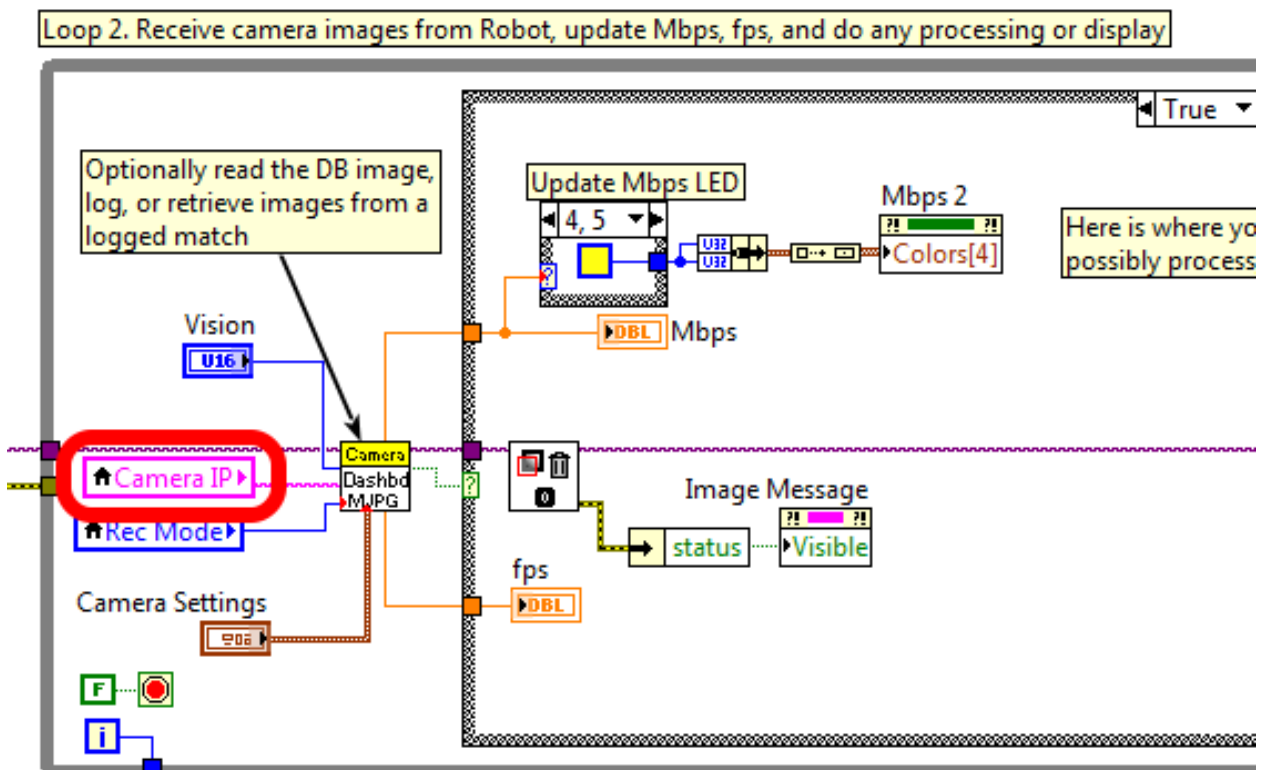
To view the camera stream in the LabVIEW Dashboard, you will need to build a customized version of the Dashboard. Note that this customized version will only work for the Axis camera and will no longer work for a USB camera. Revert to the default Dashboard to use a USB camera.

## Creating a Dashboard Project



From the LabVIEW Splash screen, select “FRC Dashboard Project”. Name the project as desired, then click Finish.

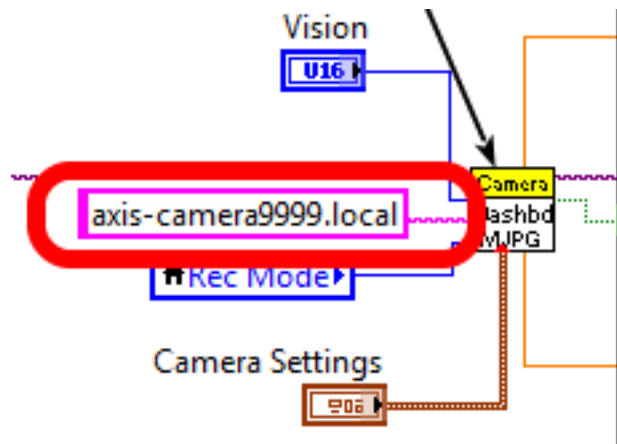
## Locating Loop 2 - Camera IP



Double click on `Dashboard Main.vi` in the project explorer to open it and press `Ctrl+e` to see the block diagram. Scroll down to the loop with the comment that says `Loop 2` and locate the

“Camera IP” input.

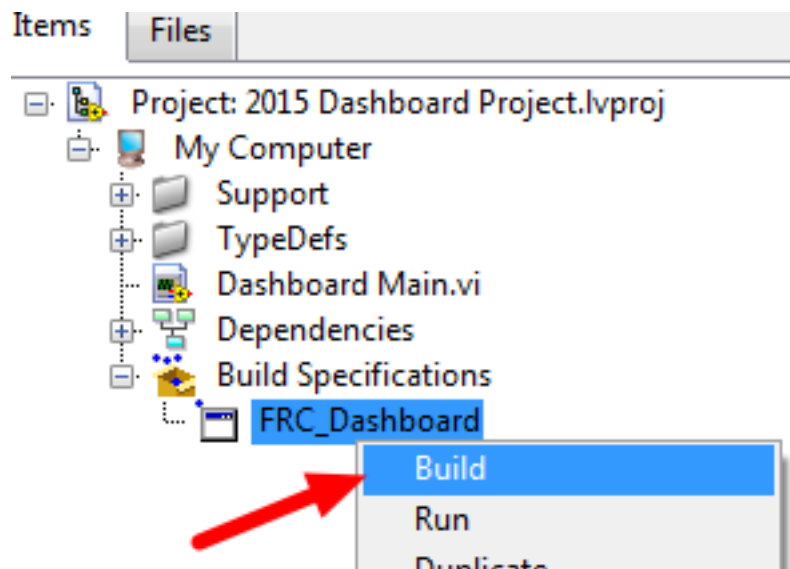
### Editing the Camera IP



Delete the Camera IP node, right click on the broken wire and click Create Constant (connect the constant to the wire if necessary). In the box, enter the mDNS name of your camera with a .local suffix (e.g. axis-cameraTEAM.local where TEAM is replaced with your team number). The example above shows a sample name for team 9999. Then click File->Save or Ctrl+S to save the VI.

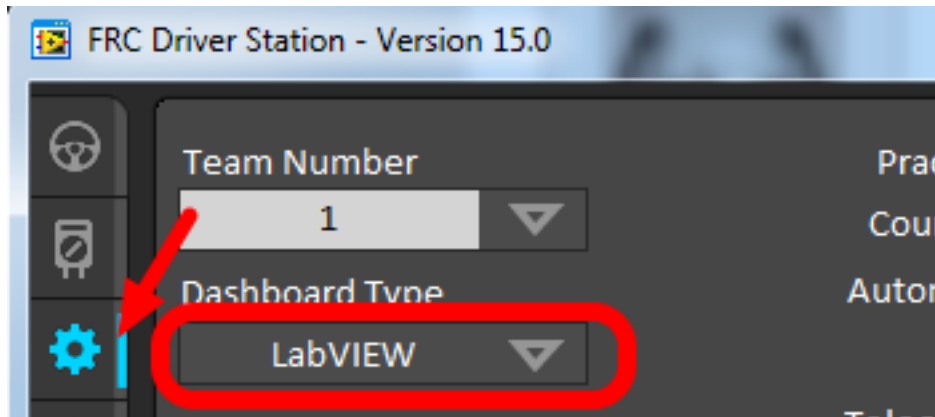
**Note:** You may also wish to make a minor modification to the Front Panel to verify that you are running the right dashboard later.

### Building the Dashboard



To build the new dashboard, expand Build Specifications in the Project Explorer, right click on FRC\_Dashboard and select Build.

### Setting the Driver Station to Launch the Modified Dashboard

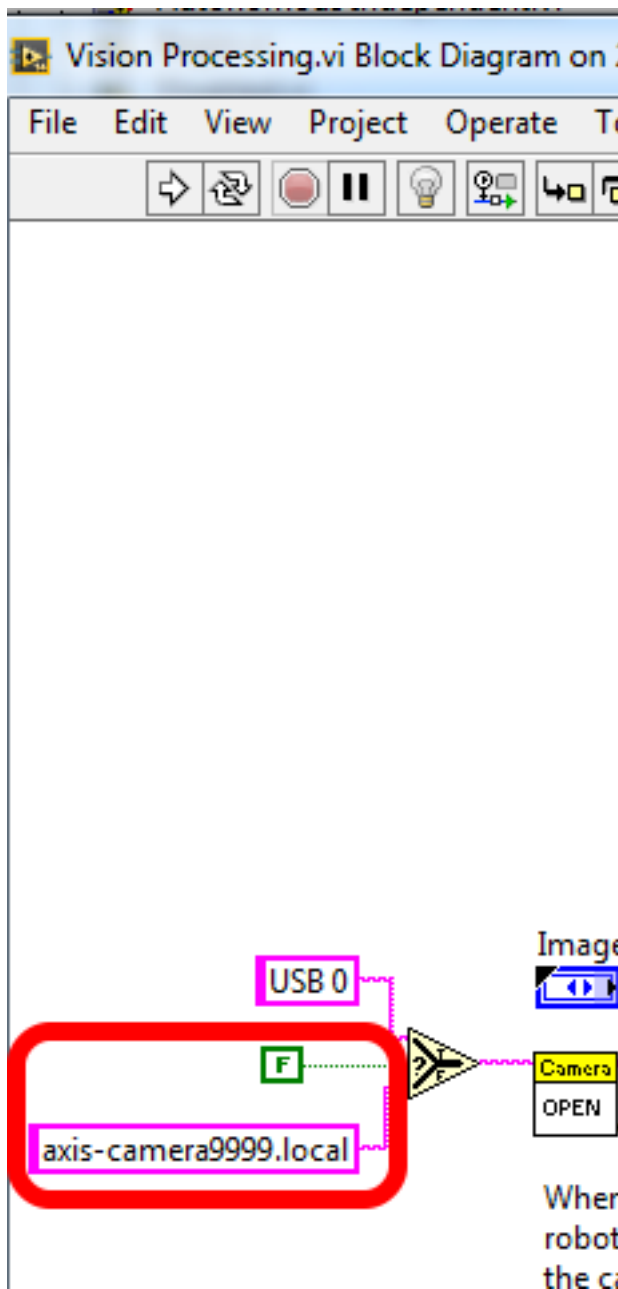


On the Setup tab of the Driver Station, change to dropdown box to LabVIEW to launch your new Dashboard.

### Accessing the Camera from Robot Code

If you wish to access the renamed camera from your robot code, you will have to modify it as well. In C++ and Java, just change the String used for the camera host name to match the new name. In LabVIEW follow the step below.

## Modifying LabVIEW Robot Code

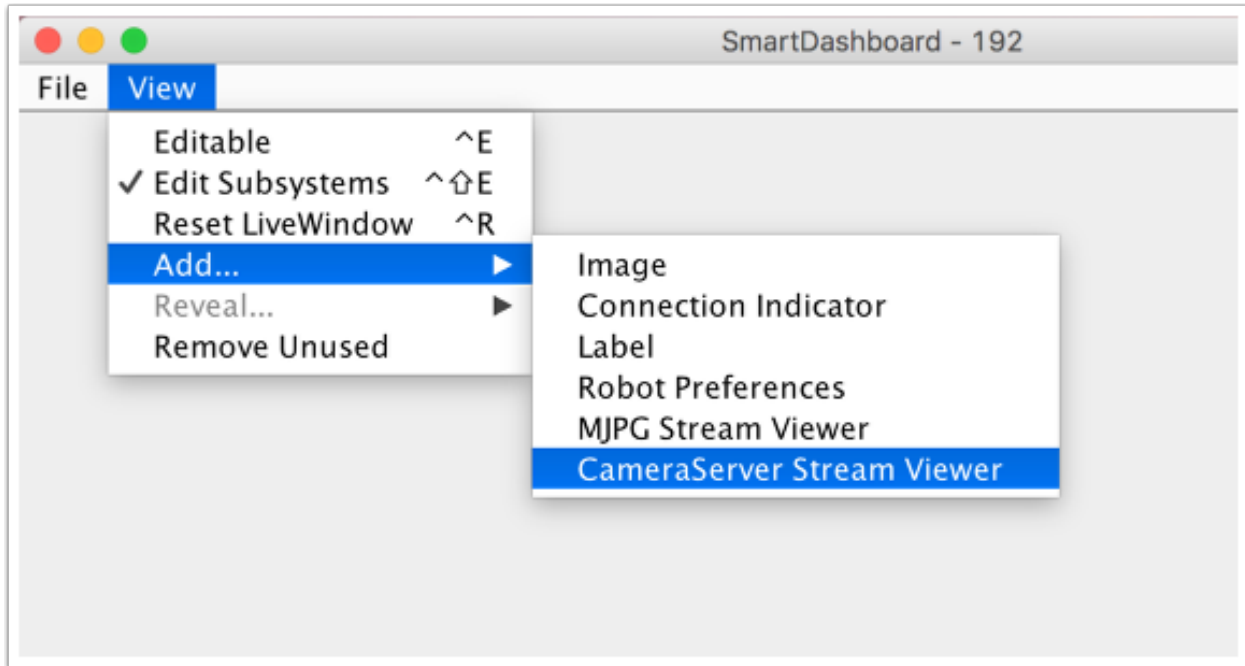


In the Project Explorer, locate `Vision Processing.VI` and double click to open it. Then press `Ctrl+e` to open the Block Diagram. Locate the string `axis-camera.local` near the left of the image and replace with `axis-cameraTEAM.local`. Also make sure the constant is set to `False` to use the Axis camera instead of USB.

### 17.1.12 Using the CameraServer on the roboRIO

## Simple CameraServer Program

The following program starts automatic capture of a USB camera like the Microsoft LifeCam that is connected to the roboRIO. In this mode, the camera will capture frames and send them to the dashboard. To view the images, create a CameraServer Stream Viewer widget using the “View”, then “Add” menu in the dashboard. The images are unprocessed and just forwarded from the camera to the dashboard.



Java

```
package org.usfirst.frc.team190.robot;

import edu.wpi.first.cameraserver.CameraServer;
import edu.wpi.first.wpilibj.IterativeRobot;

public class Robot extends IterativeRobot {

    public void robotInit() {
        CameraServer.getInstance().startAutomaticCapture();
    }
}
```

C++

```
#include "cameraserver/CameraServer.h"
class Robot: public IterativeRobot
{
private:
    void RobotInit()
    {
        CameraServer::GetInstance()->StartAutomaticCapture();
    }
};
START_ROBOT_CLASS(Robot)
```

## Advanced Camera Server Program

In the following example a thread created in `robotInit()` gets the Camera Server instance. Each frame of the video is individually processed, in this case converting a color image (BGR) to gray scale using the OpenCV `cvtColor()` method. The resultant images are then passed to the output stream and sent to the dashboard. You can replace the `cvtColor` operation with any image processing code that is necessary for your application. You can even annotate the image using OpenCV methods to write targeting information onto the image being sent to the dashboard.

Java

```
package org.usfirst.frc.team190.robot;

import org.opencv.core.Mat;
import org.opencv.imgproc.Imgproc;

import edu.wpi.cscore.CvSink;
import edu.wpi.cscore.CvSource;
import edu.wpi.cscore.UsbCamera;
import edu.wpi.first.cameraserver.CameraServer;
import edu.wpi.first.wpilibj.IterativeRobot;

public class Robot extends IterativeRobot {

    public void robotInit() {
        new Thread(() -> {
            UsbCamera camera = CameraServer.getInstance().startAutomaticCapture();
            camera.setResolution(640, 480);

            CvSink cvSink = CameraServer.getInstance().getVideo();
            CvSource outputStream = CameraServer.getInstance().putVideo("Blur", 640, 480);

            Mat source = new Mat();
            Mat output = new Mat();

            while(!Thread.interrupted()) {
                if (cvSink.grabFrame(source) == 0) {
                    continue;
                }
                Imgproc.cvtColor(source, output, Imgproc.COLOR_BGR2GRAY);
                outputStream.putFrame(output);
            }
        }).start();
    }
}
```

C++

```
#include "cameraserver/CameraServer.h"
#include <opencv2/imgproc/imgproc.hpp>
#include <opencv2/core/core.hpp>
class Robot: public IterativeRobot
{
private:
    static void VisionThread()
    {
```

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```

cs::UsbCamera camera = CameraServer::GetInstance()->StartAutomaticCapture();
camera.SetResolution(640, 480);
cs::CvSink cvSink = CameraServer::GetInstance()->GetVideo();
cs::CvSource outputStreamStd = CameraServer::GetInstance()->PutVideo("Gray", 640,
↪480);
cv::Mat source;
cv::Mat output;
while(true) {
    if (cvSink.GrabFrame(source) == 0) {
        continue;
    }
    cvtColor(source, output, cv::COLOR_BGR2GRAY);
    outputStreamStd.PutFrame(output);
}
}
void RobotInit()
{
    std::thread visionThread(VisionThread);
    visionThread.detach();
}
};
START_ROBOT_CLASS(Robot)

```

Notice that in these examples, the `PutVideo()` method writes the video to a named stream. To view that stream on Shuffleboard, select that named stream. In this case that is “Blur” for the Java program and “Gray” for the C++ sample.

### 17.1.13 Using Multiple Cameras

#### Switching the Driver Views

If you’re interested in just switching what the driver sees, and are using SmartDashboard, the SmartDashboard CameraServer Stream Viewer has an option (“Selected Camera Path”) that reads the given NT key and changes the “Camera Choice” to that value (displaying that camera). The robot code then just needs to set the NT key to the correct camera name. Assuming “Selected Camera Path” is set to “CameraSelection”, the following code uses the joystick 1 trigger button state to show camera1 and camera2.

Java

```

UsbCamera camera1;
UsbCamera camera2;
Joystick joy1 = new Joystick(0);
NetworkTableEntry cameraSelection;

@Override
public void robotInit() {
    camera1 = CameraServer.getInstance().startAutomaticCapture(0);
    camera2 = CameraServer.getInstance().startAutomaticCapture(1);

    cameraSelection = NetworkTableInstance.getDefault().getTable("").getEntry(
↪"CameraSelection");
}

```

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```
@Override
public void teleopPeriodic() {
    if (joy1.getTriggerPressed()) {
        System.out.println("Setting camera 2");
        cameraSelection.setString(camera2.getName());
    } else if (joy1.getTriggerReleased()) {
        System.out.println("Setting camera 1");
        cameraSelection.setString(camera1.getName());
    }
}
```

C++

```
cs::UsbCamera camera1;
cs::UsbCamera camera2;
frc::Joystick joy1{0};

nt::NetworkTableEntry cameraSelection;

void RobotInit() override {
    camera1 = frc::CameraServer::GetInstance()->StartAutomaticCapture(0);
    camera2 = frc::CameraServer::GetInstance()->StartAutomaticCapture(1);

    cameraSelection = nt::NetworkTableInstance::GetDefault().GetTable("")->GetEntry(
    ↪ "CameraSelection");
}

void TeleopPeriodic() override {
    if (joy1.GetTriggerPressed()) {
        std::cout << "Setting Camera 2" << std::endl;
        cameraSelection.SetString(camera2.GetName());
    } else if (joy1.GetTriggerReleased()) {
        std::cout << "Setting Camera 1" << std::endl;
        cameraSelection.SetString(camera1.GetName());
    }
}
```

If you're using some other dashboard, you can change the camera used by the camera server dynamically. If you open a stream viewer nominally to camera1, the robot code will change the stream contents to either camera1 or camera2 based on the joystick trigger.

Java

```
UsbCamera camera1;
UsbCamera camera2;
VideoSink server;
Joystick joy1 = new Joystick(0);

@Override
public void robotInit() {
    camera1 = CameraServer.getInstance().startAutomaticCapture(0);
    camera2 = CameraServer.getInstance().startAutomaticCapture(1);
    server = CameraServer.getInstance().getServer();
}

@Override
public void teleopPeriodic() {
```

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```

    if (joy1.getTriggerPressed()) {
        System.out.println("Setting camera 2");
        server.setSource(camera2);
    } else if (joy1.getTriggerReleased()) {
        System.out.println("Setting camera 1");
        server.setSource(camera1);
    }
}

```

C++

```

cs::UsbCamera camera1;
cs::UsbCamera camera2;
cs::VideoSink server;
frc::Joystick joy1{0};
bool prevTrigger = false;

void RobotInit() override {
    camera1 = frc::CameraServer::GetInstance()->StartAutomaticCapture(0);
    camera2 = frc::CameraServer::GetInstance()->StartAutomaticCapture(1);
    server = frc::CameraServer::GetInstance()->GetServer();
}

void TeleopPeriodic() override {
    if (joy1.GetTrigger() && !prevTrigger) {
        std::cout << "Setting Camera 2" << std::endl;
        server.SetSource(camera2);
    } else if (!joy1.GetTrigger() && prevTrigger) {
        std::cout << "Setting Camera 1" << std::endl;
        server.SetSource(camera1);
    }
    prevTrigger = joy1.GetTrigger();
}

```

## Keeping Streams Open

By default, the cscore library is pretty aggressive in turning off cameras not in use. What this means is that when you switch cameras, it may disconnect from the camera not in use, so switching back will have some delay as it reconnects to the camera. To keep both camera connections open, use the `SetConnectionStrategy()` method to tell the library to keep the streams open, even if you aren't using them.

Java

```

UsbCamera camera1;
UsbCamera camera2;
VideoSink server;
Joystick joy1 = new Joystick(0);

@Override
public void robotInit() {
    camera1 = CameraServer.getInstance().startAutomaticCapture(0);
    camera2 = CameraServer.getInstance().startAutomaticCapture(1);
    server = CameraServer.getInstance().getServer();
}

```

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```

camera1.setConnectionStrategy(ConnectionStrategy.kKeepOpen);
camera2.setConnectionStrategy(ConnectionStrategy.kKeepOpen);
}

@Override
public void teleopPeriodic() {
    if (joy1.getTriggerPressed()) {
        System.out.println("Setting camera 2");
        server.setSource(camera2);
    } else if (joy1.getTriggerReleased()) {
        System.out.println("Setting camera 1");
        server.setSource(camera1);
    }
}
}

```

C++

```

cs::UsbCamera camera1;
cs::UsbCamera camera2;
cs::VideoSink server;
frc::Joystick joy1{0};
bool prevTrigger = false;
void RobotInit() override {
    camera1 = frc::CameraServer::GetInstance()->StartAutomaticCapture(0);
    camera2 = frc::CameraServer::GetInstance()->StartAutomaticCapture(1);
    server = frc::CameraServer::GetInstance()->GetServer();
    camera1.
    ↳SetConnectionStrategy(cs::VideoSource::ConnectionStrategy::kConnectionKeepOpen);
    camera2.
    ↳SetConnectionStrategy(cs::VideoSource::ConnectionStrategy::kConnectionKeepOpen);
}

void TeleopPeriodic() override {
    if (joy1.GetTrigger() && !prevTrigger) {
        std::cout << "Setting Camera 2" << std::endl;
        server.SetSource(camera2);
    } else if (!joy1.GetTrigger() && prevTrigger) {
        std::cout << "Setting Camera 1" << std::endl;
        server.SetSource(camera1);
    }
    prevTrigger = joy1.GetTrigger();
}
}

```

**Note:** If both cameras are USB, you may run into USB bandwidth limitations with higher resolutions, as in all of these cases the roboRIO is going to be streaming data from both cameras to the roboRIO simultaneously (for a short period in options 1 and 2, and continuously in option 3). It is theoretically possible for the library to avoid this simultaneity in the option 2 case (only), but this is not currently implemented.

Different cameras report bandwidth usage differently. The library will tell you if you're hitting the limit; you'll get this error message:

```

could not start streaming due to USB bandwidth limitations;
try a lower resolution or a different pixel format
(VIDIOC_STREAMON: No space left on device)

```

If you're using Option 3 it will give you this error during `RobotInit()`. Thus you should just try your desired resolution and adjusting as necessary until you both don't get that error and don't exceed the radio bandwidth limitations.

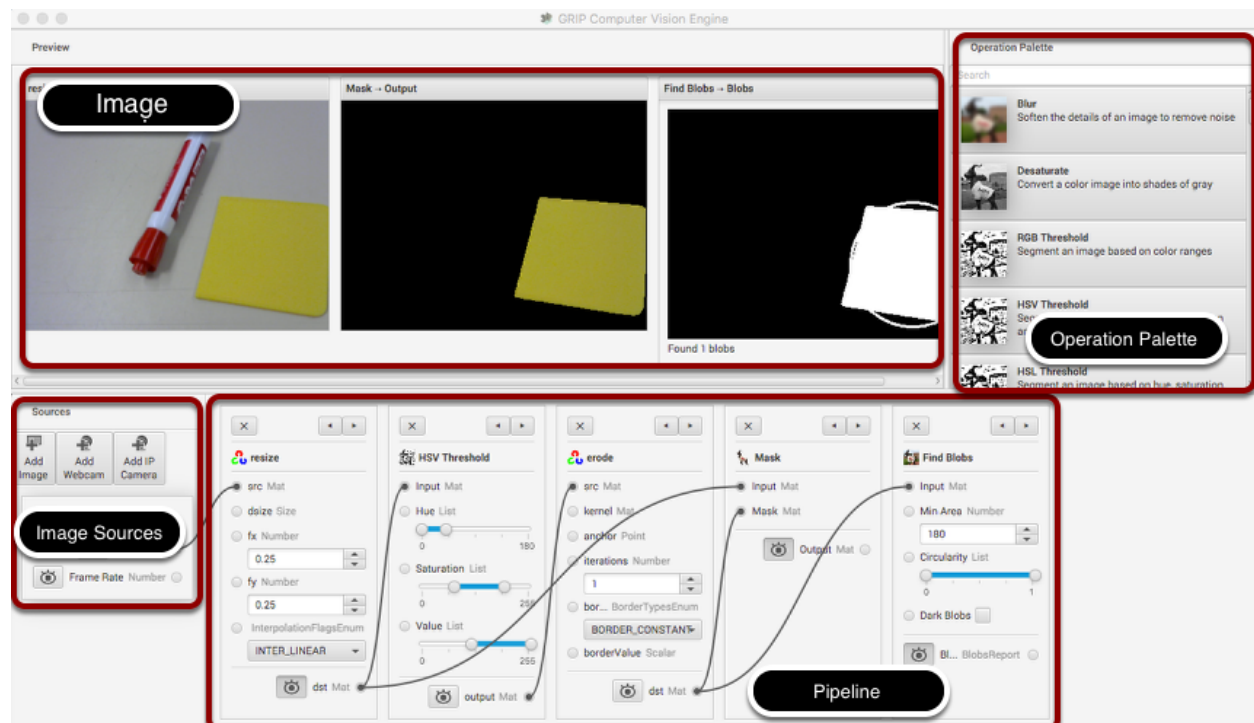
## 17.2 Vision with GRIP

### 17.2.1 Introduction to GRIP

GRIP is a tool for developing computer vision algorithms interactively rather than through trial and error coding. After developing your algorithm you may run GRIP in headless mode on your roboRIO, on a Driver Station Laptop, or on a coprocessor connected to your robot network. With Grip you choose vision operations to create a graphical pipeline that represents the sequence of operations that are performed to complete the vision algorithm.

GRIP is based on OpenCV, one of the most popular computer vision software libraries used for research, robotics, and vision algorithm implementations. The operations that are available in GRIP are almost a 1 to 1 match with the operations available if you were hand coding the same algorithm with some text-based programming language.

#### The GRIP user interface

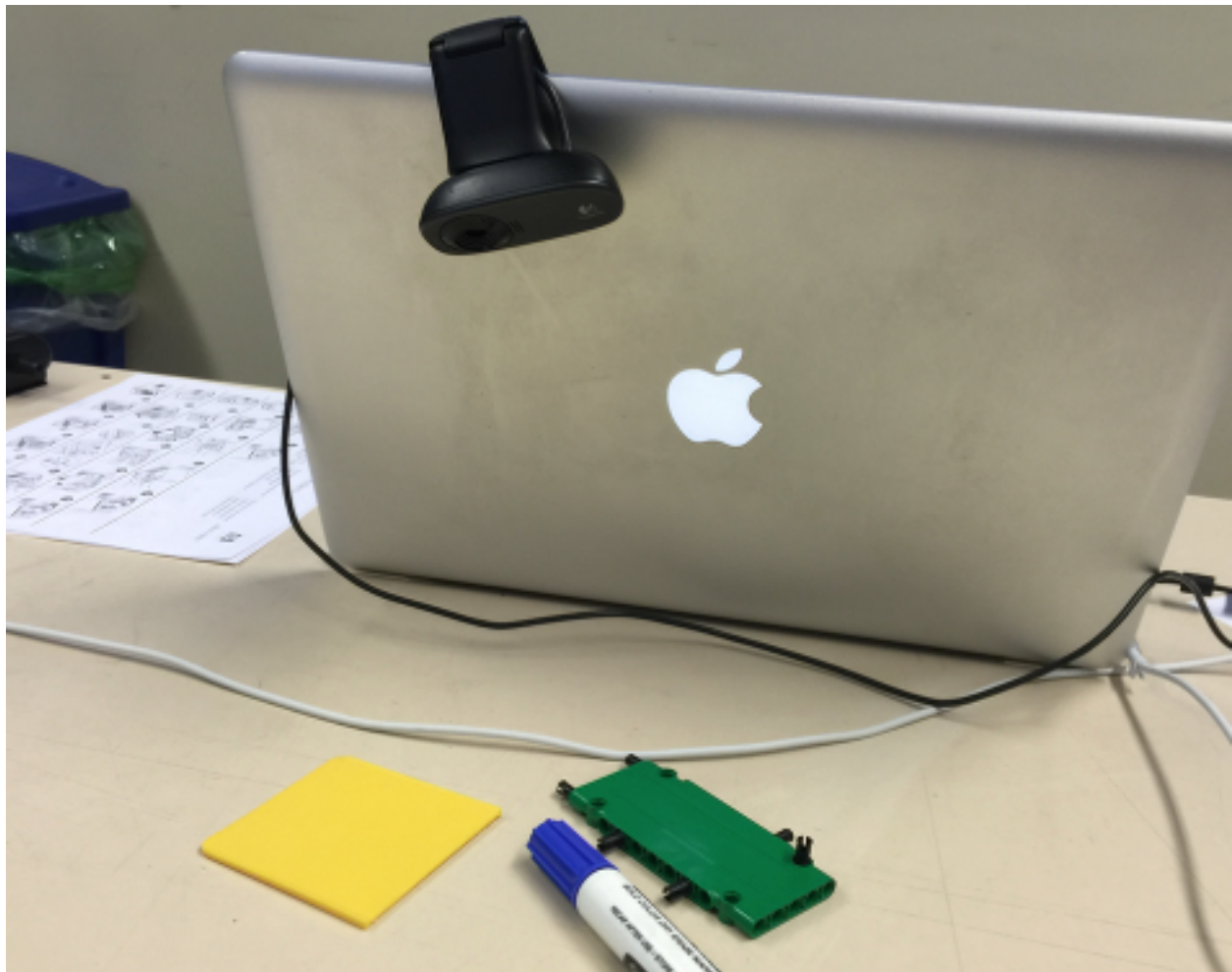


The GRIP user interface consists of 4 parts:

- **Image Sources** are the ways of getting images into the GRIP pipeline. You can provide images through attached cameras or files. Sources are almost always the beginning of the image processing algorithm.

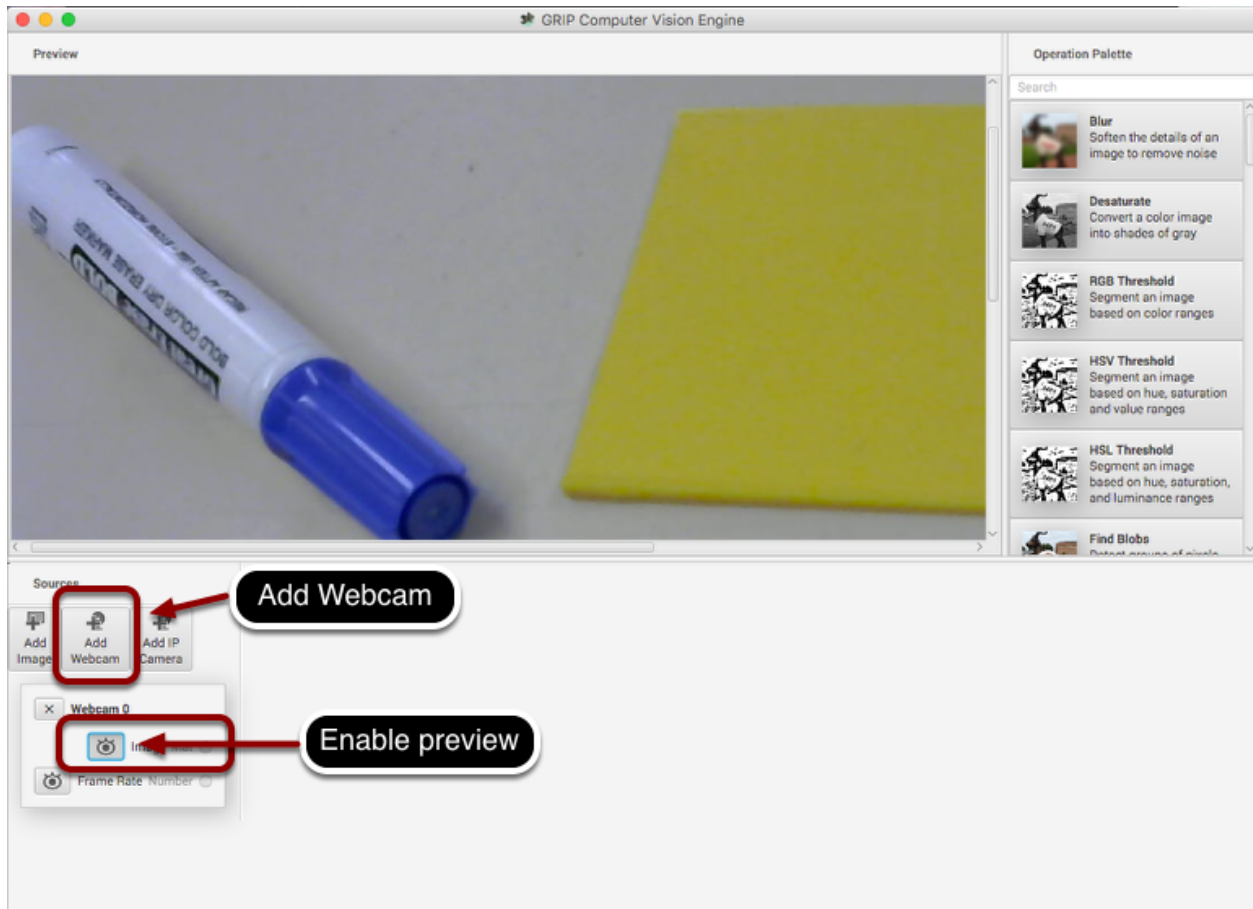
- **Operation Palette** contains the image processing steps from the OpenCV library that you can chain together in the pipeline to form your algorithm. Clicking on an operation in the palette adds it to the end of the pipeline. You can then use the left and right arrows to move the operation within the pipeline.
- **Pipeline** is the sequence of steps that make up the algorithm. Each step (operation) in the pipeline is connected to a previous step from the output of one step to an input to the next step. The data flows from generally from left to right through the connections that you create.
- **Image Preview** are shows previews of the result of each step that has it's preview button pressed. This makes it easy to debug algorithms by being able to preview the outputs of each intermediate step.

### Finding the yellow square



In this application we will try to find the yellow square in the image and display it's position. The setup is pretty simple, just a USB web camera connected to the computer looking down at some colorful objects. The yellow plastic square is the thing that we're interested in locating in the image.

### Enable the image source



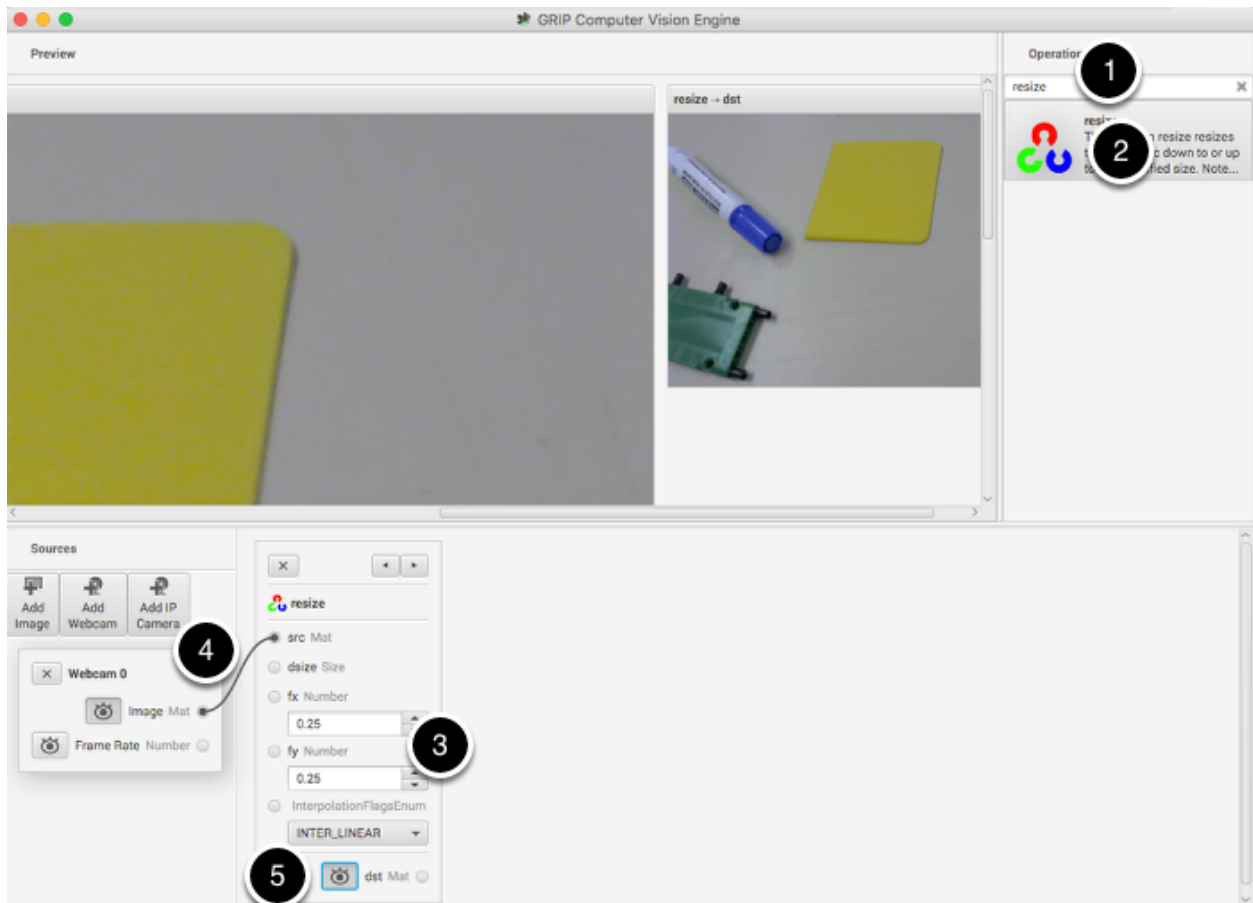
The first step is to acquire an image. To use the source, click on the “Add Webcam” button and select the camera number. In this case the Logitech USB camera that appeared as Webcam 0 and the computer monitor camera was Webcam 1. The web camera is selected in this case to grab the image behind the computer as shown in the setup. Then select the image preview button and the real-time display of the camera stream will be shown in the preview area.

### Resize the image

In this case the camera resolution is too high for our purposes, and in fact the entire image cannot even be viewed in the preview window. The “Resize” operation is clicked from the Operation Palette to add it to the end of the pipeline. To help locate the Resize operation, type “Resize” into the search box at the top of the palette. The steps are:

1. Type “Resize” into the search box on the palette
2. Click the Resize operation from the palette. It will appear in the pipeline.
3. Enter the x and y resize scale factor into the resize operation in the pipeline. In this case 0.25 was chosen for both.
4. Drag from the Webcam image output mat socket to the Resize image source mat socket. A connection will be shown indicating that the camera output is being sent to the resize input.

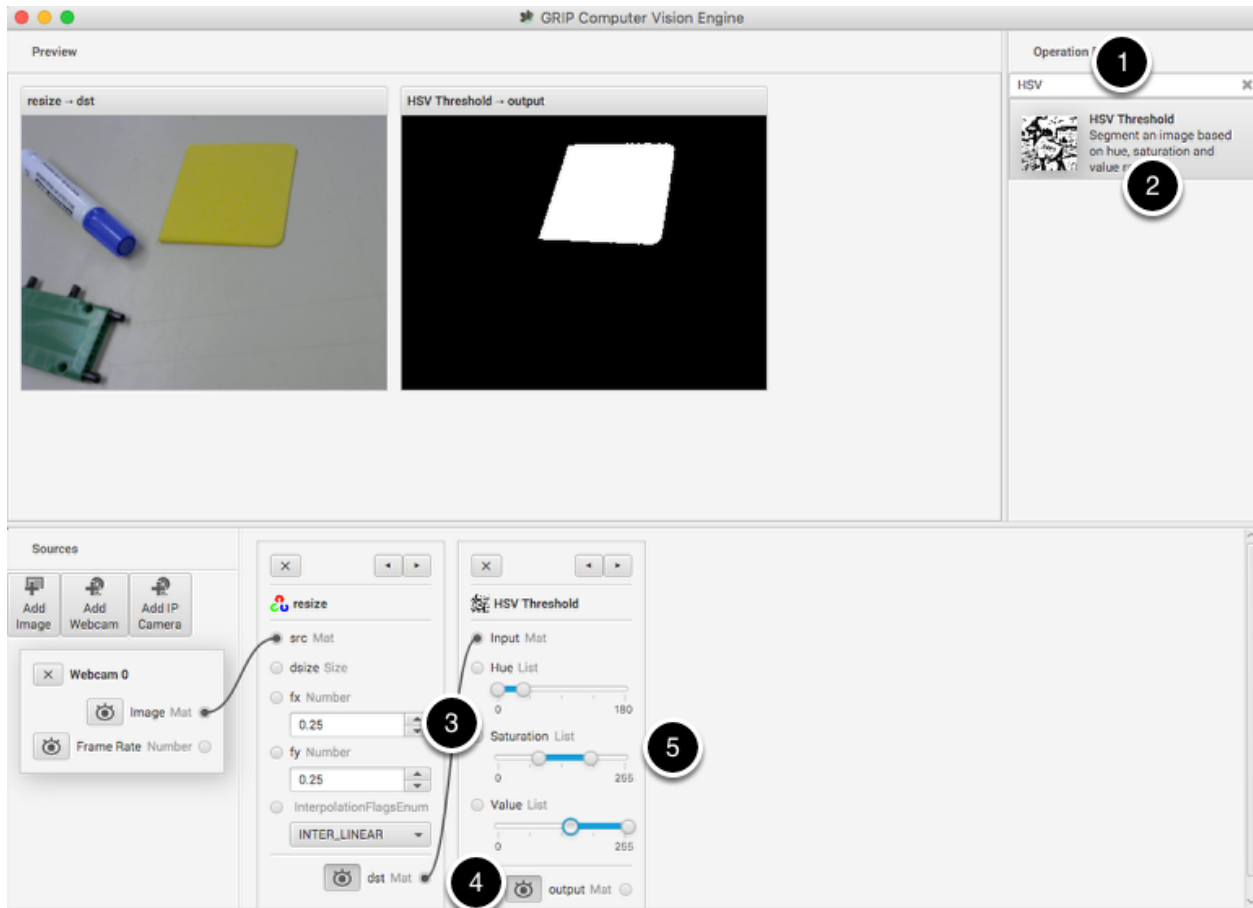






- Click on the destination preview button on the “Resize” operation in the pipeline. The smaller image will be displayed alongside the larger original image. You might need to scroll horizontally to see both as shown.
- Lastly, click the Webcam source preview button since there is no reason to look at both the large image and the smaller image at the same time.

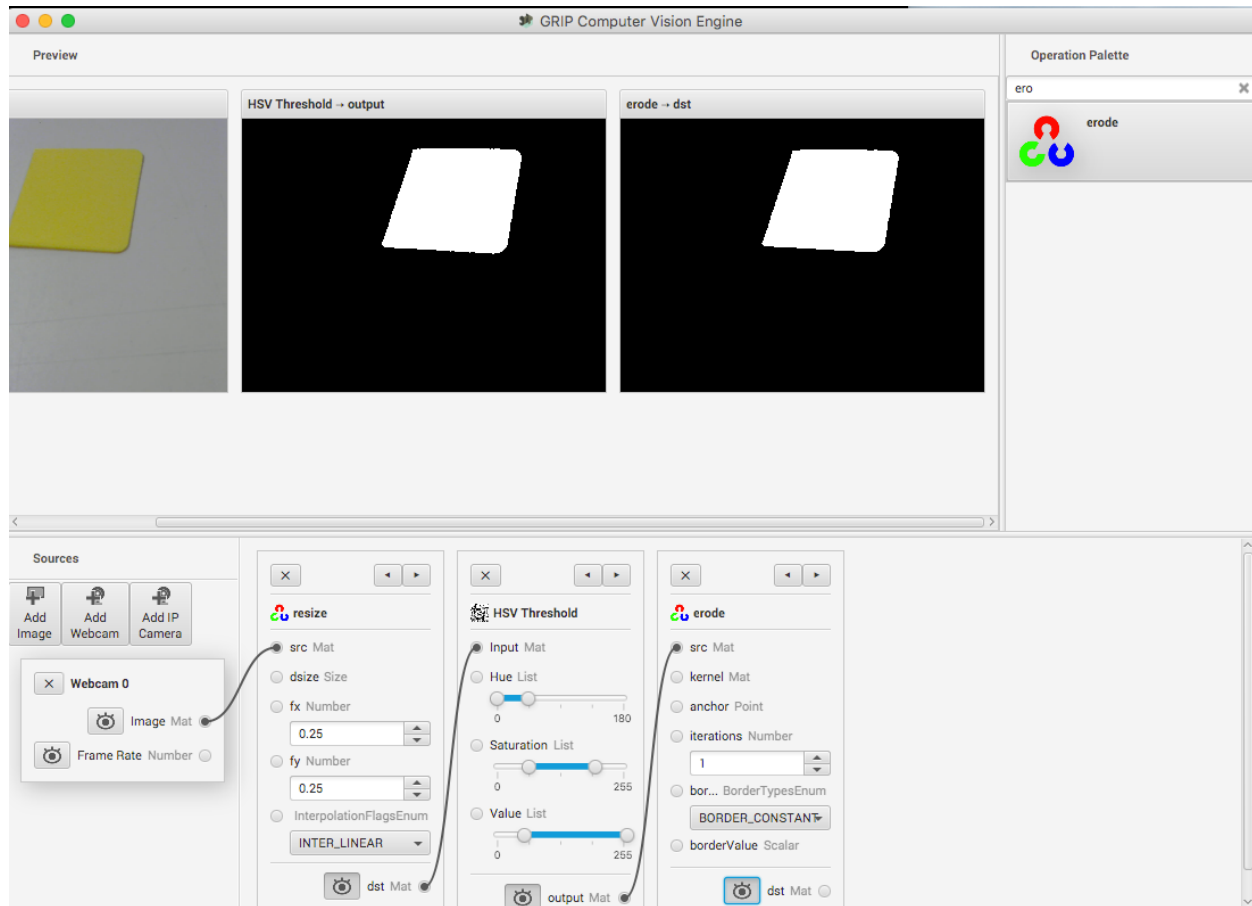
### Find only the yellow parts of the image



The next step is to remove everything from the image that doesn't match the yellow color of the piece of plastic that is the object being detected. To do that a HSV Threshold operation is chosen to set upper and lower limits of HSV values to indicate which pixels should be included in the resultant binary image. Notice that the target area is white while everything that wasn't within the threshold values are shown in black. Again, as before:

- Type HSV into the search box to find the HSV Threshold operation.
- Click on the operation in the palette and it will appear at the end of the pipeline.
- Connect the dst (output) socket on the resize operation to the input of the HSV Threshold.
- Enable the preview of the HSV Threshold operation so the result of the operation is displayed in the preview window.
- Adjust the Hue, Saturation, and Value parameters only the target object is shown in the preview window.

## Get rid of the noise and extraneous hits



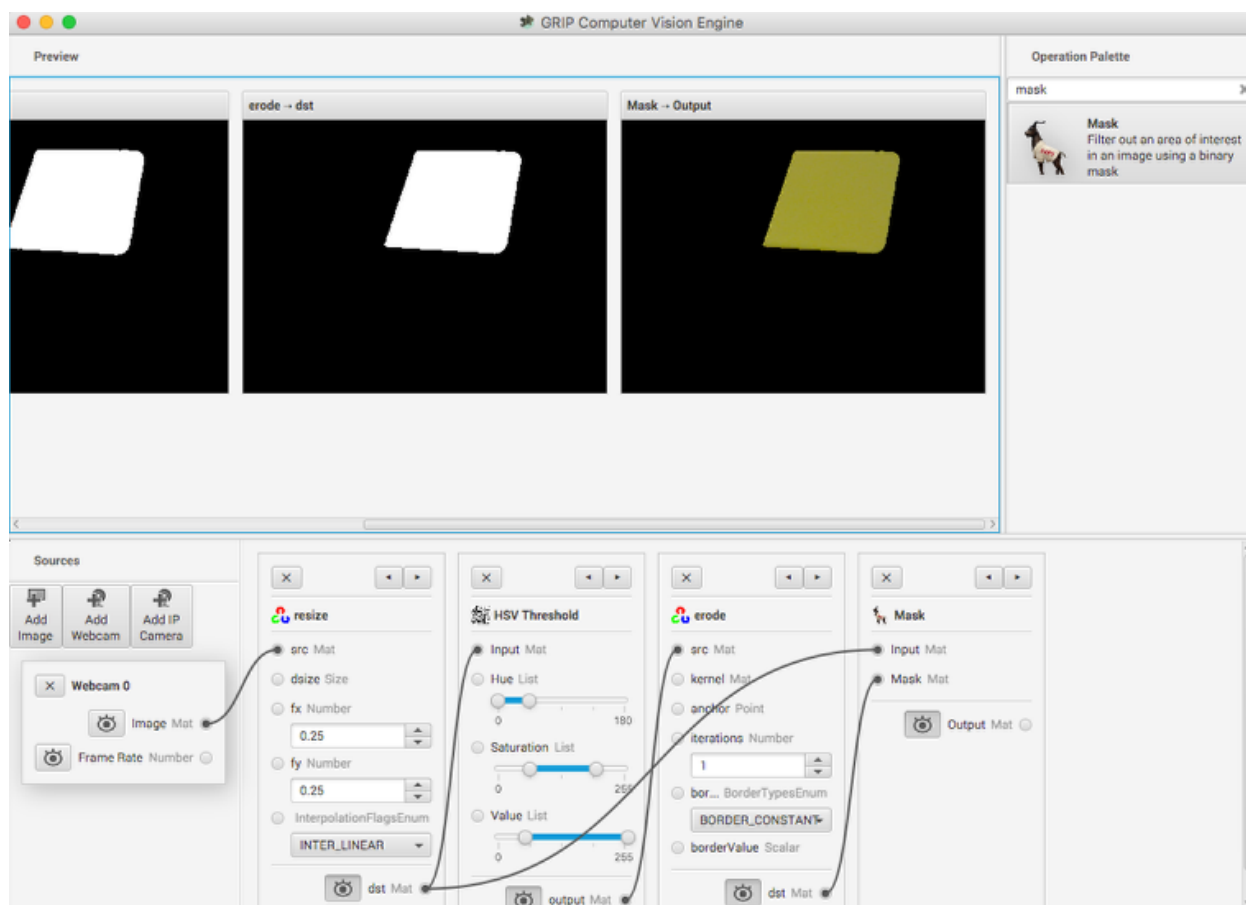
This looks pretty good so far, but sometimes there is noise from other things that couldn't quite be filtered out. To illustrate one possible technique to reduce those occasional pixels that were detected, an Erosion operation is chosen. Erosion will remove small groups of pixels that are not part of the area of interest.

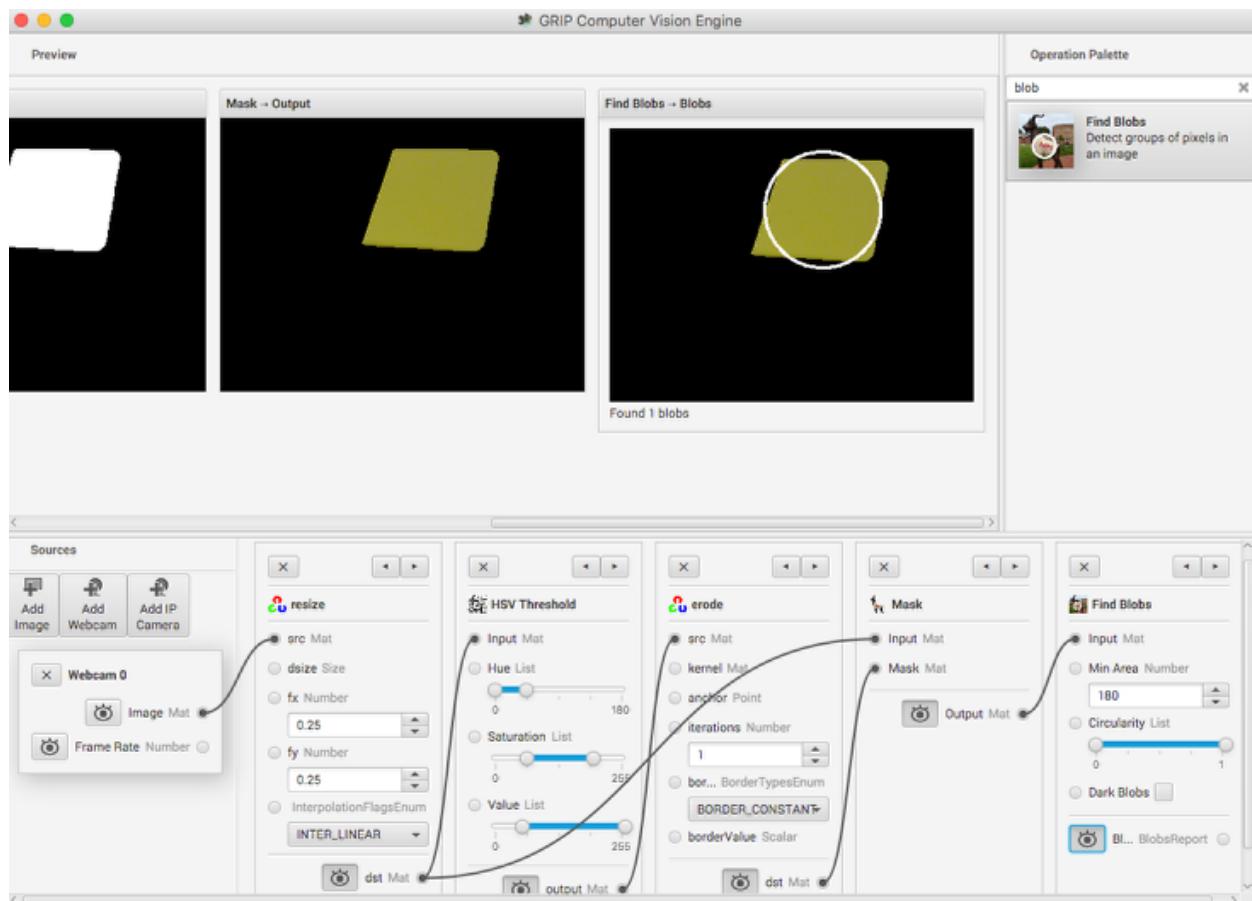
## Mask just the yellow area from the original image

Here a new image is generated by taking the original image and masking (and operation) it with the the results of the erosion. This leaves just the yellow card as seen in the original image with nothing else shown. And it makes it easy to visualize exactly what was being found through the series of filters.

## Find the yellow area (blob)

The last step is actually detecting the yellow card using a Blob Detector. This operation looks for a grouping of pixels that have some minimum area. In this case, the only non-black pixels are from the yellow card after the filtering is done. You can see that a circle is drawn around the detected portion of the image. In the release version of GRIP (watch for more updates between now and kickoff) you will be able to send parameters about the detected blob to your robot program using Network Tables.





## Status of GRIP

As you can see from this example, it is very easy and fast to be able to do simple object recognition using GRIP. While this is a very simple example, it illustrates the basic principles of using GRIP and feature extraction in general. Over the coming weeks the project team will be posting updates to GRIP as more features are added. Currently it supports cameras (Axis ethernet camera and web cameras) and image inputs. There is no provision for output yet although Network Tables and ROS (Robot Operating System) are planned.

You can either download a pre-built release of the code from the github page “Releases” section (<https://github.com/WPIRoboticsProjects/GRIP>) or you can clone the source repository and build it yourself. Directions on building GRIP are on the project page. There is also additional documentation on the project wiki.

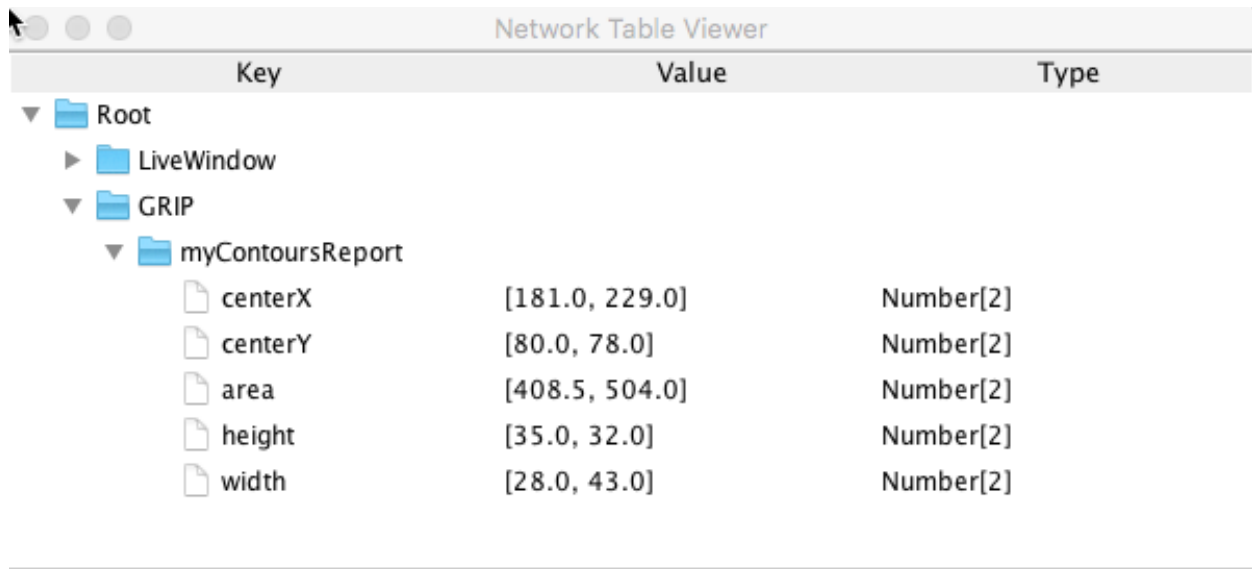
So, please play with GRIP and give us feedback here on the forum. If you find bugs, you can either post them here or as a Github project issue on the project page.

## 17.2.2 Reading array values published by NetworkTables

This article describes how to read values published by NetworkTables using a program running on the robot. This is useful when using computer vision where the images are processed on your driver station laptop and the results stored into NetworkTables possibly using a separate vision processor like a raspberry pi, or a tool on the robot like GRIP, or a python program to do the image processing.

Very often the values are for one or more areas of interest such as goals or game pieces and multiple instances are returned. In the example below, several x, y, width, height, and areas are returned by the image processor and the robot program can sort out which of the returned values are interesting through further processing.

### Verify the network table keys being published



Key	Value	Type
Root		
LiveWindow		
GRIP		
myContoursReport		
centerX	[181.0, 229.0]	Number[2]
centerY	[80.0, 78.0]	Number[2]
area	[408.5, 504.0]	Number[2]
height	[35.0, 32.0]	Number[2]
width	[28.0, 43.0]	Number[2]

You can verify the names of the network table keys used for publishing the values by using the Network Table Viewer application. It is a java program in your user directory in the

wpilib/tools folder. The application is started by selecting the “WPILib” menu in eclipse then “OutlineViewer”. In this example, with the image processing program running (GRIP) you can see the values being put into NetworkTables.

In this case the values are stored in a table called GRIP and a sub-table called myContoursReport. You can see that the values are in brackets and there are 2 values in this case for each key. The network table key names are centerX, centerY, area, height and width.

Both of the following examples are extremely simplified programs that just illustrate the use of NetworkTables. All the code is in the robotInit() method so it’s only run when the program starts up. In your programs, you would more likely get the values in code that is evaluating which direction to aim the robot in a command or a control loop during the autonomous or teleop periods.

## Writing a program to access the keys

Java

```
NetworkTable table;
double[] areas;
double[] defaultValue = new double[0];

@Override
public void robotInit() {
    table = NetworkTableInstance.getDefault().getTable("GRIP/myContoursReport");
}

@Override
public void teleopPeriodic() {
    double[] areas = table.getEntry("area").getDoubleArray(defaultValue);

    System.out.print("areas: " );

    for (double area : areas) {
        System.out.print(area + " ");
    }

    System.out.println();
}
```

C++

```
std::shared_ptr<NetworkTable> table;

void Robot::RobotInit() override {
    table = NetworkTable::GetTable("GRIP/myContoursReport");
}

void Robot::TeleopPeriodic() override {
    std::cout << "Areas: ";

    std::vector<double> arr = table->GetEntry("area").GetDoubleArray(std::vector<double>());

    for (double val : arr) std::cout << val << " ";
}
```

(continues on next page)

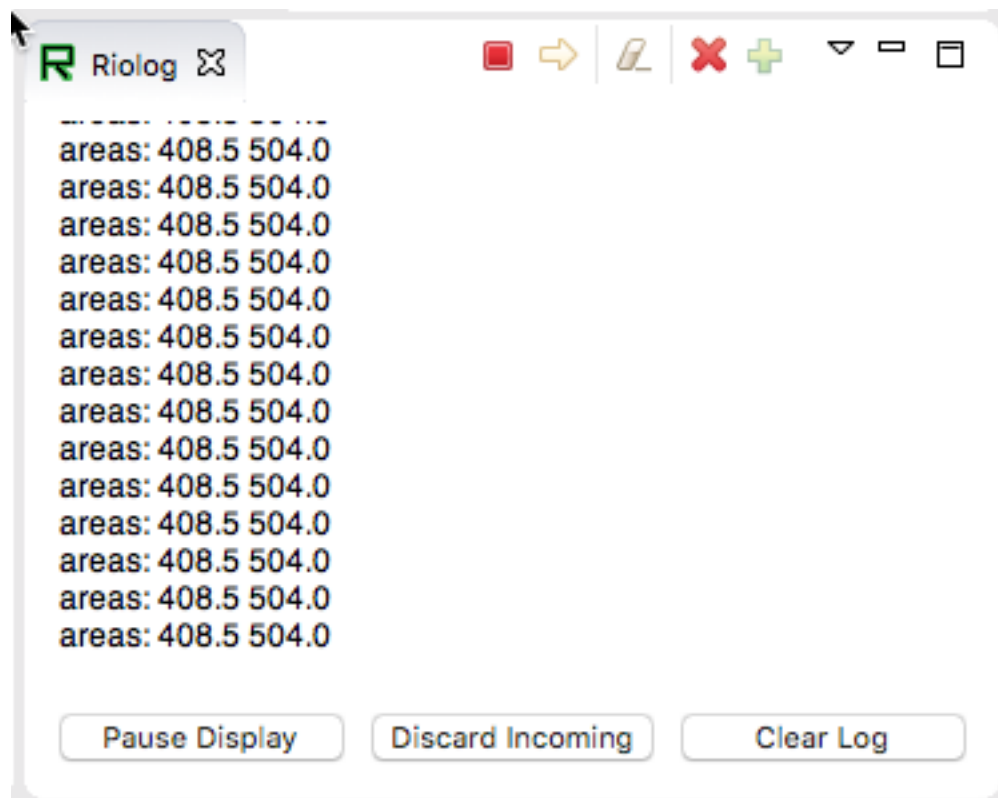
(continued from previous page)

```
std::cout << std::endl;  
}
```

The steps to getting the values and, in this program, printing them are:

1. Declare the table variable that will hold the instance of the subtable that have the values.
2. Initialize the subtable instance so that it can be used later for retrieving the values.
3. Read the array of values from NetworkTables. In the case of a communicating programs, it's possible that the program producing the output being read here might not yet be available when the robot program starts up. To avoid issues of the data not being ready, a default array of values is supplied. This default value will be returned if the network table key hasn't yet been published. This code will loop over the value of areas every 20ms.

### Program output



In this case the program is only looking at the array of areas, but in a real example all the values would more likely be used. Using the Riolog in eclipse or the DriverStation log you can see the values as they are retrieved. This program is using a sample static image so they areas don't change, but you can imagine with a camera on your robot, the values would be changing constantly.

### 17.2.3 Generating Code from GRIP

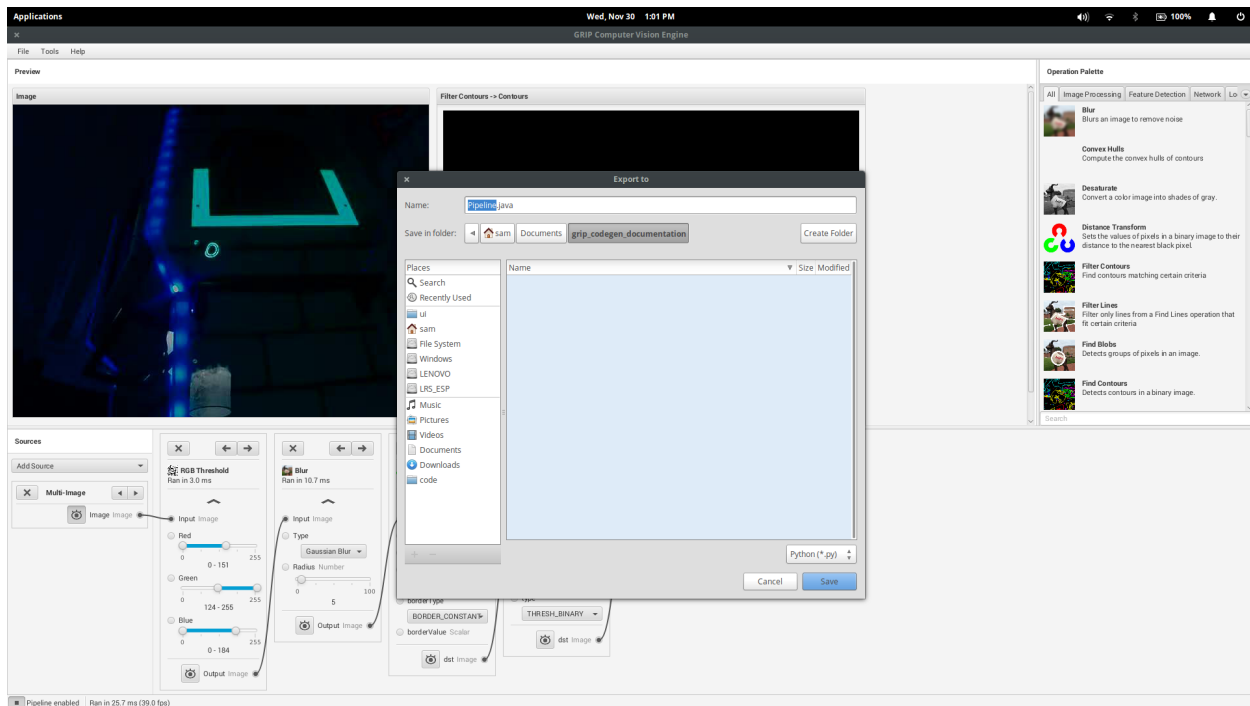
## GRIP Code Generation

When running your vision algorithm on a small processor such as a roboRIO or Raspberry PI it is encouraged to run OpenCV directly on the processor without the overhead of GRIP. To facilitate this, GRIP can generate code in C++, Java, and Python for the pipeline that you have created. This generated code can be added to your robot project and called directly from your existing robot code.

Input sources such as cameras or image directories and output steps such as NetworkTables are not generated. Your code must supply images as OpenCV mats. On the roboRIO, the CameraServer class supplies images in that format. For getting results you can just use generated getter methods for retrieving the resultant values such as contour x and y values.

## Generating Code

To generate code, go to Tools > Generate Code. This will bring up a save dialog that lets you create a C++, Java, or Python class that performs the steps in the GRIP pipeline.



If generating code to be used in a pre-existing project, choose a relevant directory to save the pipeline to.

- **C++ Users:** the pipeline class is split into a header and implementation file
- **Java Users:** the generated class lacks a package declaration, so a declaration should be added to match the directory where the file was saved.
- **Python Users:** the module name will be identical to the class, so the import statement will be something like `from Pipeline import Pipeline`



## Structure of the Generated Code

```
Pipeline:
// Process -- this will run the pipeline
process(Mat source)

// Output accessors
getFooOutput()
getBar0Output()
getBar1Output()
...
```

## Running the Pipeline

To run the Pipeline, call the process method with the sources (webcams, IP camera, image file, etc) as arguments. This will expose the outputs of every operation in the pipeline with the getFooOutput methods.

## Getting the Results

Users are able to the outputs of every step in the pipeline. The outputs of these operations would be accessible through their respective accessors. For example:

Operation	Java/C++ getter	Python variable
RGB Threshold	getRgbThresholdOutput	rgb_threshold_output
Blur	getBlurOutput	blur_output
CV Erode	getCvErodeOutput	mcv_erode_output
Find Contours	getFindContoursOutput	find_contours_output
Filter Contours	getFilterContoursOutput	filter_contours_output

If an operation appears multiple times in the pipeline, the accessors for those operations have the number of that operation:

Operation	Which appearance	Accessor
Blur	First	getBlur0Output
Blur	Second	getBlur1Output
Blur	Third	getBlur2Output

### 17.2.4 Using Generated Code in a Robot Program

GRIP generates a class that can be added to an FRC program that runs on a roboRIO and without a lot of additional code, drive the robot based on the output.

Included here is a complete sample program that uses a GRIP pipeline that drives a robot towards a piece of retroreflective material.

This program is designed to illustrate how the vision code works and does not necessarily represent the best technique for writing your robot program. When writing your own program be aware of the following considerations:

1. **Using the camera output for steering the robot could be problematic.** The camera code in this example that captures and processes images runs at a much slower rate that is desirable for a control loop for steering the robot. A better, and only slightly more complex solution, is to get headings from the camera and it's processing rate, then have a much faster control loop steering to those headings using a gyro sensor.
2. **Keep the vision code in the class that wraps the pipeline.** A better way of writing object oriented code is to subclass or instantiate the generated pipeline class and process the OpenCV results there rather than in the robot program. In this example, the robot code extracts the direction to drive by manipulating the resultant OpenCV contours. By having the OpenCV code exposed throughout the robot program it makes it difficult to change the vision algorithm should you have a better one.

## Iterative program definitions

Java

```
package org.usfirst.frc.team190.robot;

import org.usfirst.frc.team190.grip.MyVisionPipeline;

import org.opencv.core.Rect;
import org.opencv.imgproc.Imgproc;

import edu.wpi.cscore.UsbCamera;
import edu.wpi.first.cameraserver.CameraServer;
import edu.wpi.first.wpilibj.RobotDrive;
import edu.wpi.first.wpilibj.TimedRobot;
import edu.wpi.first.wpilibj.vision.VisionRunner;
import edu.wpi.first.wpilibj.vision.VisionThread;

public class Robot extends TimedRobot {

    private static final int IMG_WIDTH = 320;
    private static final int IMG_HEIGHT = 240;

    private VisionThread visionThread;
    private double centerX = 0.0;
    private RobotDrive drive;

    private final Object imgLock = new Object();
```

In this first part of the program you can see all the import statements for the WPILib classes used for this program.

- The **image width and height** are defined as 320x240 pixels.
- The **VisionThread** is a WPILib class makes it easy to do your camera processing in a separate thread from the rest of the robot program.
- **centerX** value will be the computed center X value of the detected target.
- **RobotDrive** encapsulates the 4 motors on this robot and allows simplified driving.
- **imgLock** is a variable to synchronize access to the data being simultaneously updated with each image acquisition pass and the code that's processing the coordinates and steering the robot.

Java

```

@Override
public void robotInit() {
    UsbCamera camera = CameraServer.getInstance().startAutomaticCapture();
    camera.setResolution(IMG_WIDTH, IMG_HEIGHT);

    visionThread = new VisionThread(camera, new MyVisionPipeline(), pipeline -> {
        if (!pipeline.filterContoursOutput().isEmpty()) {
            Rect r = Imgproc.boundingRect(pipeline.filterContoursOutput().get(0));
            synchronized (imgLock) {
                centerX = r.x + (r.width / 2);
            }
        }
    });
    visionThread.start();

    drive = new RobotDrive(1, 2);
}

```

The **robotInit()** method is called once when the program starts up. It creates a **CameraServer** instance that begins capturing images at the requested resolution (IMG\_WIDTH by IMG\_HEIGHT).

Next an instance of the class **VisionThread** is created. VisionThread begins capturing images from the camera asynchronously in a separate thread. After processing each image, the pipeline computed **bounding box** around the target is retrieved and its **center X** value is computed. This centerX value will be the x pixel value of the center of the rectangle in the image.

The VisionThread also takes a **VisionPipeline** instance (here, we have a subclass **MyVisionPipeline** generated by GRIP) as well as a callback that we use to handle the output of the pipeline. In this example, the pipeline outputs a list of contours (outlines of areas in an image) that mark goals or targets of some kind. The callback finds the bounding box of the first contour in order to find its center, then saves that value in the variable centerX. Note the synchronized block around the assignment: this makes sure the main robot thread will always have the most up-to-date value of the variable, as long as it also uses **synchronized** blocks to read the variable.

Java

```

@Override
public void autonomousPeriodic() {
    double centerX;
    synchronized (imgLock) {
        centerX = this.centerX;
    }
    double turn = centerX - (IMG_WIDTH / 2);
    drive.arcadeDrive(-0.6, turn * 0.005);
}

```

This, the final part of the program, is called repeatedly during the **autonomous period** of the match. It gets the **centerX** pixel value of the target and **subtracts half the image width** to change it to a value that is **zero when the rectangle is centered** in the image and **positive or negative when the target center is on the left or right side of the frame**. That value is used to steer the robot towards the target.

Note the **synchronized** block at the beginning. This takes a snapshot of the most recent centerX value found by the VisionThread.

### 17.2.5 Using GRIP with a Kangaroo Computer

A recently available computer called the Kangaroo looks like a great platform for running GRIP on FRC robots. Some of the specs for this processor include:

- Quad core 1.4Ghz Atom processor
- HDMI port
- 2 USB ports (1 USB2 and 1 USB3)
- 2GB RAM
- 32GB Flash
- Flash card slot
- WiFi
- Battery with 4 hours running time
- Power supply
- Windows 10
- and a fingerprint reader

The advantage of this setup is that it offloads the roboRIO from doing image processing and it is a normal Windows system so all of our software should work without modification. Be sure to read the caveats at the end of this page before jumping in.

**More detailed instructions** for using a Kangaroo for running GRIP can be found in the following PDF document created by Scott Taylor and FRC 1735. His explanation goes beyond what is shown here, detailing how to get the GRIP program to auto-start on boot and many other details.

[Grip Plus Kangaroo](#)

#### Setup

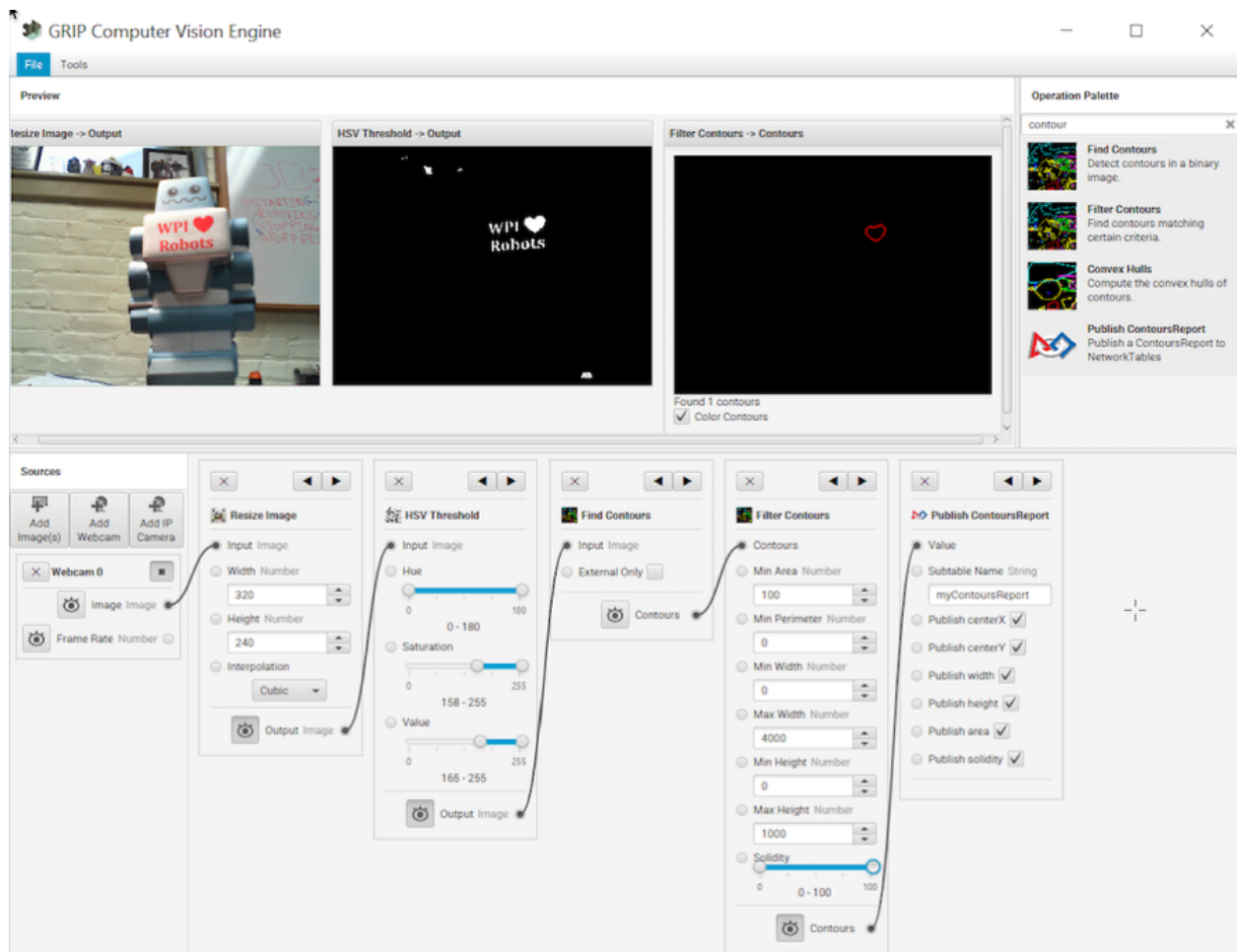
The nice thing about this setup is that you just need to plug in a monitor, keyboard, mouse and (in this case) the Microsoft web camera and you are good to go with programming the GRIP pipeline. When you are finished, disconnect the keyboard, mouse and monitor and put the Kangaroo on your robot. You will need to disable the WiFi on the Kangaroo and connect it to the robot with a USB ethernet dongle to the extra ethernet port on the robot radio.

In this example you can see the Kangaroo computer (1) connected to a USB hub (3), keyboard, and an HDMI monitor for programming. The USB hub is connected to the camera and mouse.

#### Sample GRIP program

Attached is the sample program running on the Kangaroo detecting the red heart on the little foam robot in the image (left panel). It is doing a HSV threshold to only get that red color then finding contours, and then filtering the contours using the size and solidity. At the end of the pipeline, the values are being published to NetworkTables.





Network Table Viewer		
Key	Value	Type
Root		
GRIP		
myContoursReport		
centerX	[211.0]	Number[1]
centerY	[80.0]	Number[1]
height	[16.0]	Number[1]
area	[194.0]	Number[1]
width	[20.0]	Number[1]
solidity	[0.9603960396039604]	Number[1]



## Viewing Contours Report in NetworkTables

This is the output from the OutlineViewer (<username>/WPILib/tools/OutlineViewer.jar), running on a different computer as a server (since there is no roboRIO on the network in this example) and the values being reported back for the single contour that the program detected that met the requirements of the Filter Contours operation.

## Considerations

The Kangaroo runs Windows 10, so care must be taken to make sure GRIP will keep running on the robot during a match or testing. For example, it should not try to do a Windows Update, Virus scan refresh, go to sleep, ect. Once configured, it has the advantage of being a normal Intel Architecture and should give predictable performance since it is running only one application.

## 17.3 Vision with Raspberry Pi

### 17.3.1 Using a Coprocessor for vision processing

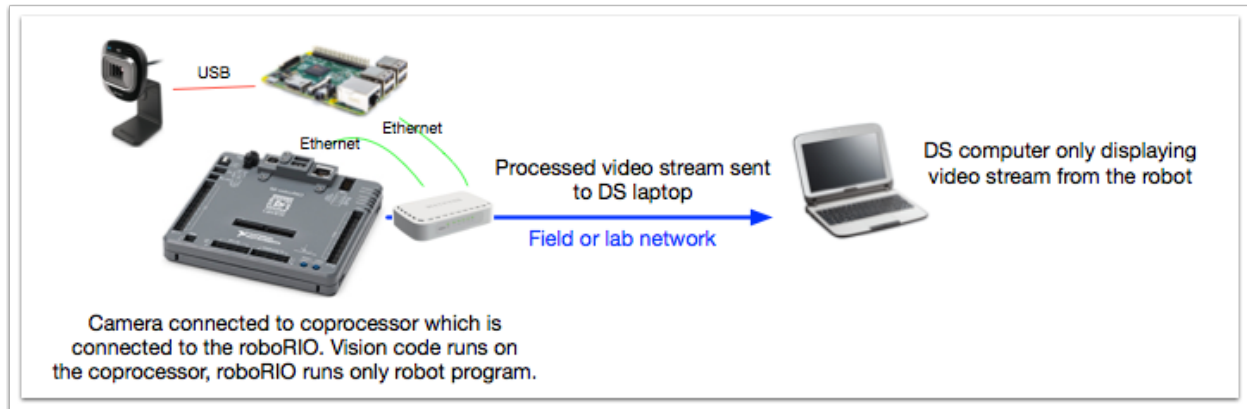
Vision processing using libraries like OpenCV for recognizing field targets or game pieces can often be a CPU intensive process. Often the load isn't too significant and the processing can easily be handled by the roboRIO. In cases where there are more camera streams or the image processing is complex, it is desirable to off-load the roboRIO by putting the code and the camera connection on a different processor. There are a number of choices of processors that are popular in FRC such as the Raspberry PI, the intel-based Kangaroo, the LimeLight for the ultimate in simplicity, or for more complex vision code a graphics accelerator such as one of the nVidia Jetson models.

## Strategy

Generally the idea is to set up the coprocessor with the required software that generally includes:

- OpenCV - the open source computer vision library
- Network tables - to commute the results of the image processing to the roboRIO program
- Camera server library - to handle the camera connections and publish streams that can be viewed on a dashboard
- The language library for whatever computer language is used for the vision program
- The actual vision program that does the object detection

The coprocessor is connected to the roboRIO network by plugging it into the extra ethernet port on the network router or, for more connections, adding a small network switch to the robot. The cameras are plugged into the coprocessor, it acquires the images, processes them, and publishes the results, usually target location information, to network tables so it is can be consumed by the robot program for steering and aiming.



### Streaming camera data to the dashboard

It is often desirable to simply stream the camera data to the dashboard over the robot network. In this case one or more camera connections can be sent to the network and viewed on a dashboard such as Shuffleboard or a web browser. Using Shuffleboard has the advantage of having easy controls to set the camera resolution and bit rate as well as integrating the camera streams with other data sent from the robot.

It is also possible to process images and add annotation to the image, such as target lines or boxes showing what the image processing code has detected then send it forward to the dashboard to make it easier for operators to see a clear picture of what's around the robot.

### 17.3.2 Using the Raspberry Pi for FRC

One of the most popular coprocessor choices is the Raspberry Pi because:

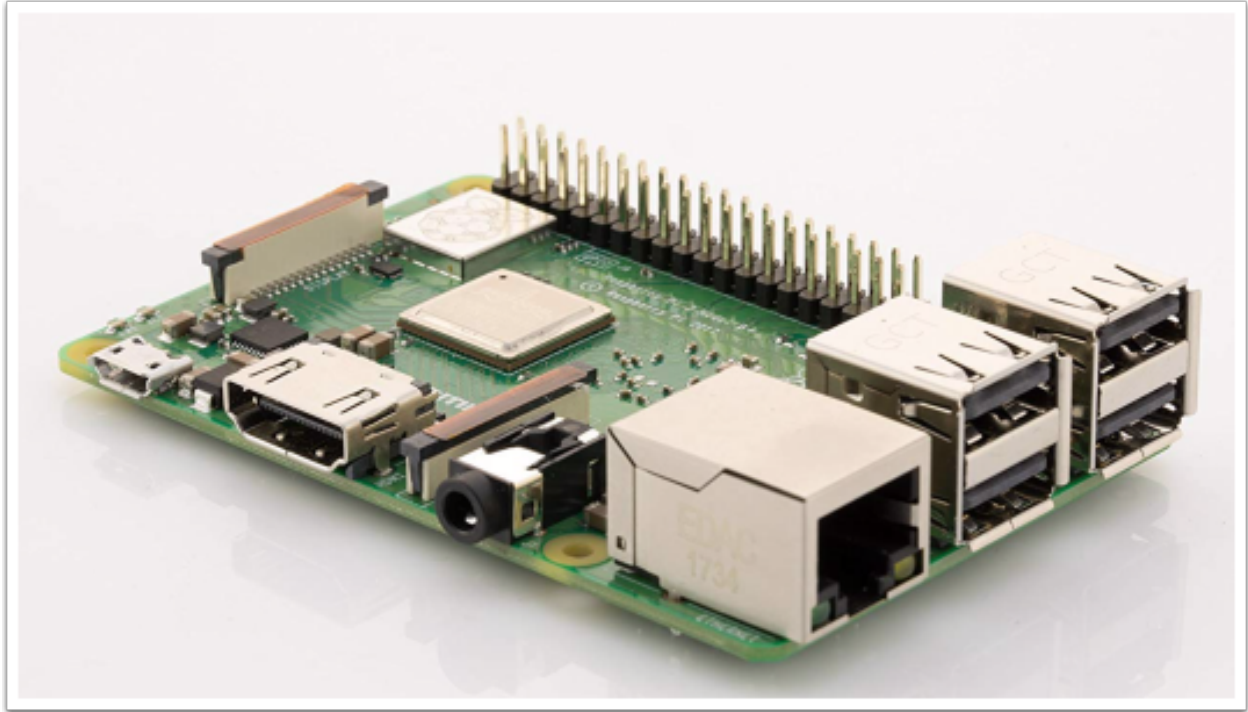
- Low cost - around \$35
- High availability - it's easy to find Raspberry Pis from a number of suppliers, including Amazon
- Very good performance - the current Raspberry Pi 3b+ has the following specifications:
- Technical Specifications: - Broadcom BCM2837BO 64 bit ARMv8 QUAD Core A53 64bit Processor powered Single Board Computer run at 1.4GHz - 1GB RAM - BCM43143 WiFi on board - Bluetooth Low Energy (BLE) on board - 40 pin extended GPIO - 4 x USB2 ports - 4 pole Stereo output and Composite video port - Full size HDMI - CSI camera port for connecting the Raspberry - Pi camera - DSI display port for connecting the Raspberry - Pi touch screen display - MicroSD port for loading your operating system and storing data - Upgraded switched Micro USB power source (now supports up to 2.5 Amps).

#### Pre-built Raspberry Pi image

To make using the Raspberry Pi as easy as possible for teams, there is a provided Raspberry Pi image. The image can be copied to a micro SD card, inserted into the Pi, and booted. By default it supports:

- A web interface for configuring it for the most common functions





- Supports an arbitrary number camera streams (defaults to one) that are published on the network interface
- OpenCV, Network Tables, Camera Server, and language libraries for C++, Java, and Python custom programs

If the only requirement is to stream one or more cameras to the network (and dashboard) then no programming is required and can be completely set up through the web interface.

The next section discusses how to install the image onto a flash card and boot the Pi.

### **17.3.3 What you need to get the Pi image running**

To start using the Raspberry Pi as a video or image coprocessor you need the following:

- A Raspberry Pi 3 B, Raspberry Pi 3 B+, or a Raspberry Pi 4 B
- A micro SD card that is at least 4Gb to hold all the provided software, with a recommended Speed Class of 10 (10MB/s)
- An ethernet cable to connect the Pi to your roboRIO network
- A USB micro power cable to connect to the Voltage Regulator Module (VRM) on your robot. It is recommended to use the VRM connection for power rather than powering it from one of the roboRIO USB ports for higher reliability
- A laptop that can write the MicroSD card, either using a USB dongle (preferred) or a SD to MicroSD adapter that ships with most MicroSD cards

Shown is an inexpensive USB dongle that will write the FRC image to the MicroSD card.



### 17.3.4 Installing the image to your MicroSD card

#### Getting the FRC Raspberry PI image

The image is stored on the GitHub release page for the FRC PI-gen repository: <https://github.com/wpilibsuite/FRCVision-pi-gen/releases>.

In addition to the instructions on this page, see the documentation on the GitHub web page (below).

The image is fairly large so have a fast internet connection when downloading it. Always use the most recent release from the top of the list of releases.

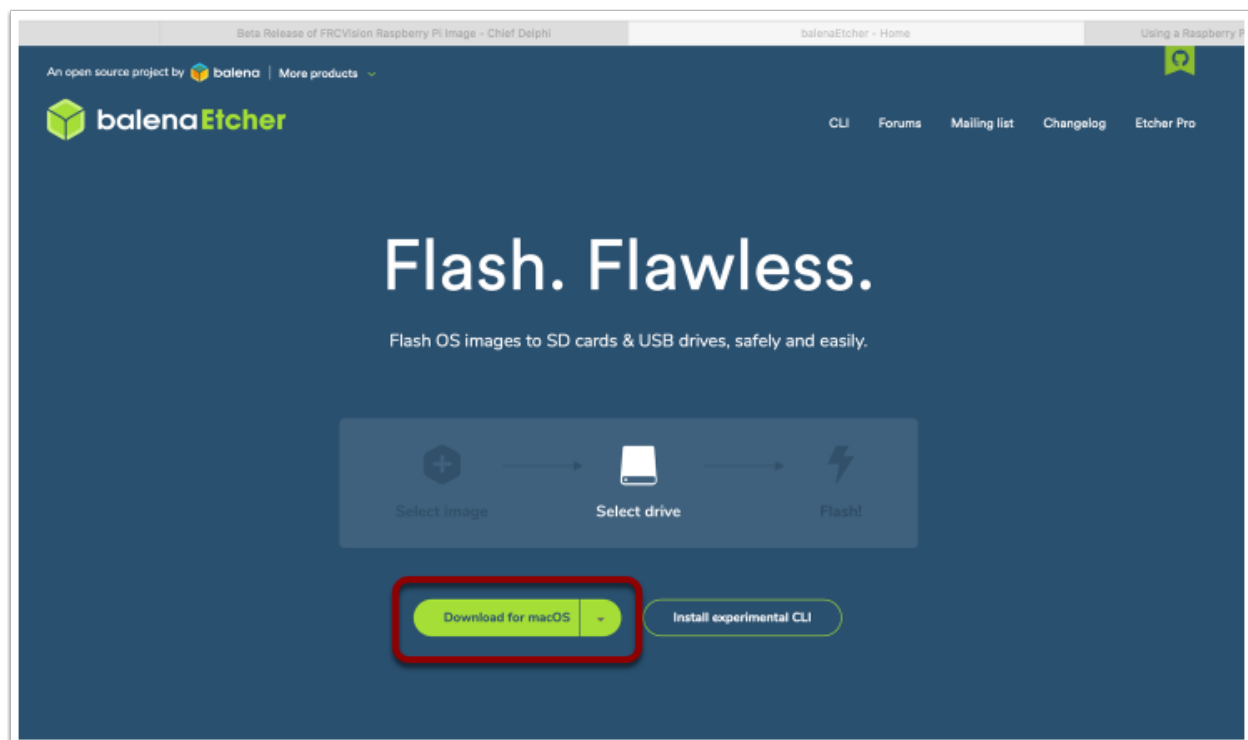
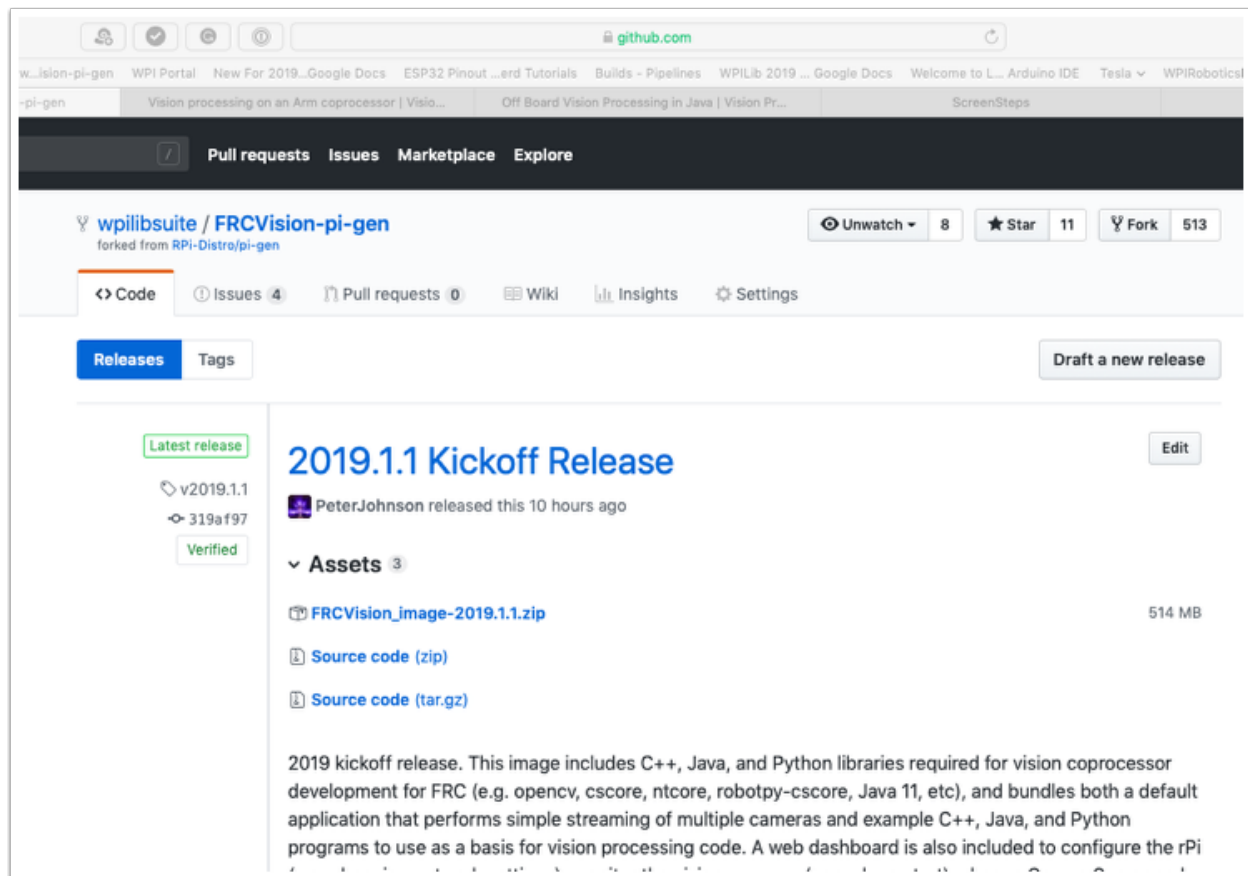
#### Copy the image to your MicroSD card

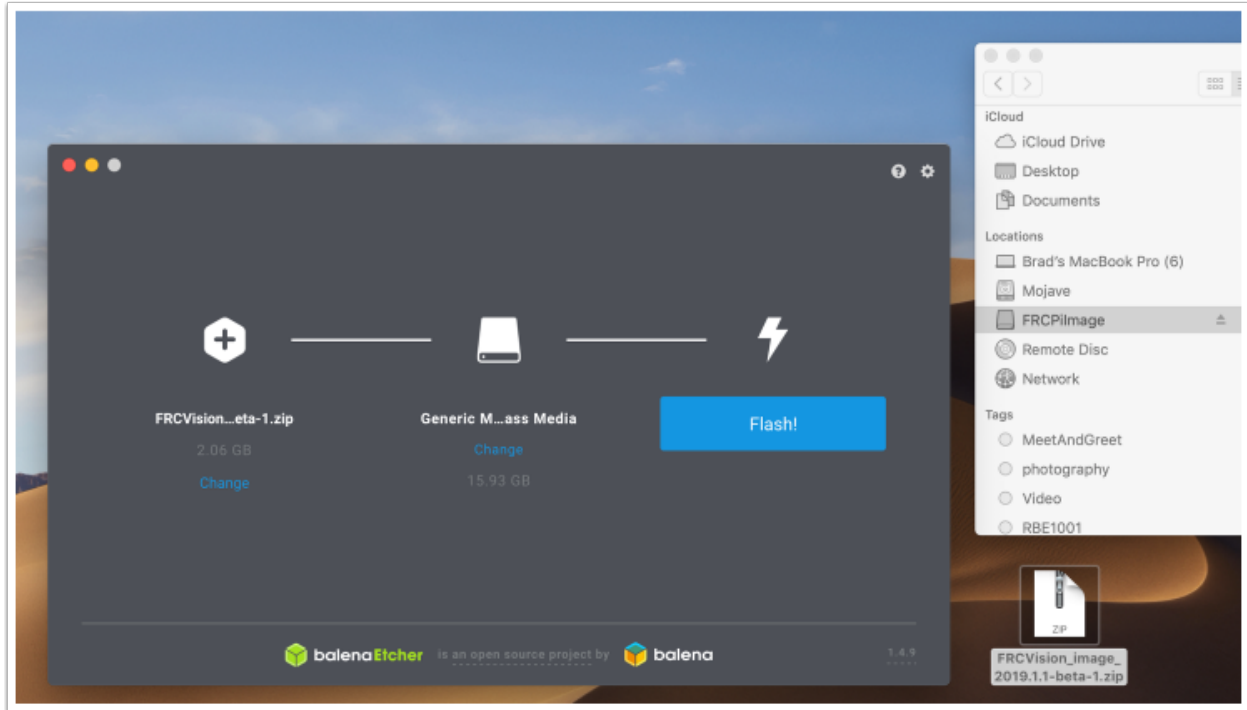
Download and install Etcher (<https://www.balena.io/etcher/>) to image the micro SD card. The micro SD card needs to be at least 4 GB. Note: a micro SD to USB dongle such as <https://www.amazon.com/gp/product/B0779V61XB> works well for writing to micro SD cards.

Flash the MicroSD card with the image using Etcher by selecting the zip file as the source, your SD card as the destination and click “Flash”. Expect the process to take about 3 minutes on a fairly fast laptop.

#### Testing the Raspberry PI

1. Put the micro SD card in a rPi 3 and apply power.
2. Connect the rPi 3 ethernet to a LAN or PC. Open a web browser and connect to <http://frcvision.local/> to open the web dashboard. On the first bootup the filesystem will be writable, but later bootups will default to read only, so it's necessary to click the “writable” button to make changes.





## Logging into the Raspberry PI

Most tasks with the rPi can be done from the web console interface. Sometimes for advanced use such as program development on the rPi it is necessary to log in. To log in, use the default Raspberry PI password:

Username: pi  
Password: raspberry

Known issues with this release (errata). These will be fixed in the next release.

- Downloading the Java example program on the web dashboard does not work. Grab it manually from /home/pi/zips instead (using ssh).
- Console output enable button on the web dashboard doesn't persist correctly through a rPi reboot (it needs to be disabled and re-enabled to again get console output).

## 17.3.5 The Raspberry PI

### FRC Console

The FRC image for the Raspberry PI includes a console that can be viewed in any web browser that makes it easy to:

- Look at the Raspberry PI status
- View the status of the background process running the camera
- View or change network settings
- Look at each camera plugged into the rPi and add additional cameras

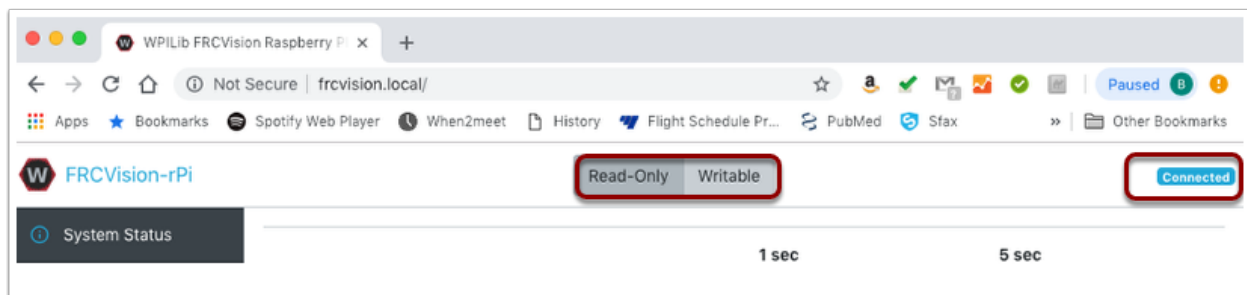
- Load a new vision program onto the rPi

### Setting the rPi to be Read-Only vs. Writable

The rPi is normally set to Read-Only which means that the file system cannot be changed. This ensures that if power is removed without first shutting down the rPi the file system isn't corrupted. When settings are changed (following sections), the new settings cannot be saved while the rPi file system is set as Read-Only. Buttons are provided that allow the file system to be changed from Read-Only to Writable and back whenever changes are made. If the other buttons that change information stored on the rPi cannot be press, check the Read-Only status of the system.

### Status of the network connection to the rPi

There is a label in the top right corner of the console that indicates if the rPi is currently connected. It will change from Connected to Disconnected if there is no longer a network connection to the rPi.



### System status

The system status shows what the CPU on the rPi is doing at any time. There are two columns of status values, one being a 1 second average and the other a 5 second average. Shown is:

- free and available RAM on the PI
- CPU usage for user processes and system processes as well as idle time.
- And network bandwidth - which allows one to determine if the used camera bandwidth is exceeding the maximum bandwidth allowed in the robot rules for any year.

### Vision Status

Allows monitoring of the task which is running the camera code in the rPi, either one of the default programs or your own program in Java, C++, or Python. You can also enable and view the console output to see messages coming from the background camera service. In this case there are number of messages about being unable to connect to network tables (NT: connect()) because in this example the rPi is simply connected to a laptop with no Network Tables server running (usually the roboRIO.)

The screenshot shows the FRCVision-rPi web interface in a browser. The address bar shows 'frcvision.local/'. The interface has a sidebar with navigation links: System Status, Vision Status, Network Settings, Vision Settings, and Application. The main content area displays system status metrics for 1 second and 5 second intervals. The status is 'Connected'.

	1 sec	5 sec
Memory (MB Free)	809	809
Memory (MB Avail)	816	816
CPU (% User)	0	0
CPU (% System)	0	0
CPU (% Idle)	100	99
Network (Kbps)	8	9

Below the table is a yellow button labeled 'Restart System'.

The screenshot shows the FRCVision-rPi web interface with the status 'Disconnected'. The sidebar is the same as the previous screenshot. The main content area has two sections:

**Background Service (Automatic Restart)** - Status: Unknown Status

Buttons: Up, Down, Terminate, Kill

**Console Output** - Enable: ☒

```

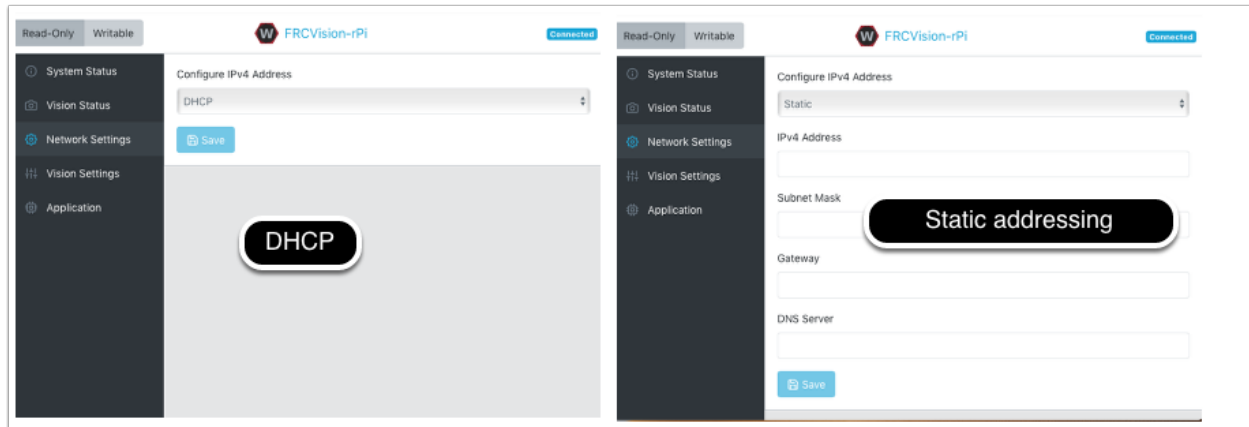
NT: connect() to 10.2.94.2 port 1735 timed out
      NT: connect() to 172.22.11.2 port 1735 timed out
NT: ERROR: select() to 10.2.94.2 port 1735 error 113 - No route to host
          (TCPConnector.cpp:173)
      NT: ERROR: select() to 172.22.11.2 port 1735 error 113 -
          No route to host (TCPConnector.cpp:173)
NT: ERROR: could not resolve roboRIO-294-FRC.local address
          (TCPConnector.cpp:99)
NT: connect() to 10.2.94.2 port 1735 timed out
      NT: connect() to 172.22.11.2 port 1735 timed out
NT: ERROR: could not resolve roboRIO-294-FRC.frc-field.local address
          (TCPConnector.cpp:99)
NT: connect() to 10.2.94.2 port 1735 timed out
      NT: connect() to 172.22.11.2 port 1735 timed out
NT: ERROR: select() to 10.2.94.2 port 1735 error 113 - No route to host
  
```



## Network Settings

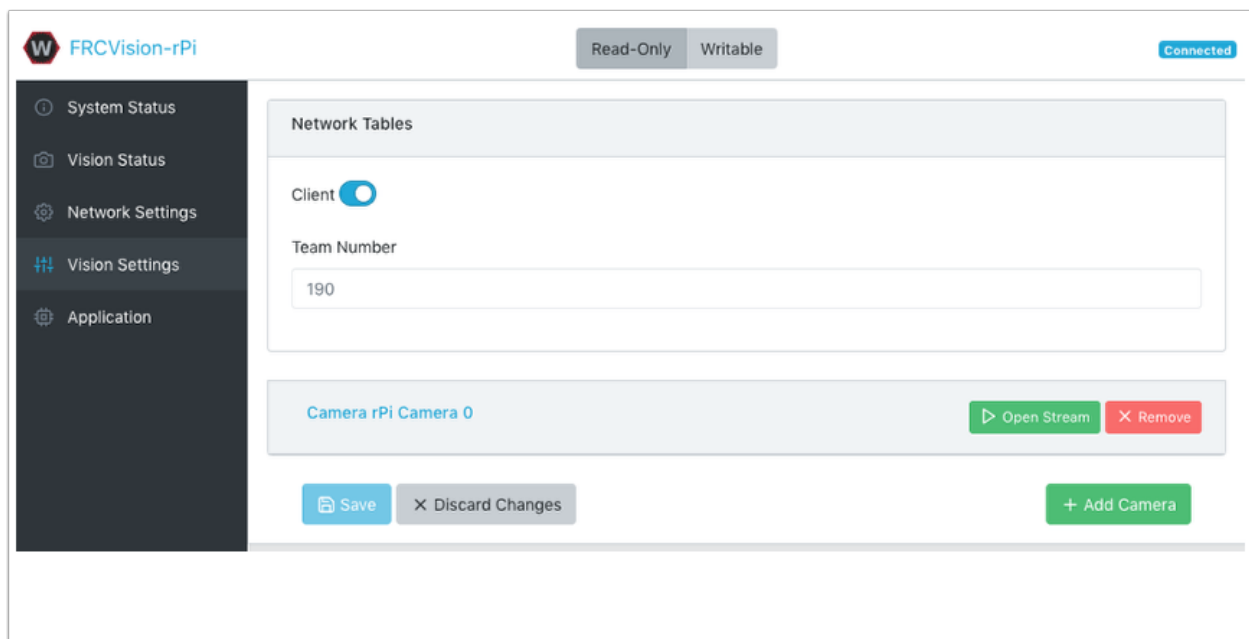
The rPi network settings have options to connect to the PI:

- DHCP - the default name resolution usually used by the roboRIO. The default name is raspberry.local.
- Static - where a fixed IP address, network mask, and router settings are filled in explicitly
- DHCP with Static Fallback - DHCP with Static Fallback - the PI will try to get an IP address via DHCP, but if it can't find a DHCP server, it will use the provided static IP address and parameters



The picture above is showing the settings for both DHCP and Static IP Addressing. The mDNS name for the rPi should always work regardless of the options selected above.

## Vision Settings



The Vision Settings are to set the parameters for each camera and whether the rPi should be a NetworkTables client or server. There can only be one server on the network and the roboRIO is always a server. Therefore when connected to a roboRIO, the rPi should always be in client mode with the team number filled in. If testing on a desktop setup with no roboRIO or anything acting as a server then it should be set to Server (Client switch is off).

To view and manipulate all the camera settings click on the camera in question. In this case the camera is called “Camera rPi Camera 0” and clicking on the name reveals the current camera view and the associated settings.

Manipulating the camera settings is reflected in the current camera view. The bottom of the page shows all the possible camera modes (combinations of Width, Height, and frame rates) that are supported by this camera.

### Getting the current settings to persist over reboots

The rPi will load all the camera settings on startup. Editing the camera configuration in the above screen is temporary. To make the values persist click on the “Load Source Config From Camera” button and the current settings will be filled in on the camera settings fields. Then click “Save” at the bottom of the page. Note: you must set the file system Writeable in order to save the settings. *The Writeable button is at the top of the page.*

There are some commonly used camera settings values shown in the camera settings (above). These values Brightness, White Balance, and Exposure are loaded into the camera before the user JSON file is applied. So if a user JSON file contains those settings they will overwrite the ones from the text field.

### Application

The Application tab shows the application that is currently running on the rPi.

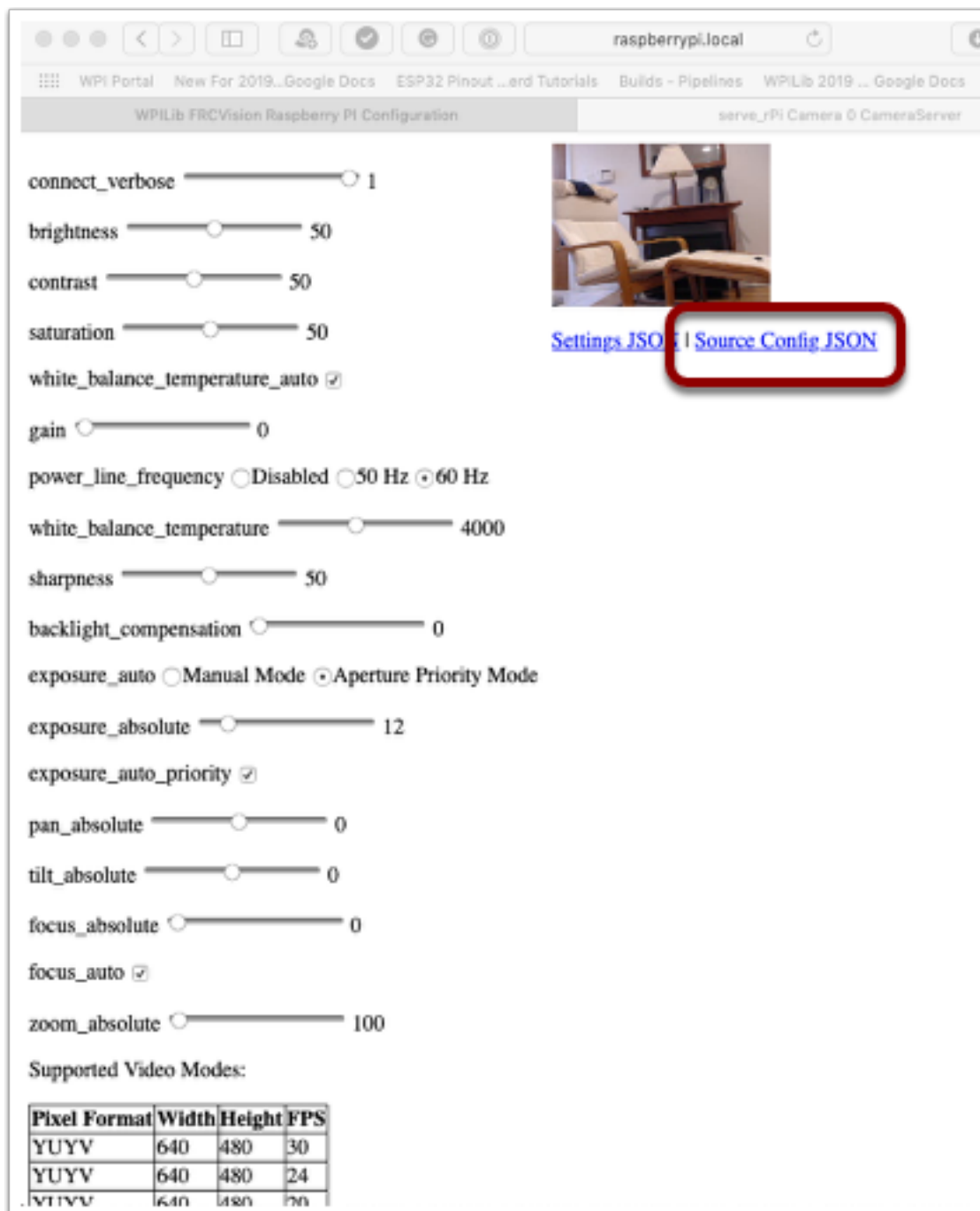
### Vision workflows

There is a sample vision program using OpenCV in each of the supported languages, C++, Java, or Python. Each sample program can capture and stream video from the rPi. In addition, the samples have some minimal OpenCV. They are all set up to be extended to replace the provided OpenCV sample code with the code needed for the robot application. The rPi Application tab supports a number of programming workflows:

- Stream one or more cameras from the rPi for consumption on the driver station computer and displayed using ShuffleBoard
- Edit and build one of the sample programs (one for each language: Java, C++ or Python) on the rPi using the included toolchains
- Download a sample program for the chosen language and edit and build it on your development computer. Then upload that built program back to the rPi
- Do everything yourself using completely custom applications and scripts (probably based on one of the samples)

The running application can be changed by selecting one of the choices in the drop-down menu. The choices are:





connect\_verbose ☐ 1

brightness ☐ 50

contrast ☐ 50

saturation ☐ 50

white\_balance\_temperature\_auto ☒

gain ☐ 0

power\_line\_frequency ☐ Disabled ☐ 50 Hz ☒ 60 Hz

white\_balance\_temperature ☐ 4000

sharpness ☐ 50

backlight\_compensation ☐ 0

exposure\_auto ☐ Manual Mode ☒ Aperture Priority Mode

exposure\_absolute ☐ 12

exposure\_auto\_priority ☒

pan\_absolute ☐ 0

tilt\_absolute ☐ 0

focus\_absolute ☐ 0

focus\_auto ☒

zoom\_absolute ☐ 100

Supported Video Modes:

Pixel Format	Width	Height	FPS
YUYV	640	480	30
YUYV	640	480	24
YUYV	640	480	15

Network Tables

Client ☒

Team Number  
190

Camera rPi Camera 0

▶ Open Stream

✕ Remove

Name


rPi Camera 0

Path

/dev/video0

Load Source Config From JSON File

Browse

 Copy Source Config From Camera

Pixel Format

Width

Height

FPS

MJPEG

160

120

30

Brightness

White Balance

Exposure

15

auto

auto

Custom Properties JSON

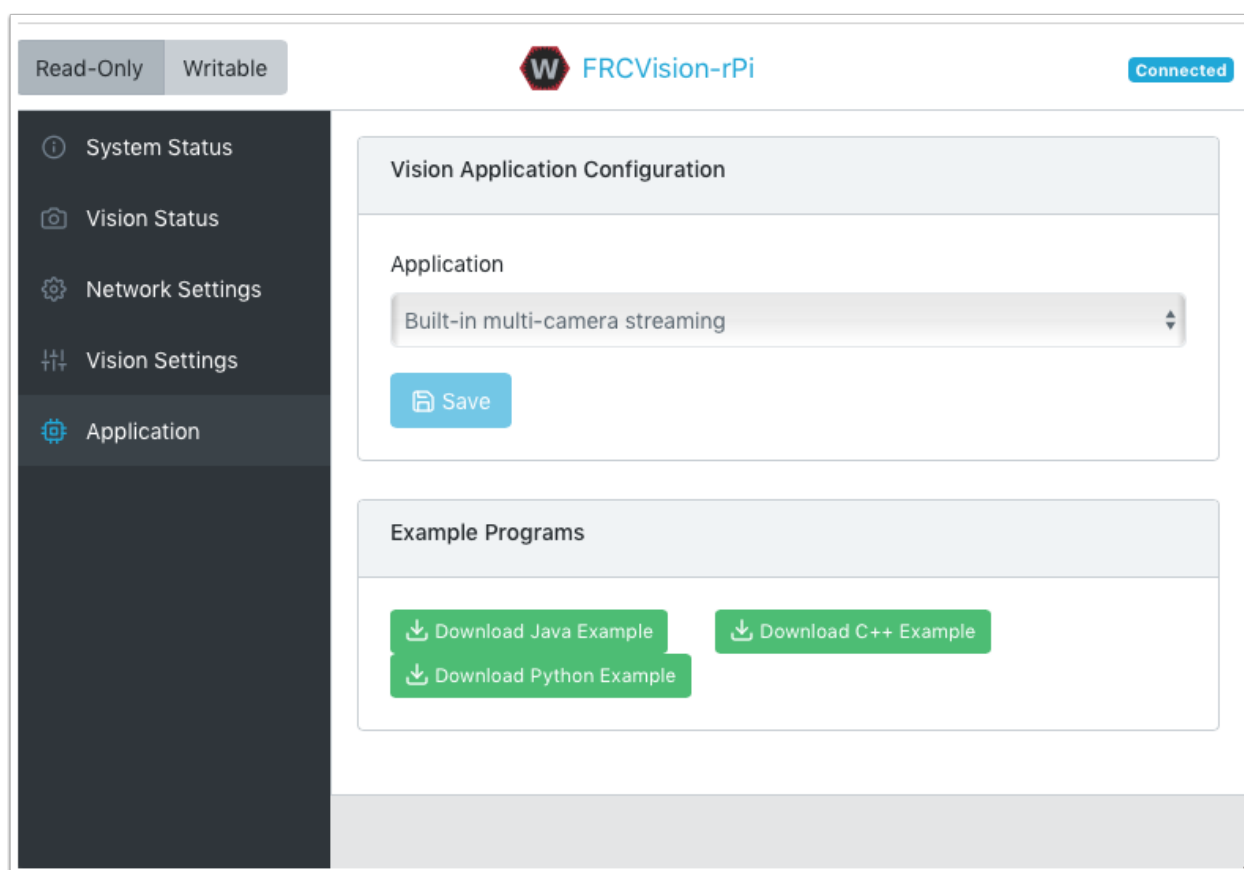
```
[{"name":"connect_verbose","value":1},{"name":"contrast","value":50}, {"name":"saturation","value":50}, {"name":"gain","value":0}, {"name":"power_line_frequency","value":2}, {"name":"sharpness","value":50}, {"name":"backlight_compensation","value":0}, {"name":"exposure_auto_priority","value":true},
```

Save

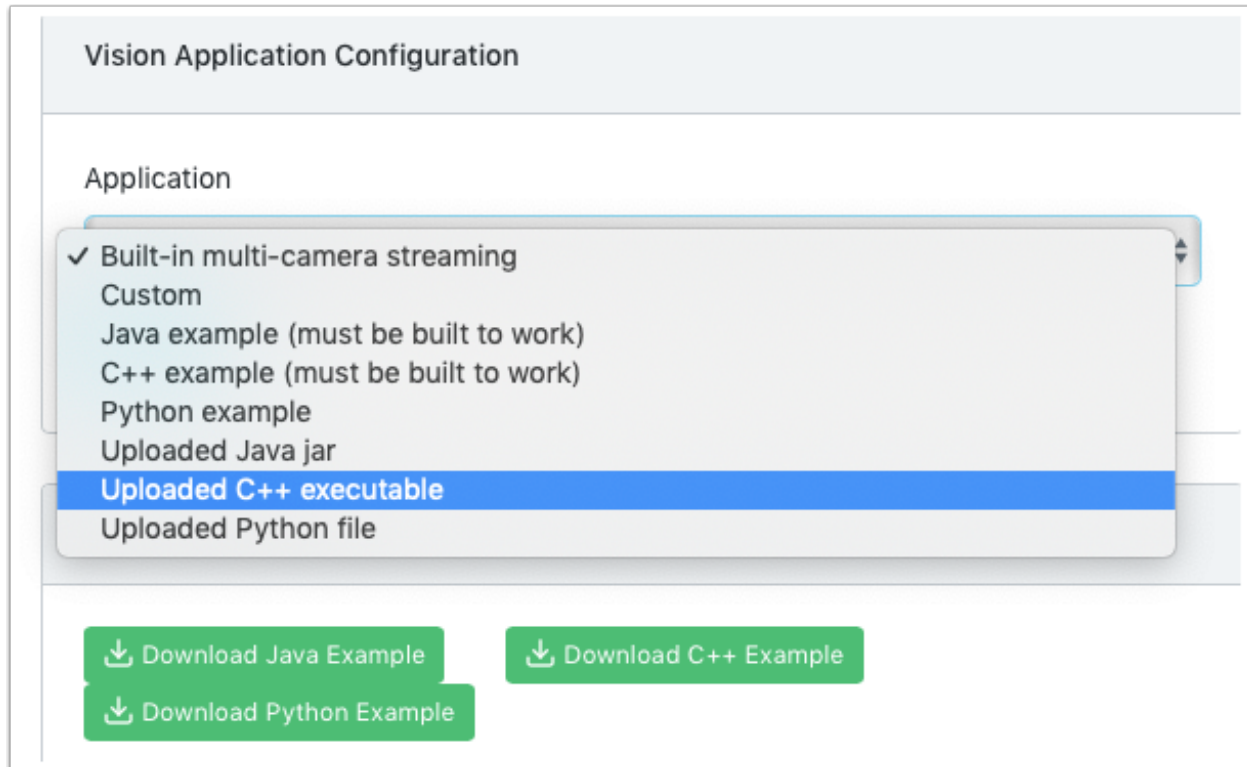
✕ Discard Changes

+ Add Camera

These settings are filled in when copying the Source Config from the camera



- Built-in multi camera streaming which streams whatever cameras are plugged into the rPi. The camera configuration including number of cameras can be set on the “Vision Settings” tab.
- Custom application which doesn’t upload anything to the rPi and assumes that the developer wants to have a custom program and script.
- Java, C++ or Python pre-installed sample programs that can be edited into your own application.
- Java, C++, or Python uploaded program. Java programs require a .jar file with the compiled program and C++ programs require an rPi executable to be uploaded to the rPi.



When selecting one of the Upload options, a file chooser is presented where the jar, executable or Python program can be selected and uploaded to the rPi. In the following picture an Uploaded Java jar is chosen and the “Choose File” button will select a file and clicking on the “Save” button will upload the selected file.

Note: in order to Save a new file onto the rPi, the file system has to be set writeable using the “Writable” button at the top left of the web page. After saving the new file, set the file system back to “Read-Only” so that it is protected against accidental changes.


Application

Uploaded Java jar


Upload executable file


Choose File


no file selected

 Save

Example Programs

 Download Java Example

 Download C++ Example

 Download Python Example

## Command-Based Programming

This sequence of articles serves as an introduction to and reference for the WPILib command-based framework.

For a collection of example projects using the command-based framework, see [Command-Based Examples](#).

### 18.1 2020 Command-Based Rewrite: What Changed?

This article provides a summary of changes from the [original command-based framework](#) to the 2020 rewrite. This summary is not necessarily comprehensive - for rigorous documentation, as always, refer to the API docs ([Java](#), [C++](#)).

#### 18.1.1 Package Location

The new command-based framework is located in the `wpilibj2` package for Java, and in the `frc2` namespace for C++. The old command-based framework is still available in the original location. The new framework must be installed using the instructions: [WPILib Command Libraries](#).

#### 18.1.2 Major Architectural Changes

The overall structure of the command-based framework has remained largely the same. However, there are some still a few major architectural changes that users should be aware of:

##### Commands and Subsystems as Interfaces

`Command` ([Java](#), [C++](#)) and `Subsystem` ([Java](#), [C++](#)) are both now interfaces as opposed to abstract classes, allowing advanced users more potential flexibility. `CommandBase` and `SubsystemBase` abstract base classes are still provided for convenience, but are not required. For more information, see [Commands](#) and [Subsystems](#).

### Multiple Command Group Classes

The `CommandGroup` class no longer exists, and has been replaced by a number of narrower classes that can be recursively composed to create more-complicated group structures. For more information see [Command Groups](#).

### Inline Command Definitions

Previously, users were required to write a subclass of `Command` in almost all cases where a command was needed. Many of the new commands are designed to allow inline definition of command functionality, and so can be used without the need for an explicit subclass. For more information, see [Convenience Features](#).

### Injection of Command Dependencies

While not an actual change to the coding of the library, the recommended use pattern for the new command-based framework utilizes injection of subsystem dependencies into commands, so that subsystems are not declared as globals. This is a cleaner, more maintainable, and more reusable pattern than the global subsystem pattern promoted previously. For more information, see [Structuring a Command-Based Robot Project](#).

### Command Ownership (C++ Only)

The previous command framework required users to use raw pointers for all commands, resulting in nearly-unavoidable memory leaks in all C++ command-based projects, as well as leaving room for common errors such as double-allocating commands within command-groups.

The new command framework offers ownership management for all commands. Default commands and commands bound to buttons are typically owned by the scheduler, and component commands are owned by their encapsulating command groups. As a result, users should generally never heap-allocate a command with `new` unless there is a very good reason to do so.

Transfer of ownership is done using [perfect forwarding](#), meaning rvalues will be *moved* and lvalues will be *copied* ([rvalue/lvalue explanation](#)).

### 18.1.3 Changes to the Scheduler

- Scheduler has been renamed to `CommandScheduler` (Java, C++).
- Interruptibility of commands is now the responsibility of the scheduler, not the commands, and can be specified during the call to `schedule`.
- Users can now pass actions to the scheduler which are taken whenever a command is scheduled, interrupted, or ends normally. This is highly useful for cases such as event logging.

### 18.1.4 Changes to Subsystem

---

**Note:** For more information on subsystems, see [Subsystems](#).

---

- As noted earlier, Subsystem is now an interface ([Java](#), [C++](#)); the closest equivalent of the old Subsystem is the new SubsystemBase class. Many of the Sendable-related constructor overloads have been removed to reduce clutter; users can call the setters directly from their own constructor, if needed.
- `initDefaultCommand` has been removed; subsystems no longer need to “know about” their default commands, which are instead registered directly with the `CommandScheduler`. The new `setDefaultCommand` method simply wraps the `CommandScheduler` call.
- Subsystems no longer “know about” the commands currently requiring them; this is handled exclusively by the `CommandScheduler`. A convenience wrapper on the `CommandScheduler` method is provided, however.

### 18.1.5 Changes to Command

---

**Note:** For more information on commands, see [Commands](#).

---

- As noted earlier, Command is now an interface ([Java](#), [C++](#)); the closest equivalent of the old Command is the new CommandBase class. Many of the Sendable-related constructor overloads have been removed to reduce clutter; users can call the setters directly from their own constructor, if needed.
- Commands no longer handle their own scheduling state; this is now the responsibility of the scheduler.
- The `interrupted()` method has been rolled into the `end()` method, which now takes a parameter specifying whether the command was interrupted (`false` if it ended normally).
- The `requires()` method has been renamed to `addRequirement()`.
- `void setRunsWhenDisabled(boolean disabled)` has been replaced by an overrideable `runsWhenDisabled()` method. Commands that should run when disabled should override this method to return `true`.
- `void setInterruptible(boolean interruptible)` has been removed; interruptibility is no longer an innate property of commands, and can be set when the command is scheduled.
- Several “*decorator*” *methods* have been added to allow easy inline modification of commands (e.g. adding a timeout).
- (C++ only) In order to allow the decorators to work with the command ownership model, a [CRTP](#) is used via the `CommandHelper` [class](#). Any user-defined Command subclass Foo *must* extend `CommandHelper<Foo, Base>` where Base is the desired base class.



### 18.1.6 Changes to PIDSubsystem/PIDCommand

**Note:** For more information, see *PID Control through PIDSubsystems and PIDCommands*

- Following the changes to PIDController, these classes now run synchronously from the main robot loop.
- The PIDController is now injected through the constructor, removing many of the forwarding methods. It can be modified after construction with `getController()`.
- PIDCommand is intended largely for inline use, as shown in the GyroDriveCommands example (Java, C++).
- If users wish to use PIDCommand more “traditionally,” overriding the protected `returnPIDInput()` and `usePIDOutput(double output)` methods has been replaced by modifying the protected `m_measurement` and `m_useOutput` fields. Similarly, rather than calling `setSetpoint`, users can modify the protected `m_setpoint` field.

## 18.2 What Is “Command-Based” Programming?

WPIlib supports a robot programming methodology called “command-based” programming. In general, “command-based” can refer both the general programming paradigm, and to the set of WPIlib library resources included to facilitate it.

“Command-based” programming is an example of what is known as a [design pattern](#). It is a general way of organizing one’s robot code that is well-suited to a particular problem-space. It is not the only way to write a robot program, but it is a very effective one; command-based robot code tends to be clean, extensible, and (with some tricks) easy to re-use from year to year.

The command-based paradigm is also an example of what is known as [declarative](#) programming. In declarative programming, the emphasis is placed on *what* the program ought to do, rather than *how* the program ought to do it. Thus, the command-based libraries allow users to define desired robot behaviors while minimizing the amount of iteration-by-iteration robot logic that they must write. For example, in a command-based program, a user can specify that “the robot should perform an action when a button is pressed” (note the use of a [lambda](#)):

Java

```
aButton.whenPressed(intake::run);
```

C++

```
aButton.WhenPressed([&intake] { intake.Run(); });
```

In contrast, in an ordinary [imperative](#) program, the user would need to check the button state every iteration, and perform the appropriate action based on the state of the button.

Java

```
if(aButton.get()) {
    if(!pressed) {
        intake.run();
        pressed = true;
    }
}
```

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```

    } else {
        pressed = false;
    }
}

```

C++

```

if(aButton.Get()) {
    if(!pressed) {
        Intake.Run();
        pressed = true;
    } else {
        pressed = false;
    }
}
}

```

### 18.2.1 Subsystems and Commands

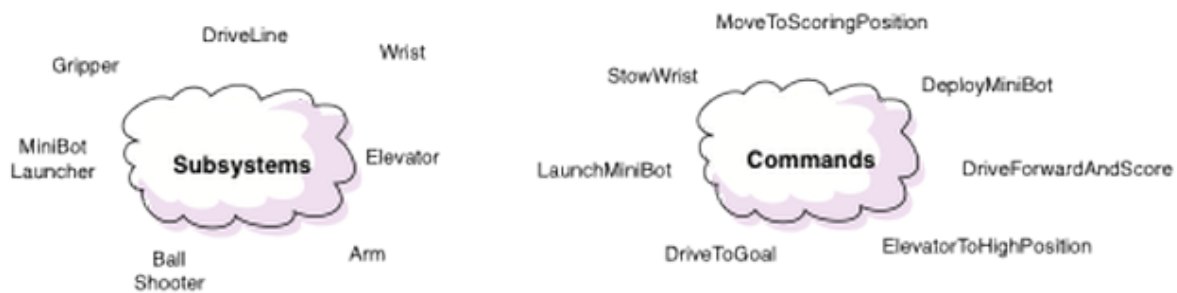


Fig. 1: image of subsystems and commands

The command-based pattern is based around two core abstractions: **commands**, and **subsystems**.

**Subsystems** are the basic unit of robot organization in the design-based paradigm. Subsystems *encapsulate* lower-level robot hardware (such as motor controllers, sensors, and/or pneumatic actuators), and define the interfaces through which that hardware can be accessed by the rest of the robot code. Subsystems allow users to “hide” the internal complexity of their actual hardware from the rest of their code - this both simplifies the rest of the robot code, and allows changes to the internal details of a subsystem without also changing the rest of the robot code. Subsystems implement the Subsystem interface.

**Commands** define high-level robot actions or behaviors that utilize the methods defined by the subsystems. A command is a simple *state machine* that is either initializing, executing, ending, or idle. Users write code specifying which action should be taken in each state. Simple commands can be composed into “command groups” to accomplish more-complicated tasks. Commands, including command groups, implement the Command interface.

## 18.2.2 How Commands Are Run

---

**Note:** For a more detailed explanation, see *The Command Scheduler*.

---

Commands are run by the `CommandScheduler`, a singleton class that is at the core of the command-based library. The `CommandScheduler` is in charge of polling buttons for new commands to schedule, checking the resources required by those commands to avoid conflicts, executing currently-scheduled commands, and removing commands that have finished or been interrupted. The scheduler's `run()` method may be called from any place in the user's code; it is generally recommended to call it from the `robotPeriodic()` method of the `Robot` class, which is run at a default frequency of 50Hz (once every 20ms).

Multiple commands can run concurrently, as long as they do not require the same resources on the robot. Resource management is handled on a per-subsystem basis: commands may specify which subsystems they interact with, and the scheduler will never schedule more than one command requiring a given subsystem at a time. This ensures that, for example, users will not end up with two different pieces of code attempting to set the same motor controller to different output values. If a new command is scheduled that requires a subsystem that is already in use, it will either interrupt the currently-running command that requires that subsystem (if the command has been scheduled as interruptible), or else it will not be scheduled.

Subsystems also can be associated with “default commands” that will be automatically scheduled when no other command is currently using the subsystem. This is useful for continuous “background” actions such as controlling the robot drive, or keeping an arm held at a setpoint.

When a command is scheduled, its `initialize()` method is called once. Its `execute()` method is then called once per call to `CommandScheduler.getInstance().run()`. A command is un-scheduled and has its `end(boolean interrupted)` method called when either its `isFinished()` method returns true, or else it is interrupted (either by another command with which it shares a required subsystem, or by being canceled).

## 18.2.3 Command Groups

It is often desirable to build complex commands from simple pieces. This is achievable by **composing** commands into “command groups.” A *command group* is a command that contains multiple commands within it, which run either in parallel or in sequence. The command-based library provides several types of command groups for teams to use, and users are encouraged to write their own, if desired. As command groups themselves implement the `Command` interface, they are **recursively composable** - one can include command groups *within* other command groups. This provides an extremely powerful way of building complex robot actions with a simple library.

## 18.3 Creating a Robot Project

Creating a project is detailed in *Creating a Robot Program*. Select “Template” then your programming language then “New Command Robot” to create a basic Command-Based Robot program.

When you create a New Command Robot project, the new command based vendor library is automatically imported. If you imported a 2019 project or created a different type of project,

the old command library is imported, and it is necessary to import the new command based vendor library per *3rd Party Libraries* and remove the old command library.

## 18.4 Subsystems

Subsystems are the basic unit of robot organization in the command-based paradigm. A subsystem is an abstraction for a collection of robot hardware that *operates together as a unit*. Subsystems *encapsulate* this hardware, “hiding” it from the rest of the robot code (e.g. commands) and restricting access to it except through the subsystem’s public methods. Restricting the access in this way provides a single convenient place for code that might otherwise be duplicated in multiple places (such as scaling motor outputs or checking limit switches) if the subsystem internals were exposed. It also allows changes to the specific details of how the subsystem works (the “implementation”) to be isolated from the rest of robot code, making it far easier to make substantial changes if/when the design constraints change.

Subsystems also serve as the backbone of the CommandScheduler’s resource management system. Commands may declare resource requirements by specifying which subsystems they interact with; the scheduler will never concurrently schedule more than one command that requires a given subsystem. An attempt to schedule a command that requires a subsystem that is already-in-use will either interrupt the currently-running command (if the command has been scheduled as interruptible), or else be ignored.

Subsystems can be associated with “default commands” that will be automatically scheduled when no other command is currently using the subsystem. This is useful for continuous “background” actions such as controlling the robot drive, or keeping an arm held at a set-point. Similar functionality can be achieved in the subsystem’s `periodic()` method, which is run once per run of the scheduler; teams should try to be consistent within their code-base about which functionality is achieved through either of these methods. Subsystems are represented in the command-based library by the Subsystem interface (Java, C++).

### 18.4.1 Creating a Subsystem

The recommended method to create a subsystem for most users is to subclass the abstract SubsystemBase class (Java, C++), as seen in the command-based template (Java, C++):

Java

```

10 import edu.wpi.first.wpilibj2.command.SubsystemBase;
11
12 public class ExampleSubsystem extends SubsystemBase {
13     /**
14      * Creates a new ExampleSubsystem.
15      */
16     public ExampleSubsystem() {
17
18     }
19
20     @Override
21     public void periodic() {
22         // This method will be called once per scheduler run
23     }
24 }
```

C++

```

8  #pragma once
9
10 #include <frc2/command/SubsystemBase.h>
11
12 class ExampleSubsystem : public frc2::SubsystemBase {
13 public:
14     ExampleSubsystem();
15
16     /**
17      * Will be called periodically whenever the CommandScheduler runs.
18      */
19     void Periodic() override;
20
21 private:
22     // Components (e.g. motor controllers and sensors) should generally be
23     // declared private and exposed only through public methods.
24 };

```

This class contains a few convenience features on top of the basic Subsystem interface: it automatically calls the `register()` method in its constructor to register the subsystem with the scheduler (this is necessary for the `periodic()` method to be called when the scheduler runs), and also implements the `Sendable` interface so that it can be sent to the dashboard to display/log relevant status information.

Advanced users seeking more flexibility may simply create a class that implements the Subsystem interface.

### 18.4.2 Simple Subsystem Example

What might a functional subsystem look like in practice? Below is a simple pneumatically-actuated hatch mechanism from the HatchBot example project (Java, C++):

Java

```

8  package edu.wpi.first.wpilibj.examples.hatchbottraditional.subsystems;
9
10 import edu.wpi.first.wpilibj.DoubleSolenoid;
11 import edu.wpi.first.wpilibj2.command.SubsystemBase;
12
13 import edu.wpi.first.wpilibj.examples.hatchbottraditional.Constants.HatchConstants;
14
15 import static edu.wpi.first.wpilibj.DoubleSolenoid.Value.kForward;
16 import static edu.wpi.first.wpilibj.DoubleSolenoid.Value.kReverse;
17
18 /**
19  * A hatch mechanism actuated by a single {@link DoubleSolenoid}.
20  */
21 public class HatchSubsystem extends SubsystemBase {
22     private final DoubleSolenoid m_hatchSolenoid =
23         new DoubleSolenoid(HatchConstants.kHatchSolenoidModule, HatchConstants.
24             ↪ kHatchSolenoidPorts[0],
25                             HatchConstants.kHatchSolenoidPorts[1]);
26
27     /**
28      * Grabs the hatch.
29      */

```

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```

29 public void grabHatch() {
30     m_hatchSolenoid.set(kForward);
31 }
32
33 /**
34  * Releases the hatch.
35  */
36 public void releaseHatch() {
37     m_hatchSolenoid.set(kReverse);
38 }
39 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc/DoubleSolenoid.h>
11 #include <frc2/command/SubsystemBase.h>
12
13 #include "Constants.h"
14
15 class HatchSubsystem : public frc2::SubsystemBase {
16 public:
17     HatchSubsystem();
18
19     // Subsystem methods go here.
20
21     /**
22      * Grabs the hatch.
23      */
24     void GrabHatch();
25
26     /**
27      * Releases the hatch.
28      */
29     void ReleaseHatch();
30
31 private:
32     // Components (e.g. motor controllers and sensors) should generally be
33     // declared private and exposed only through public methods.
34     frc::DoubleSolenoid m_hatchSolenoid;
35 };

```

## C++ (Source)

```

8  #include "subsystems/HatchSubsystem.h"
9
10 using namespace HatchConstants;
11
12 HatchSubsystem::HatchSubsystem()
13     : m_hatchSolenoid{kHatchSolenoidPorts[0], kHatchSolenoidPorts[1]} {}
14
15 void HatchSubsystem::GrabHatch() {
16     m_hatchSolenoid.Set(frc::DoubleSolenoid::kForward);
17 }
18

```

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```

19 void HatchSubsystem::ReleaseHatch() {
20     m_hatchSolenoid.Set(frc::DoubleSolenoid::kReverse);
21 }

```

Notice that the subsystem hides the presence of the `DoubleSolenoid` from outside code (it is declared `private`), and instead publicly exposes two higher-level, descriptive robot actions: `grabHatch()` and `releaseHatch()`. It is extremely important that “implementation details” such as the double solenoid be “hidden” in this manner; this ensures that code outside the subsystem will never cause the solenoid to be in an unexpected state. It also allows the user to change the implementation (for instance, a motor could be used instead of a pneumatic) without any of the code outside of the subsystem having to change with it.

### 18.4.3 Setting Default Commands

**Note:** In the C++ command-based library, the `CommandScheduler` *owns* the default command objects - accordingly, the object passed to the `SetDefaultCommand()` method will be either moved or copied, depending on whether it is an rvalue or an lvalue ([rvalue/lvalue explanation](#)). The examples here ensure that move semantics are used by casting to an rvalue with `std::move()`.

“Default commands” are commands that run automatically whenever a subsystem is not being used by another command.

Setting a default command for a subsystem is very easy; one simply calls `CommandScheduler.getInstance().setDefaultCommand()`, or, more simply, the `setDefaultCommand()` method of the `Subsystem` interface:

Java

```
CommandScheduler.getInstance().setDefaultCommand(exampleSubsystem, exampleCommand);
```

C++

```
CommandScheduler.GetInstance().SetDefaultCommand(exampleSubsystem,
↳std::move(exampleCommand));
```

Java

```
exampleSubsystem.setDefaultCommand(exampleCommand);
```

C++

```
exampleSubsystem.SetDefaultCommand(std::move(exampleCommand));
```

## 18.5 Commands

Commands are simple state machines that perform high-level robot functions using the methods defined by subsystems. Commands can be either idle, in which they do nothing, or scheduled, in which the scheduler will execute a specific set of the command’s code depending on the state of the command. The `CommandScheduler` recognizes scheduled commands as being

in one of three states: initializing, executing, or ending. Commands specify what is done in each of these states through the `initialize()`, `execute()` and `end()` methods. Commands are represented in the command-based library by the Command interface (Java, C++).

### 18.5.1 Creating Commands

**Note:** In the C++ API, a `CRT` is used to allow certain Command methods to work with the object ownership model. Users should *always* extend the `CommandHelper` class when defining their own command classes, as is shown below.

Similarly to subsystems, the recommended method for most users to create a command is to subclass the abstract `CommandBase` class (Java, C++), as seen in the command-based template (Java, C++):

Java

```

10 import edu.wpi.first.wpilibj.templates.commandbased.subsystems.ExampleSubsystem;
11 import edu.wpi.first.wpilibj2.command.CommandBase;
12
13 /**
14  * An example command that uses an example subsystem.
15  */
16 public class ExampleCommand extends CommandBase {
17     @SuppressWarnings({"PMD.UnusedPrivateField", "PMD.SingularField"})
18     private final ExampleSubsystem m_subsystem;
19
20     /**
21      * Creates a new ExampleCommand.
22      *
23      * @param subsystem The subsystem used by this command.
24      */
25     public ExampleCommand(ExampleSubsystem subsystem) {
26         m_subsystem = subsystem;
27         // Use addRequirements() here to declare subsystem dependencies.
28         addRequirements(subsystem);
29     }

```

C++

```

8  #pragma once
9
10 #include <frc2/command/CommandBase.h>
11 #include <frc2/command/CommandHelper.h>
12
13 #include "subsystems/ExampleSubsystem.h"
14
15 /**
16  * An example command that uses an example subsystem.
17  *
18  * <p>Note that this extends CommandHelper, rather extending CommandBase
19  * directly; this is crucially important, or else the decorator functions in
20  * Command will *not* work!
21  */
22 class ExampleCommand

```

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```

23 : public frc2::CommandHelper<frc2::CommandBase, ExampleCommand> {
24 public:
25     /**
26      * Creates a new ExampleCommand.
27      *
28      * @param subsystem The subsystem used by this command.
29      */
30     explicit ExampleCommand(ExampleSubsystem* subsystem);
31
32 private:
33     ExampleSubsystem* m_subsystem;
34 };

```

As before, this contains several convenience features. It automatically overrides the `getRequirements()` method for users, returning a list of requirements that is empty by default, but can be added to with the `addRequirements()` method. It also implements the `Sendable` interface, and so can be sent to the dashboard - this provides a handy way for scheduling commands for testing (via a button on the dashboard) without needing to bind them to buttons on a controller.

Also as before, advanced users seeking more flexibility are free to simply create their own class implementing the `Command` interface.

## 18.5.2 The Structure of a Command

While subsystems are fairly freeform, and may generally look like whatever the user wishes them to, commands are quite a bit more constrained. Command code must specify what the command will do in each of its possible states. This is done by overriding the `initialize()`, `execute()`, and `end()` methods. Additionally, a command must be able to tell the scheduler when (if ever) it has finished execution - this is done by overriding the `isFinished()` method. All of these methods are defaulted to reduce clutter in user code: `initialize()`, `execute()`, and `end()` are defaulted to simply do nothing, while `isFinished()` is defaulted to return false (resulting in a command that never ends).

### Initialization

The `initialize()` method (Java, C++) is run exactly once per time a command is scheduled, as part of the scheduler's `schedule()` method. The scheduler's `run()` method does not need to be called for the `initialize()` method to run. The initialize block should be used to place the command in a known starting state for execution. It is also useful for performing tasks that only need to be performed once per time scheduled, such as setting motors to run at a constant speed or setting the state of a solenoid actuator.

### Execution

The `execute()` method (Java, C++) is called repeatedly while the command is scheduled, whenever the scheduler's `run()` method is called (this is generally done in the main robot periodic method, which runs every 20ms by default). The execute block should be used for any task that needs to be done continually while the command is scheduled, such as updating motor outputs to match joystick inputs, or using the output of a control loop.

## Ending

The `end()` method (Java, C++) is called once when the command ends, whether it finishes normally (i.e. `isFinished()` returned true) or it was interrupted (either by another command or by being explicitly canceled). The method argument specifies the manner in which the command ended; users can use this to differentiate the behavior of their command end accordingly. The end block should be used to “wrap up” command state in a neat way, such as setting motors back to zero or reverting a solenoid actuator to a “default” state.

## Specifying end conditions

The `isFinished()` method (Java, C++) is called repeatedly while the command is scheduled, whenever the scheduler’s `run()` method is called. As soon as it returns true, the command’s `end()` method is called and it is un-scheduled. The `isFinished()` method is called *after* the `execute()` method, so the command *will* execute once on the same iteration that it is un-scheduled.

### 18.5.3 Simple Command Example

What might a functional command look like in practice? As before, below is a simple command from the HatchBot example project (Java, C++) that uses the `HatchSubsystem` introduced in the previous section:

Java

```

8 package edu.wpi.first.wpilibj.examples.hatchbottraditional.commands;
9
10 import edu.wpi.first.wpilibj2.command.CommandBase;
11
12 import edu.wpi.first.wpilibj.examples.hatchbottraditional.subsystems.HatchSubsystem;
13
14 /**
15  * A simple command that grabs a hatch with the {@link HatchSubsystem}. Written
16  * explicitly for
17  * pedagogical purposes. Actual code should inline a command this simple with {@link
18  * edu.wpi.first.wpilibj2.command.InstantCommand}.
19  */
20 public class GrabHatch extends CommandBase {
21     // The subsystem the command runs on
22     private final HatchSubsystem m_hatchSubsystem;
23
24     public GrabHatch(HatchSubsystem subsystem) {
25         m_hatchSubsystem = subsystem;
26         addRequirements(m_hatchSubsystem);
27     }
28
29     @Override
30     public void initialize() {
31         m_hatchSubsystem.grabHatch();
32     }
33
34     @Override
35     public boolean isFinished() {
36         return true;
37     }

```

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```

36     }
37 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc2/command/CommandBase.h>
11 #include <frc2/command/CommandHelper.h>
12
13 #include "subsystems/HatchSubsystem.h"
14
15 /**
16  * A simple command that grabs a hatch with the HatchSubsystem. Written
17  * explicitly for pedagogical purposes. Actual code should inline a command
18  * this simple with InstantCommand.
19  *
20  * @see InstantCommand
21  */
22 class GrabHatch : public frc2::CommandHelper<frc2::CommandBase, GrabHatch> {
23 public:
24     explicit GrabHatch(HatchSubsystem* subsystem);
25
26     void Initialize() override;
27
28     bool IsFinished() override;
29
30 private:
31     HatchSubsystem* m_hatch;
32 };

```

## C++ (Source)

```

8  #include "commands/GrabHatch.h"
9
10 GrabHatch::GrabHatch(HatchSubsystem* subsystem) : m_hatch(subsystem) {
11     AddRequirements({subsystem});
12 }
13
14 void GrabHatch::Initialize() { m_hatch->GrabHatch(); }
15
16 bool GrabHatch::IsFinished() { return true; }

```

Notice that the hatch subsystem used by the command is passed into the command through the command's constructor. This is a pattern called [dependency injection](#), and allows users to avoid declaring their subsystems as global variables. This is widely accepted as a best-practice - the reasoning behind this is discussed in a [later section](#).

Notice also that the above command calls the subsystem method once from initialize, and then immediately ends (as `isFinished()` simply returns true). This is typical for commands that toggle the states of subsystems, and in fact the command-based library includes code to make [commands like this](#) even more succinctly.

What about a more complicated case? Below is a drive command, from the same example project:

Java

```

8 package edu.wpi.first.wpilibj.examples.hatchbottraditional.commands;
9
10 import java.util.function.DoubleSupplier;
11
12 import edu.wpi.first.wpilibj2.command.CommandBase;
13
14 import edu.wpi.first.wpilibj.examples.hatchbottraditional.subsystems.DriveSubsystem;
15
16 /**
17  * A command to drive the robot with joystick input (passed in as {@link
18  * ↳DoubleSupplier}s). Written
19  * explicitly for pedagogical purposes - actual code should inline a command this
20  * ↳simple with {@link
21  * edu.wpi.first.wpilibj2.command.RunCommand}.
22  */
23 public class DefaultDrive extends CommandBase {
24     private final DriveSubsystem m_drive;
25     private final DoubleSupplier m_forward;
26     private final DoubleSupplier m_rotation;
27
28     /**
29      * Creates a new DefaultDrive.
30      *
31      * @param subsystem The drive subsystem this command wil run on.
32      * @param forward The control input for driving forwards/backwards
33      * @param rotation The control input for turning
34      */
35     public DefaultDrive(DriveSubsystem subsystem, DoubleSupplier forward,
36     ↳DoubleSupplier rotation) {
37         m_drive = subsystem;
38         m_forward = forward;
39         m_rotation = rotation;
40         addRequirements(m_drive);
41     }
42
43     @Override
44     public void execute() {
45         m_drive.arcadeDrive(m_forward.getAsDouble(), m_rotation.getAsDouble());
46     }
47 }

```

## C++ (Header)

```

8 #pragma once
9
10 #include <frc2/command/CommandBase.h>
11 #include <frc2/command/CommandHelper.h>
12
13 #include "subsystems/DriveSubsystem.h"
14
15 /**
16  * A command to drive the robot with joystick input passed in through lambdas.
17  * Written explicitly for pedagogical purposes - actual code should inline a
18  * command this simple with RunCommand.
19  *
20  * @see RunCommand
21  */

```

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```

22 class DefaultDrive
23 : public frc2::CommandHelper<frc2::CommandBase, DefaultDrive> {
24 public:
25     /**
26      * Creates a new DefaultDrive.
27      *
28      * @param subsystem The drive subsystem this command wil run on.
29      * @param forward The control input for driving forwards/backwards
30      * @param rotation The control input for turning
31      */
32     DefaultDrive(DriveSubsystem* subsystem, std::function<double()> forward,
33                 std::function<double()> rotation);
34
35     void Execute() override;
36
37 private:
38     DriveSubsystem* m_drive;
39     std::function<double()> m_forward;
40     std::function<double()> m_rotation;
41 };

```

C++ (Source)

```

8  #include "commands/DefaultDrive.h"
9
10 DefaultDrive::DefaultDrive(DriveSubsystem* subsystem,
11                             std::function<double()> forward,
12                             std::function<double()> rotation)
13     : m_drive{subsystem}, m_forward{forward}, m_rotation{rotation} {
14     AddRequirements({subsystem});
15 }
16
17 void DefaultDrive::Execute() {
18     m_drive->ArcadeDrive(m_forward(), m_rotation());
19 }

```

Notice that this command does not override `isFinished()`, and thus will never end; this is the norm for commands that are intended to be used as default commands (and, as can be guessed, the library includes tools to make *this kind of command* easier to write, too!).

## 18.6 Command Groups

Individual commands are capable of accomplishing a large variety of robot tasks, but the simple three-state format can quickly become cumbersome when more advanced functionality requiring extended sequences of robot tasks or coordination of multiple robot subsystems is required. In order to accomplish this, users are encouraged to use the powerful command group functionality included in the command-based library.

As the name suggests, command groups are combinations of multiple commands. The act of combining multiple objects (such as commands) into a bigger object is known as **composition**. Command groups *compose* multiple commands into a *composite* command. This allows code to be kept much cleaner and simpler, as the individual *component* commands may be written independently of the code that combines them, greatly reducing the amount of complexity at any given step of the process.

Most importantly, however, command groups *are themselves commands* - they implement the Command interface. This allows command groups to be **recursively composed** - that is, a command group may contain *other command groups* as components.

### 18.6.1 Types of Command Groups

---

**Note:** In the C++ command-based library, command groups *own* their component commands. This means that commands passed to command groups will be either moved or copied depending on whether they are rvalues or lvalues (**rvalue/lvalue explanation**). Due to certain technical concerns, command groups themselves are not copyable, and so recursive composition *must* use move semantics.

---

The command-based library supports four basic types of command groups: `SequentialCommandGroup`, `ParallelCommandGroup`, `ParallelRaceGroup`, and `ParallelDeadlineGroup`. Each of these command groups combines multiple commands into a composite command - however, they do so in different ways:

#### SequentialCommandGroup

A `SequentialCommandGroup` (**Java**, **C++**) runs a list of commands in sequence - the first command will be executed, then the second, then the third, and so on until the list finishes. The sequential group finishes after the last command in the sequence finishes. It is therefore usually important to ensure that each command in the sequence does actually finish (if a given command does not finish, the next command will never start!).

#### ParallelCommandGroup

A `ParallelCommandGroup` (**Java**, **C++**) runs a set of commands concurrently - all commands will execute at the same time. The parallel group will end when all commands have finished.

#### ParallelRaceGroup

A `ParallelRaceGroup` (**Java**, **C++**) is much like a `ParallelCommandGroup`, in that it runs a set of commands concurrently. However, the race group ends as soon as any command in the group ends - all other commands are interrupted at that point.

#### ParallelDeadlineGroup

A `ParallelDeadlineGroup` (**Java**, **C++**) also runs a set of commands concurrently. However, the deadline group ends when a *specific* command (the “deadline”) ends, interrupting all other commands in the group that are still running at that point.

## 18.6.2 Creating Command Groups

Users have several options for creating command groups. One way - similar to the previous implementation of the command-based library - is to subclass one of the command group classes. Consider the following from the Hatch Bot example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.hatchbottraditional.commands;
9
10 import edu.wpi.first.wpilibj2.command.SequentialCommandGroup;
11
12 import edu.wpi.first.wpilibj.examples.hatchbottraditional.Constants.AutoConstants;
13 import edu.wpi.first.wpilibj.examples.hatchbottraditional.subsystems.DriveSubsystem;
14 import edu.wpi.first.wpilibj.examples.hatchbottraditional.subsystems.HatchSubsystem;
15
16 /**
17  * A complex auto command that drives forward, releases a hatch, and then drives
18  * backward.
19  */
20 public class ComplexAuto extends SequentialCommandGroup {
21     /**
22      * Creates a new ComplexAuto.
23      *
24      * @param drive The drive subsystem this command will run on
25      * @param hatch The hatch subsystem this command will run on
26      */
27     public ComplexAuto(DriveSubsystem drive, HatchSubsystem hatch) {
28         addCommands(
29             // Drive forward the specified distance
30             new DriveDistance(AutoConstants.kAutoDriveDistanceInches, AutoConstants.
31                 kAutoDriveSpeed,
32                 drive),
33             // Release the hatch
34             new ReleaseHatch(hatch),
35             // Drive backward the specified distance
36             new DriveDistance(AutoConstants.kAutoBackupDistanceInches, -AutoConstants.
37                 kAutoDriveSpeed,
38                 drive));
39     }
40 }

```

C++ (Header)

```

8 #pragma once
9
10 #include <frc2/command/CommandHelper.h>
11 #include <frc2/command/SequentialCommandGroup.h>
12
13 #include "Constants.h"
14 #include "commands/DriveDistance.h"
15 #include "commands/ReleaseHatch.h"
16
17 /**
18  * A complex auto command that drives forward, releases a hatch, and then drives

```

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```

19  * backward.
20  */
21  class ComplexAuto
22      : public frc2::CommandHelper<frc2::SequentialCommandGroup, ComplexAuto> {
23  public:
24      /**
25       * Creates a new ComplexAuto.
26       *
27       * @param drive The drive subsystem this command will run on
28       * @param hatch The hatch subsystem this command will run on
29       */
30      ComplexAuto(DriveSubsystem* drive, HatchSubsystem* hatch);
31  };

```

C++ (Source)

```

8  #include "commands/ComplexAuto.h"
9
10 using namespace AutoConstants;
11
12 ComplexAuto::ComplexAuto(DriveSubsystem* drive, HatchSubsystem* hatch) {
13     AddCommands(
14         // Drive forward the specified distance
15         DriveDistance(kAutoDriveDistanceInches, kAutoDriveSpeed, drive),
16         // Release the hatch
17         ReleaseHatch(hatch),
18         // Drive backward the specified distance
19         DriveDistance(kAutoBackupDistanceInches, -kAutoDriveSpeed, drive));
20 }

```

The `addCommands()` method adds commands to the group, and is present in all four types of command group.

### 18.6.3 Inline Command Groups

**Note:** Due to the verbosity of Java's new syntax, the Java `CommandGroupBase` object offers a factory method for each of the four command-group types: `sequence`, `parallel`, `race`, and `deadline`.

Command groups can be used without subclassing at all: one can simply pass in the desired commands through the constructor:

Java

```
new SequentialCommandGroup(new FooCommand(), new BarCommand());
```

C++

```
frc2::SequentialCommandGroup{FooCommand(), BarCommand()};
```

This is called an *inline* command definition, and is very handy for circumstances where command groups are not likely to be reused, and writing an entire class for them would be wasteful.



### 18.6.4 Recursive Composition of Command Groups

As mentioned earlier, command groups are *recursively composable* - since command groups are themselves commands, they may be included as components of other command groups. This is an extremely powerful feature of command groups, and allows users to build very complex robot actions from simple pieces. For example, consider the following code:

Java

```
new SequentialCommandGroup(  
    new DriveToGoal(m_drive),  
    new ParallelCommandGroup(  
        new RaiseElevator(m_elevator),  
        new SetWristPosition(m_wrist)),  
    new ScoreTube(m_wrist));
```

C++

```
frc2::SequentialCommandGroup{  
    DriveToGoal(&m_drive),  
    frc2::ParallelCommandGroup{  
        RaiseElevator(&m_elevator),  
        SetWristPosition(&m_wrist)},  
    ScoreTube(&m_wrist)};
```

This creates a sequential command group that *contains* a parallel command group. The resulting control flow looks something like this:

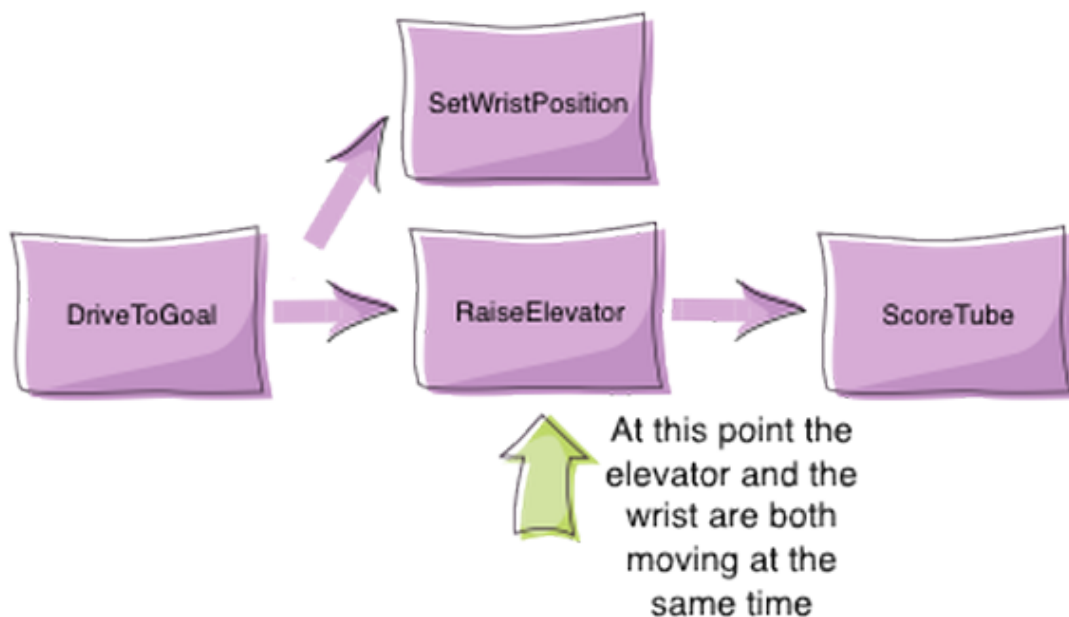


Fig. 2: command group with concurrency

Notice how the recursive composition allows the embedding of a parallel control structure within a sequential one. Notice also that this entire, more-complex structure, could be again embedded in another structure. Composition is an extremely powerful tool, and one that users should be sure to use extensively.

### 18.6.5 Command Groups and Requirements

As command groups are commands, they also must declare their requirements. However, users are not required to specify requirements manually for command groups - requirements are automatically inferred from the commands included. As a rule, *command groups include the union of all of the subsystems required by their component commands*. Thus, the ComplexAuto shown previously will require both the drive subsystem and the hatch subsystem of the robot.

Additionally, requirements are enforced within all three types of parallel groups - a parallel group may *not* contain multiple commands that require the same subsystem.

Some advanced users may find this overly-restrictive - for said users, the library offers a ScheduleCommand class (Java, C++) that can be used to independently “branch off” from command groups to provide finer granularity in requirement management.

### 18.6.6 Restrictions on Command Group Components

---

**Note:** The following is only relevant for the Java command-based library; the C++ library’s ownership model naturally prevents users from making this category of mistake.

---

Since command group components are run through their encapsulating command groups, errors could occur if those same command instances were independently scheduled at the same time as the group - the command would be being run from multiple places at once, and thus could end up with inconsistent internal state, causing unexpected and hard-to-diagnose behavior.

For this reason, command instances that have been added to a command group cannot be independently scheduled or added to a second command group. Attempting to do so will throw an exception and crash the user program.

Advanced users who wish to re-use a command instance and are *certain* that it is safe to do so may bypass this restriction with the clearGroupedCommand() method in the CommandGroupBase class.

## 18.7 The Command Scheduler

The CommandScheduler (Java, C++) is the class responsible for actually running commands. Each iteration (ordinarily once per 20ms), the scheduler polls all registered buttons, schedules commands for execution accordingly, runs the command bodies of all scheduled commands, and ends those commands that have finished or are interrupted.

The CommandScheduler also runs the periodic() method of each registered Subsystem.

### **18.7.1 Using the Command Scheduler**

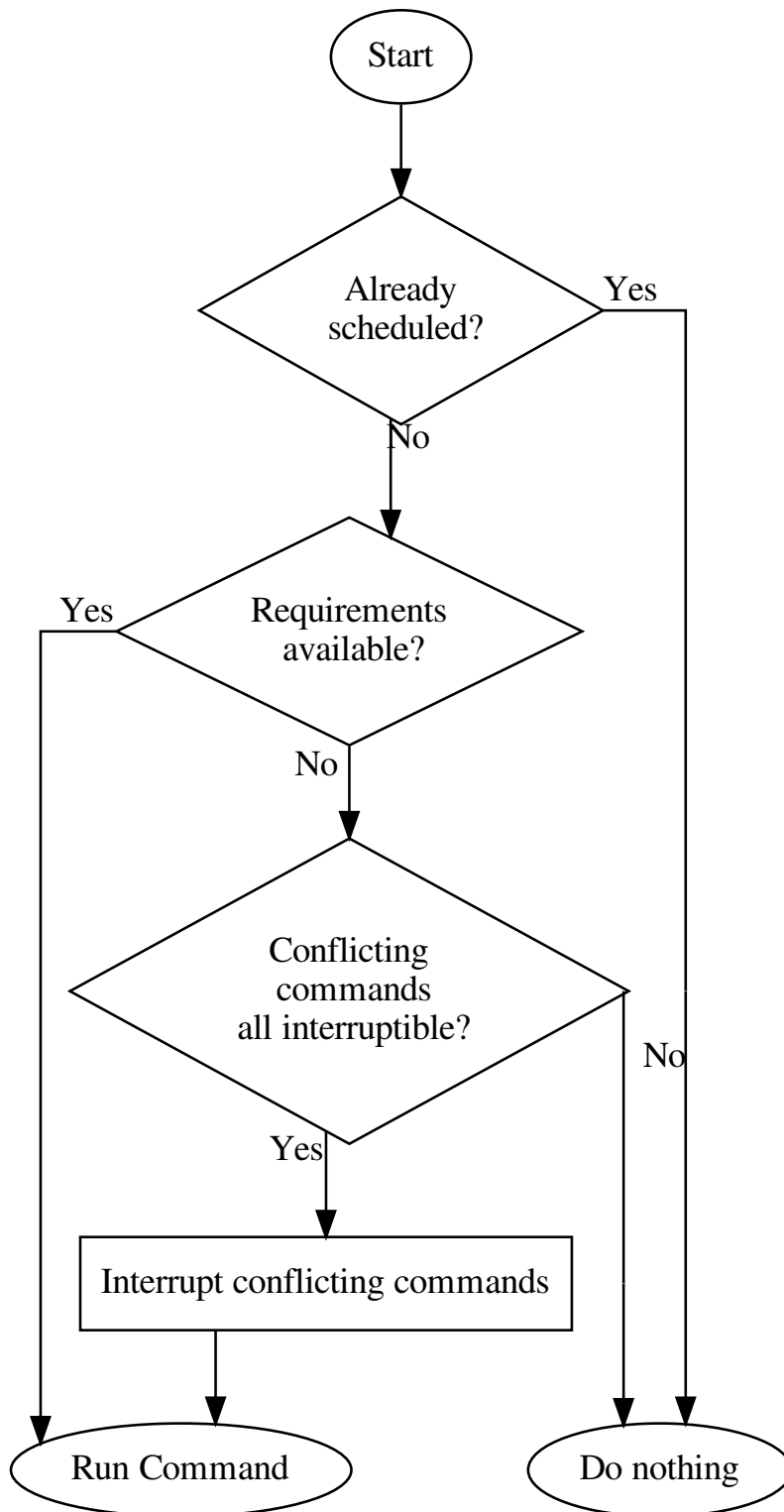
The `CommandScheduler` is a *singleton*, meaning that it is a globally-accessible class with only one instance. Accordingly, in order to access the scheduler, users must call the `CommandScheduler.getInstance()` command.

For the most part, users do not have to call scheduler methods directly - almost all important scheduler methods have convenience wrappers elsewhere (e.g. in the `Command` and `Subsystem` interfaces).

However, there is one exception: users *must* call `CommandScheduler.getInstance().run()` from the `robotPeriodic()` method of their `Robot` class. If this is not done, the scheduler will never run, and the command framework will not work. The provided command-based project template has this call already included.



### 18.7.2 The `schedule()` Method



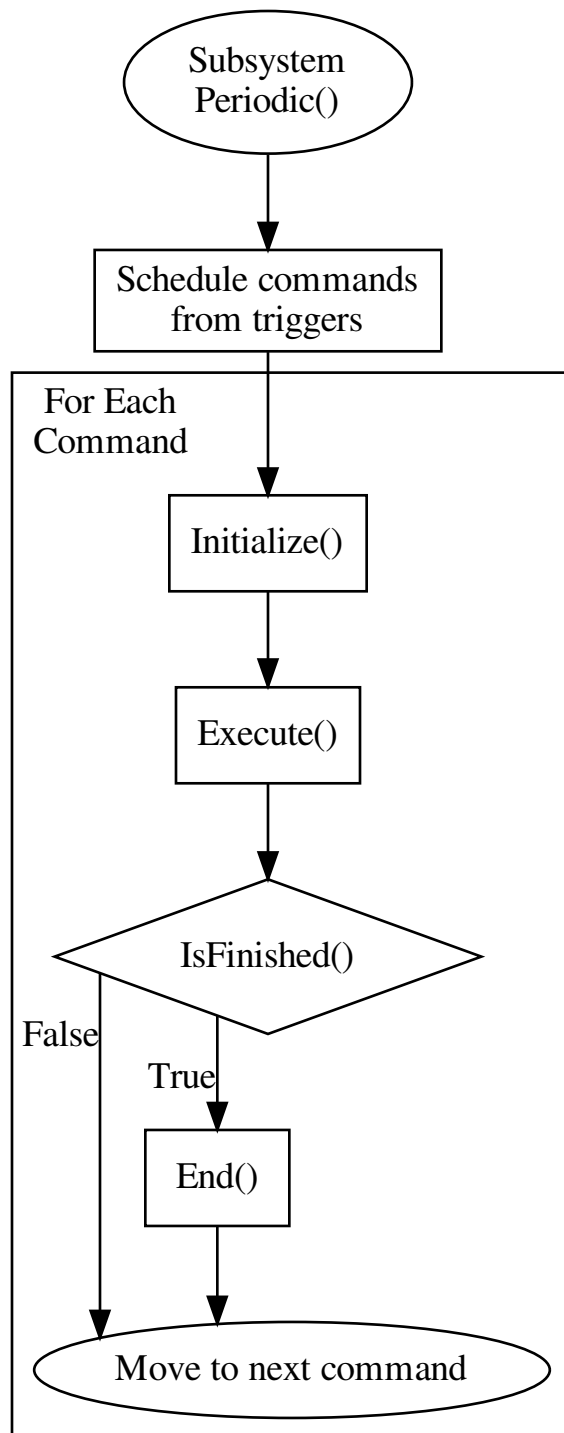
To schedule a command, users call the `schedule()` method (Java, C++). This method takes a command (and, optionally, a specification as to whether that command is interruptible), and attempts to add it to list of currently-running commands, pending whether it is already running or whether its requirements are available. If it is added, its `initialize()` method is called.

### 18.7.3 The Scheduler Run Sequence

---

**Note:** The `initialize()` method of each `Command` is called when the command is scheduled, which is not necessarily when the scheduler runs (unless that command is bound to a button).

---



What does a single iteration of the scheduler's `run()` method (Java, C++) actually do? The

following section walks through the logic of a scheduler iteration.

### Step 1: Run Subsystem Periodic Methods

First, the scheduler runs the `periodic()` method of each registered Subsystem.

### Step 2: Poll Command Scheduling Triggers

---

**Note:** For more information on how trigger bindings work, see [Binding Commands to Triggers](#)

---

Secondly, the scheduler polls the state of all registered triggers to see if any new commands that have been bound to those triggers should be scheduled. If the conditions for scheduling a bound command are met, the command is scheduled and its `Initialize()` method is run.

### Step 3: Run/Finish Scheduled Commands

Thirdly, the scheduler calls the `execute()` method of each currently-scheduled command, and then checks whether the command has finished by calling the `isFinished()` method. If the command has finished, the `end()` method is also called, and the command is de-scheduled and its required subsystems are freed.

Note that this sequence of calls is done in order for each command - thus, one command may have its `end()` method called before another has its `execute()` method called. Commands are handled in the order they were scheduled.

### Step 4: Schedule Default Commands

Finally, any registered Subsystem has its default command scheduled (if it has one). Note that the `initialize()` method of the default command will be called at this time.

## 18.7.4 Disabling the Scheduler

The scheduler can be disabled by calling `CommandScheduler.getInstance().disable()`. When disabled, the scheduler's `schedule()` and `run()` commands will not do anything.

The scheduler may be re-enabled by calling `CommandScheduler.getInstance().enable()`.

## 18.7.5 Command Event Methods

Occasionally, it is desirable to have the scheduler execute a custom action whenever a certain command event (initialization, execution, or ending) occurs. This can be done with the following three methods:



### **onCommandInitialize**

The `onCommandInitialize` method (Java, C++) runs a specified action whenever a command is initialized.

### **onCommandExecute**

The `onCommandExecute` method (Java, C++) runs a specified action whenever a command is executed.

### **onCommandFinish**

The `onCommandFinish` method (Java, C++) runs a specified action whenever a command finishes normally (i.e. the `isFinished()` method returned true).

### **onCommandInterrupt**

The `onCommandInterrupt` method (Java, C++) runs a specified action whenever a command is interrupted (i.e. by being explicitly canceled or by another command that shares one of its requirements).

A typical use-case for these methods is adding markers in an event log whenever a command scheduling event takes place, as demonstrated in the `SchedulerEventLogging` example project (Java, C++):

Java

```
48     m_waitCommand.setName("Wait 5 Seconds Command");
49
50     // Set the scheduler to log Shuffleboard events for command initialize, interrupt,
51     ↪ finish
52     CommandScheduler.getInstance().onCommandInitialize(command -> Shuffleboard.
53     ↪ addEventMarker(
54         "Command initialized", command.getName(), EventImportance.kNormal));
55     CommandScheduler.getInstance().onCommandInterrupt(command -> Shuffleboard.
56     ↪ addEventMarker(
57         "Command interrupted", command.getName(), EventImportance.kNormal));
```

C++ (Source)

```
22     // Set the scheduler to log Shuffleboard events for command initialize,
23     // interrupt, finish
24     frc2::CommandScheduler::GetInstance().OnCommandInitialize(
25         [](const frc2::Command& command) {
26             frc::Shuffleboard::AddEventMarker(
27                 "Command Initialized", command.GetName(),
28                 frc::ShuffleboardEventImportance::kNormal);
29         });
30     frc2::CommandScheduler::GetInstance().OnCommandInterrupt(
31         [](const frc2::Command& command) {
32             frc::Shuffleboard::AddEventMarker(
33                 "Command Interrupted", command.GetName(),
34                 frc::ShuffleboardEventImportance::kNormal);
```

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```

35     });
36     frc2::CommandScheduler::GetInstance().OnCommandFinish(
37         [](const frc2::Command& command) {
38             frc::Shuffleboard::AddEventMarker(
39                 "Command Finished", command.GetName(),
40                 frc::ShuffleboardEventImportance::kNormal);
41         });

```

## 18.8 Binding Commands to Triggers

Apart from autonomous commands, which are scheduled at the start of the autonomous period, and default commands, which are automatically scheduled whenever their subsystem is not currently in-use, the most common way to run a command is by binding it to a triggering event, such as a button being pressed by a human operator. The command-based paradigm makes this extremely easy to do.

As mentioned earlier, command-based is a **declarative** paradigm. Accordingly, binding buttons to commands is done declaratively; the association of a button and a command is “declared” once, during robot initialization. The library then does all the hard work of checking the button state and scheduling (or cancelling) the command as needed, behind-the-scenes. Users only need to worry about designing their desired UI setup - not about implementing it!

Command binding is done through the `Trigger` class (Java, C++) and its various `Button` subclasses (Java, C++).

### 18.8.1 Trigger/Button Bindings

**Note:** The C++ command-based library offers two overloads of each button binding method - one that takes a forwarding reference, and one that takes a raw pointer. The forwarding reference overload transfers ownership (by either moving or copying depending on if the command is an **rvalue** or **lvalue**) to the scheduler, while the raw pointer overload leaves the user responsible for the lifespan of the command object. It is recommended that users preferentially use the forwarding reference overload unless there is a specific need to retain a handle to the command in the calling code.

There are a number of bindings available for the `Trigger` class. All of these bindings will automatically schedule a command when a certain trigger activation event occurs - however, each binding has different specific behavior. `Button` and its subclasses have bindings with identical behaviors, but slightly different names that better-match a button rather than an arbitrary triggering event.

#### whenActive/whenPressed

This binding schedules a command when a trigger changes from inactive to active (or, accordingly, when a button changes is initially pressed). The command will be scheduled on the iteration when the state changes, and will not be scheduled again unless the trigger becomes inactive and then active again (or the button is released and then re-pressed).

**whileActiveContinuous/whileHeld**

This binding schedules a command repeatedly while a trigger is active (or, accordingly, while a button is held), and cancels it when the trigger becomes inactive (or when the button is released). Note that scheduling an already-running command has no effect; but if the command finishes while the trigger is still active, it will be re-scheduled.

**whileActiveOnce/whenHeld**

This binding schedules a command when a trigger changes from inactive to active (or, accordingly, when a button is initially pressed) and cancels it when the trigger becomes inactive again (or the button is released). The command will *not* be re-scheduled if it finishes while the trigger is still active.

**whenInactive/whenReleased**

This binding schedules a command when a trigger changes from active to inactive (or, accordingly, when a button is initially released). The command will be scheduled on the iteration when the state changes, and will not be re-scheduled unless the trigger becomes active and then inactive again (or the button is pressed and then re-released).

**toggleWhenActive/toggleWhenPressed**

This binding toggles a command, scheduling it when a trigger changes from inactive to active (or a button is initially pressed), and cancelling it under the same condition if the command is currently running. Note that while this functionality is supported, toggles are *not* a highly-recommended option for user control, as they require the driver to mentally keep track of the robot state.

**cancelWhenActive/cancelWhenPressed**

This binding cancels a command when a trigger changes from inactive to active (or, accordingly, when a button is initially pressed). the command is canceled on the iteration when the state changes, and will not be canceled again unless the trigger becomes inactive and then active again (or the button is released and re-pressed). Note that cancelling a command that is not currently running has no effect.

## **18.8.2 Binding a command to a joystick button**

The most-common way to trigger a command is to bind a command to a button on a joystick or other HID (human interface device). To do this, users should use the JoystickButton class.

**Creating a JoystickButton**

In order to create a JoystickButton, we first need a Joystick. All types of joysticks (including gamepads) are represented in code by the GenericHID class (Java, C++), or one of its subclasses:

Java

```
Joystick exampleStick = new Joystick(1); // Creates a joystick on port 1
XboxController exampleController = new XboxController(2); // Creates an
↳ XboxController on port 2.
```

C++

```
frc::Joystick exampleStick{1}; // Creates a joystick on port 1
frc::XboxController exampleController{2} // Creates an XboxController on port 2
```

**Note:** When creating a JoystickButton with an XboxController, it is usually a good idea to use the button enum (Java, C++) to get the button number corresponding to a given button.

After the joystick is instantiated, users can then pass it to a JoystickButton object (Java, C++):

**Warning:** There is an issue with using JoystickButtons and POVButtons in C++. Take a look at the [known issues](#) page for more information.

Java

```
JoystickButton exampleButton = new JoystickButton(exampleStick, 1); // Creates a new
↳ JoystickButton object for button 1 on exampleStick
```

C++

```
frc2::JoystickButton exampleButton(&exampleStick, 1); // Creates a new JoystickButton
↳ object for button 1 on exampleStick
```

## Binding a Command to a JoystickButton

**Note:** In the C++ command-based library, button objects *do not need to survive past the call to a binding method*, and so the binding methods may be simply called on a temp.

Putting it all together, it is very simple to bind a button to a JoystickButton:

Java

```
// Binds an ExampleCommand to be scheduled when the trigger of the example joystick
↳ is pressed
exampleButton.whenPressed(new ExampleCommand());
```

C++

```
// Binds an ExampleCommand to be scheduled when the trigger of the example joystick
↳ is pressed
exampleButton.WhenPressed(ExampleCommand());
```

It is useful to note that the command binding methods all return the trigger/button that they were initially called on, and thus can be chained to bind multiple commands to different states of the same button. For example:

Java

```
exampleButton
    // Binds a FooCommand to be scheduled when the 'X' button of the driver gamepad
    ↪is pressed
    .whenPressed(new FooCommand())
    // Binds a BarCommand to be scheduled when that same button is released
    .whenReleased(new BarCommand());
```

C++

```
exampleButton
    // Binds a FooCommand to be scheduled when the 'X' button of the driver gamepad
    ↪is pressed
    .WhenPressed(FooCommand())
    // Binds a BarCommand to be scheduled when that same button is released
    .WhenReleased(BarCommand());
```

Remember that button binding is *declarative*: bindings only need to be declared once, ideally some time during robot initialization. The library handles everything else.

### 18.8.3 Composing Triggers

The Trigger class (including its Button subclasses) can be composed to create composite triggers through the `and()`, `or()`, and `negate()` methods (or, in C++, the `&&`, `||`, and `!` operators). For example:

Java

```
// Binds an ExampleCommand to be scheduled when both the 'X' and 'Y' buttons of the
↪driver gamepad are pressed
new JoystickButton(exampleController, XboxController.Button.kX.value)
    .and(new JoystickButton(exampleController, XboxController.Button.kY.value))
    .whenActive(new ExampleCommand());
```

C++

```
// Binds an ExampleCommand to be scheduled when both the 'X' and 'Y' buttons of the
↪driver gamepad are pressed
(frc2::JoystickButton(&exampleController, frc2::XboxController::Button::kX)
    && JoystickButton(&exampleController, frc2::XboxController::Button::kY))
    .WhenActive(new ExampleCommand());
```

Note that these methods return a Trigger, not a Button, so the Trigger binding method names must be used even when buttons are composed.

### 18.8.4 Creating Your Own Custom Trigger

While binding to HID buttons is by far the most common use case, advanced users may occasionally want to bind commands to arbitrary triggering events. This can be easily done by simply writing your own subclass of trigger or button:

Java

```
public class ExampleTrigger extends Trigger {
    @Override
    public boolean get() {
        // This returns whether the trigger is active
    }
}
```

C++

```
class ExampleTrigger : public frc2::Trigger {
public:
    bool get() override {
        // This returns whether the trigger is active
    }
}
```

Alternatively, this can also be done inline by passing a lambda to the constructor of `trigger` or `button`:

Java

```
// Here it is assumed that "condition" is an object with a method "get" that returns 
↳ whether the trigger should be active
Trigger exampleTrigger = new Trigger(condition::get);
```

C++

```
// Here it is assumed that "condition" is a boolean that determines whether the 
↳ trigger should be active
frc2::Trigger exampleTrigger([&condition] { return condition; });
```

## 18.9 Structuring a Command-Based Robot Project

While users are free to use the command-based libraries however they like (and advanced users are encouraged to do so), new users may want some guidance on how to structure a basic command-based robot project.

A standard template for a command-based robot project is included in the WPILib examples repository (Java, C++). This section will walk users through the structure of this template.

The root package/directory generally will contain four classes:

**Main**, which is the main robot application (Java only). New users *should not* touch this class. **Robot**, which is responsible for the main control flow of the robot code. **RobotContainer**, which holds robot subsystems and commands, and is where most of the declarative robot setup (e.g. button bindings) is performed. **Constants**, which holds globally-accessible constants to be used throughout the robot.

The root directory will also contain two sub-packages/sub-directories: **Subsystems** contains all user-defined subsystem classes. **Commands** contains all user-defined command classes.

## 18.9.1 Robot

As Robot (Java, C++ (Header), C++ (Source)) is responsible for the program's control flow, and command-based is a declarative paradigm designed to minimize the amount of attention the user has to pay to explicit program control flow, the Robot class of a command-based project should be mostly empty. However, there are a few important things that must be included

Java

```

25  /**
26  * This function is run when the robot is first started up and should be used for
↳ any
27  * initialization code.
28  */
29  @Override
30  public void robotInit() {
31      // Instantiate our RobotContainer. This will perform all our button bindings,
↳ and put our
32      // autonomous chooser on the dashboard.
33      m_robotContainer = new RobotContainer();
34  }

```

In Java, an instance of RobotContainer should be constructed during the robotInit() method - this is important, as most of the declarative robot setup will be called from the RobotContainer constructor.

In C++, this is not needed as RobotContainer is a value member and will be constructed during the construction of Robot.

Java

```

36  /**
37  * This function is called every robot packet, no matter the mode. Use this for
↳ items like
38  * diagnostics that you want ran during disabled, autonomous, teleoperated and test.
39  *
40  * <p>This runs after the mode specific periodic functions, but before
41  * LiveWindow and SmartDashboard integrated updating.
42  */
43  @Override
44  public void robotPeriodic() {
45      // Runs the Scheduler. This is responsible for polling buttons, adding newly-
↳ scheduled
46      // commands, running already-scheduled commands, removing finished or interrupted
↳ commands,
47      // and running subsystem periodic() methods. This must be called from the robot
↳ 's periodic
48      // block in order for anything in the Command-based framework to work.
49      CommandScheduler.getInstance().run();
50  }

```

C++ (Source)

```

15  /**
16  * This function is called every robot packet, no matter the mode. Use
17  * this for items like diagnostics that you want to run during disabled,
18  * autonomous, teleoperated and test.

```

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```

19  *
20  * <p> This runs after the mode specific periodic functions, but before
21  * LiveWindow and SmartDashboard integrated updating.
22  */
23  void Robot::RobotPeriodic() { frc2::CommandScheduler::GetInstance().Run(); }

```

The inclusion of the `CommandScheduler.getInstance().run()` call in the `robotPeriodic()` method is essential; without this call, the scheduler will not execute any scheduled commands. Since `TimedRobot` runs with a default main loop frequency of 50Hz, this is the frequency with which periodic command and subsystem methods will be called. It is not recommended for new users to call this method from anywhere else in their code.

Java

```

63  /**
64   * This autonomous runs the autonomous command selected by your {@link
65   * RobotContainer} class.
66   */
67  @Override
68  public void autonomousInit() {
69      m_autonomousCommand = m_robotContainer.getAutonomousCommand();
70
71      // schedule the autonomous command (example)
72      if (m_autonomousCommand != null) {
73          m_autonomousCommand.schedule();
74      }
75  }

```

C++ (Source)

```

34  /**
35   * This autonomous runs the autonomous command selected by your {@link
36   * RobotContainer} class.
37   */
38  void Robot::AutonomousInit() {
39      m_autonomousCommand = m_container.GetAutonomousCommand();
40
41      if (m_autonomousCommand != nullptr) {
42          m_autonomousCommand->Schedule();
43      }
44  }

```

The `autonomousInit()` method schedules an autonomous command returned by the `RobotContainer` instance. The logic for selecting which autonomous command to run can be handled inside of `RobotContainer`.

Java

```

83  @Override
84  public void teleopInit() {
85      // This makes sure that the autonomous stops running when
86      // teleop starts running. If you want the autonomous to
87      // continue until interrupted by another command, remove
88      // this line or comment it out.
89      if (m_autonomousCommand != null) {
90          m_autonomousCommand.cancel();
91      }
92  }

```

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```

91     }
92 }

```

## C++ (Source)

```

48 void Robot::TeleopInit() {
49     // This makes sure that the autonomous stops running when
50     // teleop starts running. If you want the autonomous to
51     // continue until interrupted by another command, remove
52     // this line or comment it out.
53     if (m_autonomousCommand != nullptr) {
54         m_autonomousCommand->Cancel();
55         m_autonomousCommand = nullptr;
56     }
57 }

```

The `teleopInit()` method cancels any still-running autonomous commands. This is generally good practice.

Advanced users are free to add additional code to the various init and periodic methods as they see fit; however, it should be noted that including large amounts of imperative robot code in `Robot.java` is contrary to the declarative design philosophy of the command-based paradigm, and can result in confusingly-structured/disorganized code.

### 18.9.2 RobotContainer

This class ([Java](#), [C++ \(Header\)](#), [C++ \(Source\)](#)) is where most of the setup for your command-based robot will take place. In this class, you will define your robot's subsystems and commands, bind those commands to triggering events (such as buttons), and specify which command you will run in your autonomous routine. There are a few aspects of this class new users may want explanations for:

## Java

```

24 private final ExampleSubsystem m_exampleSubsystem = new ExampleSubsystem();

```

## C++ (Header)

```

28 private:
29     // The robot's subsystems and commands are defined here...
30     ExampleSubsystem m_subsystem;

```

Notice that subsystems are declared as private fields in `RobotContainer`. This is in stark contrast to the previous incarnation of the command-based framework, but is much more-aligned with agreed-upon object-oriented best-practices. If subsystems are declared as global variables, it allows the user to access them from anywhere in the code. While this can make certain things easier (for example, there would be no need to pass subsystems to commands in order for those commands to access them), it makes the control flow of the program much harder to keep track of as it is not immediately obvious which parts of the code can change or be changed by which other parts of the code. This also circumvents the ability of the resource-management system to do its job, as ease-of-access makes it easy for users to accidentally make conflicting calls to subsystem methods outside of the resource-managed commands.

## Java

```
private final ExampleCommand m_autoCommand = new ExampleCommand(m_exampleSubsystem);
```

C++ (Source)

```
RobotContainer::RobotContainer() : m_autonomousCommand(&m_subsystem) {
```

Since subsystems are declared as private members, they must be explicitly passed to commands (a pattern called “dependency injection”) in order for those commands to call methods on them. This is done here with ExampleCommand, which is passed a pointer to an ExampleSubsystem.

Java

```
/**
 * Use this method to define your button->command mappings. Buttons can be created
 * by
 * instantiating a {@link GenericHID} or one of its subclasses ({@link
 * edu.wpi.first.wpilibj.Joystick} or {@link XboxController}), and then passing it
 * to a
 * {@link edu.wpi.first.wpilibj2.command.button.JoystickButton}.
 */
private void configureButtonBindings() {
```

C++ (Source)

```
void RobotContainer::ConfigureButtonBindings() {
    // Configure your button bindings here
}
```

As mentioned before, the RobotContainer() constructor is where most of the declarative setup for the robot should take place, including button bindings, configuring autonomous selectors, etc. If the constructor gets too “busy,” users are encouraged to migrate code into separate subroutines (such as the configureButtonBindings() method included by default) which are called from the constructor.

Java

```
/**
 * Use this to pass the autonomous command to the main {@link Robot} class.
 *
 * @return the command to run in autonomous
 */
public Command getAutonomousCommand() {
    // An ExampleCommand will run in autonomous
    return m_autoCommand;
}
```

C++ (Source)

```
frc2::Command* RobotContainer::GetAutonomousCommand() {
    // An example command will be run in autonomous
    return &m_autonomousCommand;
}
```

Finally, the getAutonomousCommand() method provides a convenient way for users to send their selected autonomous command to the main Robot class (which needs access to it)

schedule it when autonomous starts).

### 18.9.3 Constants

The Constants class ([Java](#), [C++ \(Header\)](#)) (in C++ this is not a class, but simply a header file in which several namespaces are defined) is where globally-accessible robot constants (such as speeds, unit conversion factors, PID gains, and sensor/motor ports) can be stored. It is recommended that users separate these constants into individual inner classes corresponding to subsystems or robot modes, to keep variable names shorter.

In Java, all constants should be declared `public static final` so that they are globally accessible and cannot be changed. In C++, all constants should be `constexpr`.

For more illustrative examples of what a constants class should look like in practice, see those of the various command-based example projects:

- [FrisbeeBot \(Java, C++\)](#)
- [GyroDriveCommands \(Java, C++\)](#)
- [Hatchbot \(Java, C++\)](#)

In Java, it is recommended that the constants be used from other classes by statically importing the necessary inner class. An `import static` statement imports the static namespace of a class into the class in which you are working, so that any `static` constants can be referenced directly as if they had been defined in that class. In C++, the same effect can be attained with `using namespace`:

Java

```
import static edu.wpi.first.wpilibj.templates.commandbased.Constants.OIConstants.*;
```

C++

```
using namespace OIConstants;
```

### 18.9.4 Subsystems

User-defined subsystems should go in this package/directory.

### 18.9.5 Commands

User-defined commands should go in this package/directory.

## 18.10 Convenience Features

While the previously-described methodologies will work fine for writing command-based robot code, the command-based libraries contain several convenience features for more-advanced users that can greatly reduce the verbosity/complexity of command-based code. It is highly recommended that users familiarize themselves with these features to maximize the value they get out of the command-based libraries.

### 18.10.1 Inline Command Definitions

While users are able to create commands by explicitly writing command classes (either by subclassing `CommandBase` or implementing `Command`), for many commands (such as those that simply call a single subsystem method) this involves a lot of wasteful boilerplate code. To help alleviate this, many of the prewritten commands included in the command-based library may be *inlined* - that is, the command body can be defined in a single line of code at command construction.

#### Passing Subroutines As Parameters

In order to inline a command definition, users require some way to specify what code the commands will run as constructor parameters. Fortunately, both Java and C++ offer users the ability to pass subroutines as parameters.

#### Method References (Java)

In Java, a reference to a subroutine that can be passed as a parameter is called a method reference. The general syntax for a method reference is `object::method`. Note that no method parameters are included, since the method *itself* is the parameter. The method is not being called - it is being passed to another piece of code (in this case, a command) so that *that* code can call it when needed. For further information on method references, see [the official Oracle documentation](#).

#### Lambda Expressions (Java)

While method references work well for passing a subroutine that has already been written, often it is inconvenient/wasteful to write a subroutine solely for the purpose of sending as a method reference, if that subroutine will never be used elsewhere. To avoid this, Java also supports a feature called “lambda expressions.” A lambda expression is an inline method definition - it allows a subroutine to be defined *inside of a parameter list*. For specifics on how to write Java lambda expressions, see [this tutorial](#).

#### Lambda Expressions (C++)

C++ lacks a close equivalent to Java method references - pointers to member functions are generally not directly useable as parameters due to the presence of the implicit `this` parameter. However, C++ does offer lambda expressions - in addition, the lambda expressions offered by C++ are in many ways more powerful than those in Java. For specifics on how to write C++ lambda expressions, see [cppreference](#).

#### Inlined Command Example

So, what does an inlined command definition look like in practice?

The `InstantCommand` class provides an example of a type of command that benefits greatly from inlining. Consider the following from the `HatchBotInlined` example project ([Java](#), [C++](#)):

Java

```

99     new JoystickButton(m_driverController, Button.kB.value)
100     .whenPressed(new InstantCommand(m_hatchSubsystem::releaseHatch, m_
↪ hatchSubsystem));
101     // While holding the shoulder button, drive at half speed
102     new JoystickButton(m_driverController, Button.kBumperRight.value)
103     .whenPressed(() -> m_robotDrive.setMaxOutput(0.5))
104     .whenReleased(() -> m_robotDrive.setMaxOutput(1));

```

## C++ (Header)

```

63     frc2::InstantCommand m_grabHatch{[this] { m_hatch.GrabHatch(); }, {&m_hatch}};
64     frc2::InstantCommand m_releaseHatch{[this] { m_hatch.ReleaseHatch(); },
65                                         {&m_hatch}};

```

## C++ (Source)

```

39     // Grab the hatch when the 'A' button is pressed.
40     frc2::JoystickButton(&m_driverController, 1).WhenPressed(&m_grabHatch);
41     // Release the hatch when the 'B' button is pressed.
42     frc2::JoystickButton(&m_driverController, 2).WhenPressed(&m_releaseHatch);

```

Instead of wastefully writing separate GrabHatch and ReleaseHatch commands which call only one method before ending, both can be accomplished with a simple inline definition by passing appropriate subsystem method.

## 18.10.2 Included Command Types

The command-based library includes a variety of pre-written commands for commonly-encountered use cases. Many of these commands are intended to be used “out-of-the-box” via *inlining*, however they may be subclassed, as well. A list of the included pre-made commands can be found below, along with brief examples of each - for more rigorous documentation, see the API docs (Java, C++).

### ConditionalCommand

The ConditionalCommand class (Java, C++) runs one of two commands when executed, depending on a user-specified true-or-false condition:

## Java

```

// Runs either commandOnTrue or commandOnFalse depending on the value of m_
↪ limitSwitch.get()
new ConditionalCommand(commandOnTrue, commandOnFalse, m_limitSwitch::get)

```

## C++

```

// Runs either commandOnTrue or commandOnFalse depending on the value of m_
↪ limitSwitch.get()
frc2::ConditionalCommand(commandOnTrue, commandOnFalse, [&m_limitSwitch] { return m_
↪ limitSwitch.Get(); })

```

## SelectCommand

**Note:** While the Java version of SelectCommand simply uses an Object as a key, the C++ version is templated on the key type.

**Note:** An alternate version of SelectCommand simply takes a method that supplies the command to be run - this can be very succinct, but makes inferring the command's requirements impossible, and so leaves the user responsible for manually adding the requirements to the SelectCommand.

The SelectCommand class (Java, C++) is a generalization of the ConditionalCommand class that runs one of a selection of commands based on the value of a user-specified selector. The following example code is taken from the SelectCommand example project (Java, C++):

Java

```

25 // The enum used as keys for selecting the command to run.
26 private enum CommandSelector {
27     ONE, TWO, THREE
28 }
29
30 // An example selector method for the selectcommand. Returns the selector that
31 // will select
32 // which command to run. Can base this choice on logical conditions evaluated at
33 // runtime.
34 private CommandSelector select() {
35     return CommandSelector.ONE;
36 }
37
38 // An example selectcommand. Will select from the three commands based on the
39 // value returned
40 // by the selector method at runtime. Note that selectcommand works on Object(),
41 // so the
42 // selector does not have to be an enum; it could be any desired type (string,
43 // integer,
44 // boolean, double...)
45 private final Command m_exampleSelectCommand =
46     new SelectCommand(
47         // Maps selector values to commands
48         Map.ofEntries(
49             Map.entry(CommandSelector.ONE, new PrintCommand("Command one was
50 // selected!")),
51             Map.entry(CommandSelector.TWO, new PrintCommand("Command two was
52 // selected!")),
53             Map.entry(CommandSelector.THREE, new PrintCommand("Command three was
54 // selected!"))
55         ),
56         this::select
57     );

```

C++ (Header)

```

28 // The enum used as keys for selecting the command to run.
29 enum CommandSelector { ONE, TWO, THREE };

```

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```

30
31 // An example selector method for the selectcommand. Returns the selector
32 // that will select which command to run. Can base this choice on logical
33 // conditions evaluated at runtime.
34 CommandSelector Select() { return ONE; }
35
36 // The robot's subsystems and commands are defined here...
37
38 // An example selectcommand. Will select from the three commands based on the
39 // value returned by the selector method at runtime. Note that selectcommand
40 // takes a generic type, so the selector does not have to be an enum; it could
41 // be any desired type (string, integer, boolean, double...)
42 frc2::SelectCommand<CommandSelector> m_exampleSelectCommand{
43     [this] { return Select(); },
44     // Maps selector values to commands
45     std::pair{ONE, frc2::PrintCommand{"Command one was selected!"}},
46     std::pair{TWO, frc2::PrintCommand{"Command two was selected!"}},
47     std::pair{THREE, frc2::PrintCommand{"Command three was selected!"}}};

```

## InstantCommand

The InstantCommand class (Java, C++) executes a single action on initialization, and then ends immediately:

Java

```

// Actuates the hatch subsystem to grab the hatch
new InstantCommand(m_hatchSubsystem::grabHatch, m_hatchSubsystem)

```

C++

```

// Actuates the hatch subsystem to grab the hatch
frc2::InstantCommand([&m_hatchSubsystem] { m_hatchSubsystem.GrabHatch(); }, {&m_
    ↪ hatchSubsystem})

```

## RunCommand

The RunCommand class (Java, C++) runs a specified method repeatedly in its execute() block. It does not have end conditions by default; users can either subclass it, or *decorate* it to add them.

Java

```

// A split-stick arcade command, with forward/backward controlled by the left
// hand, and turning controlled by the right.
new RunCommand(() -> m_robotDrive.arcadeDrive(
    driverController.getY(GenericHID.Hand.kLeft),
    driverController.getX(GenericHID.Hand.kRight)),
    m_robotDrive)

```

C++

```
// A split-stick arcade command, with forward/backward controlled by the left
// hand, and turning controlled by the right.
frc2::RunCommand(
    [this] {
        m_drive.ArcadeDrive(
            m_driverController.GetY(frc::GenericHID::kLeftHand),
            m_driverController.GetX(frc::GenericHID::kRightHand));
    },
    {&m_drive}))
```

## StartEndCommand

The StartEndCommand class (Java, C++) executes an action when starting, and a second one when ending. It does not have end conditions by default; users can either subclass it, or *decorate* an inlined command to add them.

Java

```
new StartEndCommand(
    // Start driving forward at the start of the command
    () -> m_robotDrive.arcadeDrive(kAutoDriveSpeed, 0),
    // Stop driving at the end of the command
    () -> m_robotDrive.arcadeDrive(0, 0),
    // Requires the drive subsystem
    m_robotDrive
)
```

C++

```
frc2::StartEndCommand(
    // Start driving forward at the start of the command
    [this] { m_drive.ArcadeDrive(ac::kAutoDriveSpeed, 0); },
    // Stop driving at the end of the command
    [this] { m_drive.ArcadeDrive(0, 0); },
    // Requires the drive subsystem
    {&m_drive}
)
```

## FunctionalCommand

The FunctionalCommand class (Java, C++) allows all four Command methods to be passed in as method references or lambdas:

Java

```
new FunctionalCommand(
    // Reset encoders on command start
    m_robotDrive::resetEncoders,
    // Start driving forward at the start of the command
    () -> m_robotDrive.arcadeDrive(kAutoDriveSpeed, 0),
    // Stop driving at the end of the command
    () -> m_robotDrive.arcadeDrive(0, 0),
    // End the command when the robot's driven distance exceeds the desired value
    () -> m_robotDrive.getAverageEncoderDistance() >= kAutoDriveDistanceInches,
```

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```
// Require the drive subsystem
m_robotDrive
)
```

C++

```
frc2::FunctionalCommand(
// Reset encoders on command start
[this] { m_drive.ResetEncoders(); },
// Start driving forward at the start of the command
[this] { m_drive.ArcadeDrive(ac::kAutoDriveSpeed, 0); },
// Stop driving at the end of the command
[this] { m_drive.ArcadeDrive(0, 0); },
// End the command when the robot's driven distance exceeds the desired value
[this] { return m_drive.GetAverageEncoderDistance() >= kAutoDriveDistanceInches; },
// Requires the drive subsystem
{&m_drive}
)
```

## PrintCommand

The PrintCommand class (Java, C++) prints a given string.

Java

```
new PrintCommand("This message will be printed!")
```

C++

```
frc2::PrintCommand("This message will be printed!")
```

## ScheduleCommand

The ScheduleCommand class (Java, C++) schedules a specified command, and ends instantly:

Java

```
// Schedules commandToSchedule when run
new ScheduleCommand(commandToSchedule)
```

C++

```
// Schedules commandToSchedule when run
frc2::ScheduleCommand(&commandToSchedule)
```

This is often useful for “forking off” from command groups: by default, commands in command groups are run *through* the command group, and are never themselves seen by the scheduler. Accordingly, their requirements are added to the group’s requirements. While this is usually fine, sometimes it is undesirable for the entire command group to gain the requirements of a single command - a good solution is to “fork off” from the command group and schedule that command separately.

## ProxyScheduleCommand

The ProxyScheduleCommand class (Java, C++) schedules a specified command, and does not end until that command ends:

Java

```
// Schedules commandToSchedule when run, does not end until commandToSchedule is no
↳ longer scheduled
new ProxyScheduleCommand(commandToSchedule)
```

C++

```
// Schedules commandToSchedule when run, does not end until commandToSchedule is no
↳ longer scheduled
frc2::ProxyScheduleCommand(&commandToSchedule)
```

This is often useful for “forking off” from command groups: by default, commands in command groups are run *through* the command group, and are never themselves seen by the scheduler. Accordingly, their requirements are added to the group’s requirements. While this is usually fine, sometimes it is undesirable for the entire command group to gain the requirements of a single command - a good solution is to “fork off” from the command group and schedule the command separately.

## WaitCommand

The WaitCommand class (Java, C++) does nothing, and ends after a specified period of time elapses after its initial scheduling:

Java

```
// Ends 5 seconds after being scheduled
new WaitCommand(5)
```

C++

```
// Ends 5 seconds after being scheduled
frc2::WaitCommand(5.0_s)
```

This is often useful as a component of a command group.

## WaitUntilCommand

**Warning:** The match timer used by WaitUntilCommand does *not* provide an official match time! While it is fairly accurate, use of this timer can *not* guarantee the legality of your robot’s actions.

The WaitUntilCommand class (Java, C++) does nothing, and ends once a specified condition becomes true, or until a specified match time passes.

Java

```
// Ends after the 60-second mark of the current match
new WaitUntilCommand(60)

// Ends after m_limitSwitch.get() returns true
new WaitUntilCommand(m_limitSwitch::get)
```

C++

```
// Ends after the 60-second mark of the current match
frc2::WaitUntilCommand(60.0_s)

// Ends after m_limitSwitch.Get() returns true
frc2::WaitUntilCommand([&m_limitSwitch] { return m_limitSwitch.Get(); })
```

### PerpetualCommand

The PerpetualCommand class (Java, C++) runs a given command with its end condition removed, so that it runs forever (unless externally interrupted):

Java

```
// Will run commandToRunForever perpetually, even if its isFinished() method returns_
↳true
new PerpetualCommand(commandToRunForever)
```

C++

```
// Will run commandToRunForever perpetually, even if its isFinished() method returns_
↳true
frc2::PerpetualCommand(commandToRunForever)
```

### 18.10.3 Command Decorator Methods

The Command interface contains a number of defaulted “decorator” methods which can be used to add additional functionality to existing commands. A “decorator” method is a method that takes an object (in this case, a command) and returns an object of the same type (i.e. a command) with some additional functionality added to it. A list of the included decorator methods with brief examples is included below - for rigorous documentation, see the API docs (Java, C++).

#### withTimeout

The withTimeout() decorator (Java, C++) adds a timeout to a command. The decorated command will be interrupted if the timeout expires:

Java

```
// Will time out 5 seconds after being scheduled, and be interrupted
button.whenPressed(command.withTimeout(5));
```

C++

```
// Will time out 5 seconds after being scheduled, and be interrupted
button.WhenPressed(command.WithTimeout(5.0_s));
```

### withInterrupt

The `withInterrupt()` (Java, C++) decorator adds a condition on which the command will be interrupted:

Java

```
// Will be interrupted if m_limitSwitch.get() returns true
button.whenPressed(command.withInterrupt(m_limitSwitch::get));
```

C++

```
// Will be interrupted if m_limitSwitch.get() returns true
button.WhenPressed(command.WithInterrupt([&m_limitSwitch] { return m_limitSwitch.
    ↪Get(); }));
```

### whenFinished

The `whenFinished()` decorator (Java, C++) adds a method to be executed after the command ends:

Java

```
// Will print "hello" after ending
button.whenPressed(command.whenFinished(() -> System.out.println("hello")));
```

C++

```
// Will print "hello" after ending
button.WhenPressed(command.WhenFinished([] { std::cout << "hello"; }));
```

### beforeStarting

The `beforeStarting()` decorator (Java, C++) adds a method to be executed before the command starts:

Java

```
// Will print "hello" before starting
button.whenPressed(command.beforeStarting(() -> System.out.println("hello")));
```

C++

```
// Will print "hello" before starting
button.WhenPressed(command.BeforeStarting([] { std::cout << "hello"; }));
```

### andThen (Java only)

**Note:** This decorator is not supported in C++ due to technical constraints - users should simply construct a sequential command group the ordinary way instead.

---

The `andThen()` decorator returns a sequential command group containing the command, followed by the list of commands passed as arguments:

```
// Will be the sequence fooCommand -> barCommand -> bazCommand
button.whenPressed(fooCommand.andThen(barCommand, bazCommand));
```

### alongWith (Java only)

**Note:** This decorator is not supported in C++ due to technical constraints - users should simply construct a parallel command group the ordinary way instead.

---

The `alongWith()` decorator returns a parallel command group containing the command, along with all the other commands passed in as arguments:

```
// Will be a parallel command group containing fooCommand, barCommand, and bazCommand
button.whenPressed(fooCommand.alongWith(barCommand, bazCommand));
```

### raceWith (Java only)

**Note:** This decorator is not supported in C++ due to technical constraints - users should simply construct a parallel race group the ordinary way instead.

---

The `raceWith()` decorator returns a parallel command race containing the command, along with all the other commands passed in as arguments:

```
// Will be a parallel command race containing fooCommand, barCommand, and bazCommand
button.whenPressed(fooCommand.raceWith(barCommand, bazCommand));
```

### deadlineWith (Java only)

**Note:** This decorator is not supported in C++ due to technical constraints - users should simply construct a parallel deadline group the ordinary way instead.

---

The `deadlineWith()` decorator returns a parallel deadline group containing the command, along with all the other commands passed in as arguments:

```
// Will be a parallel deadline group containing fooCommand, barCommand, and
↳ bazCommand; fooCommand is the deadline
button.whenPressed(fooCommand.deadlineWith(barCommand, bazCommand));
```

## perpetually

The `perpetually()` decorator (Java, C++) removes the end condition of a command, so that it runs forever.

Java

```
// Will run forever unless externally interrupted, regardless of command.isFinished()
button.whenPressed(command.perpetually());
```

C++

```
// Will run forever unless externally interrupted, regardless of command.isFinished()
button.WhenPressed(command.Perpetually());
```

## Composing Decorators

Remember that decorators, like all command groups, can be composed! This allows very powerful and concise inline expressions:

```
// Will run fooCommand, and then a race between barCommand and bazCommand
button.whenPressed( fooCommand.andThen( barCommand.raceWith( bazCommand) ) );
```

### 18.10.4 Static Factory Methods for Command Groups (Java only)

**Note:** These factory methods are not included in the C++ command library, as the reduction in verbosity would be minimal - C++ commands should be stack-allocated, removing the need for the new keyword.

If users do not wish to use the `andThen`, `alongWith`, `raceWith`, and `deadlineWith` decorators for declaring command groups, but still wish to reduce verbosity compared to calling the constructors, the `CommandGroupBase` class contains four static factory methods for declaring command groups: `sequence()`, `parallel()`, `race()`, and `deadline()`. When used from within a command group subclass or in combination with `import static`, these become extremely concise and greatly aid in command composition:

```
public class ExampleSequence extends SequentialCommandGroup {

    // Will run a FooCommand, and then a race between a BarCommand and a BazCommand
    public ExampleSequence() {
        addCommands(
            new FooCommand(),
            race(
                new BarCommand(),
                new BazCommand()
            )
        );
    }
}
```

## 18.11 PID Control through PIDSubsystems and PIDCommands

---

**Note:** For a description of the WPILib PID control features used by these command-based wrappers, see [PID Control in WPILib](#).

---

---

**Note:** Unlike the earlier version of `PIDController`, the 2020 `PIDController` class runs *synchronously*, and is not handled in its own thread. Accordingly, changing its period parameter will *not* change the actual frequency at which it runs in any of these wrapper classes. Users should never modify the period parameter unless they are certain of what they are doing.

---

One of the most common control algorithms used in FRC is the [PID controller](#). WPILib offers its own [PIDController](#) class to help teams implement this functionality on their robots. To further help teams integrate PID control into a command-based robot project, the command-based library includes two convenience wrappers for the `PIDController` class: `PIDSubsystem`, which integrates the PID controller into a subsystem, and `PIDCommand`, which integrates the PID controller into a command.

### 18.11.1 PIDSubsystems

The `PIDSubsystem` class (Java, C++) allows users to conveniently create a subsystem with a built-in `PIDController`. In order to use the `PIDSubsystem` class, users must create a subclass of it.

#### Creating a PIDSubsystem

When subclassing `PIDSubsystem`, users must override two abstract methods to provide functionality that the class will use in its ordinary operation:

##### `getMeasurement()`

Java

```
protected abstract double getMeasurement();
```

C++

```
virtual double GetMeasurement() = 0;
```

The `getMeasurement` method returns the current measurement of the process variable. The `PIDSubsystem` will automatically call this method from its `periodic()` block, and pass its value to the control loop.

Users should override this method to return whatever sensor reading they wish to use as their process variable measurement.

## useOutput()

Java

```
protected abstract void useOutput(double output, double setpoint);
```

C++

```
virtual void UseOutput(double output, double setpoint) = 0;
```

The `useOutput()` method consumes the output of the PID controller, and the current setpoint (which is often useful for computing a feedforward). The `PIDSubsystem` will automatically call this method from its `periodic()` block, and pass it the computed output of the control loop.

Users should override this method to pass the final computed control output to their subsystem's motors.

## Passing In the Controller

Users must also pass in a `PIDController` to the `PIDSubsystem` base class through the superclass constructor call of their subclass. This serves to specify the PID gains, as well as the period (if the user is using a non-standard main robot loop period).

Additional modifications (e.g. enabling continuous input) can be made to the controller in the constructor body by calling `getController()`.

## Using a PIDSubsystem

Once an instance of a `PIDSubsystem` subclass has been created, it can be used by commands through the following methods:

### setSetpoint()

The `setSetpoint()` method can be used to set the setpoint of the `PIDSubsystem`. The subsystem will automatically track to the setpoint using the defined output:

Java

```
// The subsystem will track to a setpoint of 5.
examplePIDSubsystem.setSetpoint(5);
```

C++

```
// The subsystem will track to a setpoint of 5.
examplePIDSubsystem.SetSetpoint(5);
```

### enable() and disable()

The `enable()` and `disable()` methods enable and disable the PID control of the `PIDSubsystem`. When the subsystem is enabled, it will automatically run the control loop and track the setpoint. When it is disabled, no control is performed.



Additionally, the `enable()` method resets the internal `PIDController`, and the `disable()` method calls the user-defined `useOutput()` method with both output and setpoint set to 0.

## Full PIDSubsystem Example

What does a `PIDSubsystem` look like when used in practice? The following examples are taken from the FrisbeeBot example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.frisbeebot.subsystems;
9
10 import edu.wpi.first.wpilibj.Encoder;
11 import edu.wpi.first.wpilibj.PWMVictorSPX;
12 import edu.wpi.first.wpilibj.controller.PIDController;
13 import edu.wpi.first.wpilibj.controller.SimpleMotorFeedforward;
14 import edu.wpi.first.wpilibj2.command.PIDSubsystem;
15
16 import edu.wpi.first.wpilibj.examples.frisbeebot.Constants.ShooterConstants;
17
18 public class ShooterSubsystem extends PIDSubsystem {
19     private final PWMVictorSPX m_shooterMotor = new PWMVictorSPX(ShooterConstants.
20 ↪ kShooterMotorPort);
21     private final PWMVictorSPX m_feederMotor = new PWMVictorSPX(ShooterConstants.
22 ↪ kFeederMotorPort);
23     private final Encoder m_shooterEncoder =
24         new Encoder(ShooterConstants.kEncoderPorts[0], ShooterConstants.
25 ↪ kEncoderPorts[1],
26             ShooterConstants.kEncoderReversed);
27     private final SimpleMotorFeedforward m_shooterFeedforward =
28         new SimpleMotorFeedforward(ShooterConstants.kSVolts,
29             ShooterConstants.kVVoltSecondsPerRotation);
30
31     /**
32      * The shooter subsystem for the robot.
33      */
34     public ShooterSubsystem() {
35         super(new PIDController(ShooterConstants.kP, ShooterConstants.kI,
36 ↪ ShooterConstants.kD));
37         getController().setTolerance(ShooterConstants.kShooterToleranceRPS);
38         m_shooterEncoder.setDistancePerPulse(ShooterConstants.kEncoderDistancePerPulse);
39         setSetpoint(ShooterConstants.kShooterTargetRPS);
40     }
41
42     @Override
43     public void useOutput(double output, double setpoint) {
44         m_shooterMotor.setVoltage(output + m_shooterFeedforward.calculate(setpoint));
45     }
46
47     @Override
48     public double getMeasurement() {
49         return m_shooterEncoder.getRate();
50     }
51
52     public boolean atSetpoint() {
53         return m_controller.atSetpoint();
54     }
55 }

```

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```

51
52 public void runFeeder() {
53     m_feederMotor.set(ShooterConstants.kFeederSpeed);
54 }
55
56 public void stopFeeder() {
57     m_feederMotor.set(0);
58 }
59 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc/Encoder.h>
11 #include <frc/PWMVictorSPX.h>
12 #include <frc/controller/SimpleMotorFeedforward.h>
13 #include <frc2/command/PIDSubsystem.h>
14 #include <units/units.h>
15
16 class ShooterSubsystem : public frc2::PIDSubsystem {
17 public:
18     ShooterSubsystem();
19
20     void UseOutput(double output, double setpoint) override;
21
22     double GetMeasurement() override;
23
24     bool AtSetpoint();
25
26     void RunFeeder();
27
28     void StopFeeder();
29
30 private:
31     frc::PWMVictorSPX m_shooterMotor;
32     frc::PWMVictorSPX m_feederMotor;
33     frc::Encoder m_shooterEncoder;
34     frc::SimpleMotorFeedforward<units::turns> m_shooterFeedforward;
35 };

```

## C++ (Source)

```

8  #include "subsystems/ShooterSubsystem.h"
9
10 #include <frc/controller/PIDController.h>
11
12 #include "Constants.h"
13
14 using namespace ShooterConstants;
15
16 ShooterSubsystem::ShooterSubsystem()
17     : PIDSubsystem(frc2::PIDController(kP, kI, kD)),
18       m_shooterMotor(kShooterMotorPort),
19       m_feederMotor(kFeederMotorPort),
20       m_shooterEncoder(kEncoderPorts[0], kEncoderPorts[1]),

```

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```

21     m_shooterFeedforward(kS, kV) {
22     m_controller.SetTolerance(kShooterToleranceRPS.to<double>());
23     m_shooterEncoder.SetDistancePerPulse(kEncoderDistancePerPulse);
24     SetSetpoint(kShooterTargetRPS.to<double>());
25 }
26
27 void ShooterSubsystem::UseOutput(double output, double setpoint) {
28     m_shooterMotor.SetVoltage(units::volt_t(output) +
29                               m_shooterFeedforward.Calculate(kShooterTargetRPS));
30 }
31
32 bool ShooterSubsystem::AtSetpoint() { return m_controller.AtSetpoint(); }
33
34 double ShooterSubsystem::GetMeasurement() { return m_shooterEncoder.GetRate(); }
35
36 void ShooterSubsystem::RunFeeder() { m_feederMotor.Set(kFeederSpeed); }
37
38 void ShooterSubsystem::StopFeeder() { m_feederMotor.Set(0); }

```

Using a PIDSubsystem with commands can be very simple:

Java

```

85 // Spin up the shooter when the 'A' button is pressed
86 new JoystickButton(m_driverController, Button.kA.value)
87     .whenPressed(new InstantCommand(m_shooter::enable, m_shooter));
88
89 // Turn off the shooter when the 'B' button is pressed
90 new JoystickButton(m_driverController, Button.kB.value)
91     .whenPressed(new InstantCommand(m_shooter::disable, m_shooter));

```

C++ (Header)

```

73 frc2::InstantCommand m_spinUpShooter{[this] { m_shooter.Enable(); },
74                                       {&m_shooter}};
75
76 frc2::InstantCommand m_stopShooter{[this] { m_shooter.Disable(); },
77                                     {&m_shooter}};

```

C++ (Source)

```

32 // Spin up the shooter when the 'A' button is pressed
33 frc2::JoystickButton(&m_driverController, 1).WhenPressed(&m_spinUpShooter);
34
35 // Turn off the shooter when the 'B' button is pressed
36 frc2::JoystickButton(&m_driverController, 2).WhenPressed(&m_stopShooter);

```

### 18.11.2 PIDCommand

The PIDCommand class allows users to easily create commands with a built-in PIDController. As with PIDSubsystem, users can create a PIDCommand by subclassing the PIDCommand class. However, as with many of the other command classes in the command-based library, users may want to save code by defining a PIDCommand *inline*.

## Creating a PIDCommand

A `PIDCommand` can be created two ways - by subclassing the `PIDCommand` class, or by defining the command *inline*. Both methods ultimately extremely similar, and ultimately the choice of which to use comes down to where the user desires that the relevant code be located.

In either case, a `PIDCommand` is created by passing the necessary parameters to its constructor (if defining a subclass, this can be done with a *super()* call):

Java

```

29  /**
30   * Creates a new PIDCommand, which controls the given output with a PIDController.
31   *
32   * @param controller      the controller that controls the output.
33   * @param measurementSource the measurement of the process variable
34   * @param setpointSource   the controller's setpoint
35   * @param useOutput        the controller's output
36   * @param requirements     the subsystems required by this command
37   */
38  public PIDCommand(PIDController controller, DoubleSupplier measurementSource,
39                    DoubleSupplier setpointSource, DoubleConsumer useOutput,
40                    Subsystem... requirements) {
41      requireNonNullParam(controller, "controller", "SynchronousPIDCommand");
42      requireNonNullParam(measurementSource, "measurementSource", "SynchronousPIDCommand
43  →");
44      requireNonNullParam(setpointSource, "setpointSource", "SynchronousPIDCommand");
45      requireNonNullParam(useOutput, "useOutput", "SynchronousPIDCommand");
46
47      m_controller = controller;
48      m_useOutput = useOutput;
49      m_measurement = measurementSource;
50      m_setpoint = setpointSource;
51      m_requirements.addAll(Set.of(requirements));
52  }

```

C++

```

29  /**
30   * Creates a new PIDCommand, which controls the given output with a
31   * PIDController.
32   *
33   * @param controller      the controller that controls the output.
34   * @param measurementSource the measurement of the process variable
35   * @param setpointSource   the controller's reference (aka setpoint)
36   * @param useOutput        the controller's output
37   * @param requirements     the subsystems required by this command
38   */
39  PIDCommand(PIDController controller,
40             std::function<double()> measurementSource,
41             std::function<double()> setpointSource,
42             std::function<void(double)> useOutput,
43             std::initializer_list<Subsystem*> requirements);

```

### controller

The controller parameter is the `PIDController` object that will be used by the command. By passing this in, users can specify the PID gains and the period for the controller (if the user is using a nonstandard main robot loop period).

When subclassing `PIDCommand`, additional modifications (e.g. enabling continuous input) can be made to the controller in the constructor body by calling `getController()`.

### measurementSource

The measurementSource parameter is a function (usually passed as a *lambda*) that returns the measurement of the process variable. Passing in the measurementSource function in `PIDCommand` is functionally analogous to overriding the *getMeasurement()* function in `PIDSubsystem`.

When subclassing `PIDCommand`, advanced users may further modify the measurement supplier by modifying the class's `m_measurement` field.

### setpointSource

The setpointSource parameter is a function (usually passed as a *lambda*) that returns the current setpoint for the control loop. If only a constant setpoint is needed, an overload exists that takes a constant setpoint rather than a supplier.

When subclassing `PIDCommand`, advanced users may further modify the setpoint supplier by modifying the class's `m_setpoint` field.

### useOutput

The useOutput parameter is a function (usually passed as a *lambda*) that consumes the output and setpoint of the control loop. Passing in the useOutput function in `PIDCommand` is functionally analogous to overriding the *useOutput()* function in `PIDSubsystem`.

When subclassing `PIDCommand`, advanced users may further modify the output consumer by modifying the class's `m_useOutput` field.

### requirements

Like all inlineable commands, `PIDCommand` allows the user to specify its subsystem requirements as a constructor parameter.

### Full PIDCommand Example

What does a `PIDCommand` look like when used in practice? The following examples are from the GyroDriveCommands example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.gyrodrivecommands.commands;
9
10 import edu.wpi.first.wpilibj.controller.PIDController;
11 import edu.wpi.first.wpilibj2.command.PIDCommand;
12
13 import edu.wpi.first.wpilibj.examples.gyrodrivecommands.Constants.DriveConstants;
14 import edu.wpi.first.wpilibj.examples.gyrodrivecommands.subsystems.DriveSubsystem;
15
16 /**
17  * A command that will turn the robot to the specified angle.
18  */
19 public class TurnToAngle extends PIDCommand {
20     /**
21      * Turns to robot to the specified angle.
22      *
23      * @param targetAngleDegrees The angle to turn to
24      * @param drive The drive subsystem to use
25      */
26     public TurnToAngle(double targetAngleDegrees, DriveSubsystem drive) {
27         super(
28             new PIDController(DriveConstants.kTurnP, DriveConstants.kTurnI,
29 ↪ DriveConstants.kTurnD),
30             // Close loop on heading
31             drive::getHeading,
32             // Set reference to target
33             targetAngleDegrees,
34             // Pipe output to turn robot
35             output -> drive.arcadeDrive(0, output),
36             // Require the drive
37             drive);
38
39         // Set the controller to be continuous (because it is an angle controller)
40         getController().enableContinuousInput(-180, 180);
41         // Set the controller tolerance - the delta tolerance ensures the robot is
42 ↪ stationary at the
43         // setpoint before it is considered as having reached the reference
44         getController()
45             .setTolerance(DriveConstants.kTurnToleranceDeg, DriveConstants.
46 ↪ kTurnRateToleranceDegPerS);
47     }
48
49     @Override
50     public boolean isFinished() {
51         // End when the controller is at the reference.
52         return getController().atSetpoint();
53     }
54 }

```

## C++ (Header)

```

8 #pragma once
9
10 #include <frc2/command/CommandHelper.h>
11 #include <frc2/command/PIDCommand.h>
12
13 #include "subsystems/DriveSubsystem.h"
14

```

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```

15  /**
16   * A command that will turn the robot to the specified angle.
17   */
18  class TurnToAngle : public frc2::CommandHelper<frc2::PIDCommand, TurnToAngle> {
19  public:
20    /**
21     * Turns to robot to the specified angle.
22     *
23     * @param targetAngleDegrees The angle to turn to
24     * @param drive               The drive subsystem to use
25     */
26    TurnToAngle(units::degree_t target, DriveSubsystem* drive);
27
28    bool IsFinished() override;
29  };

```

C++ (Source)

```

8  #include "commands/TurnToAngle.h"
9
10 #include <frc/controller/PIDController.h>
11
12 using namespace DriveConstants;
13
14 TurnToAngle::TurnToAngle(units::degree_t target, DriveSubsystem* drive)
15   : CommandHelper(frc2::PIDController(kTurnP, kTurnI, kTurnD),
16     // Close loop on heading
17     [drive] { return drive->GetHeading().to<double>(); },
18     // Set reference to target
19     target.to<double>(),
20     // Pipe output to turn robot
21     [drive](double output) { drive->ArcadeDrive(0, output); },
22     // Require the drive
23     {drive}) {
24   // Set the controller to be continuous (because it is an angle controller)
25   m_controller.EnableContinuousInput(-180, 180);
26   // Set the controller tolerance - the delta tolerance ensures the robot is
27   // stationary at the setpoint before it is considered as having reached the
28   // reference
29   m_controller.SetTolerance(kTurnTolerance.to<double>(),
30     kTurnRateTolerance.to<double>());
31
32   AddRequirements({drive});
33 }
34
35 bool TurnToAngle::IsFinished() { return GetController().AtSetpoint(); }

```

And, for an *inlined* example:

Java

```

70   // Stabilize robot to drive straight with gyro when left bumper is held
71   new JoystickButton(m_driverController, Button.kBumperLeft.value).whenHeld(new
72   ↪ PIDCommand(
73     new PIDController(DriveConstants.kStabilizationP, DriveConstants.
74   ↪ kStabilizationI,
75     DriveConstants.kStabilizationD),

```

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```

74 // Close the loop on the turn rate
75 m_robotDrive::getTurnRate,
76 // Setpoint is 0
77 0,
78 // Pipe the output to the turning controls
79 output -> m_robotDrive.arcadeDrive(m_driverController.getY(GenericHID.Hand.
↪kLeft), output),
80 // Require the robot drive
81 m_robotDrive));

```

**C++**

```

37 // Stabilize robot to drive straight with gyro when left bumper is held
38 frc2::JoystickButton(&m_driverController, 5)
39 .WhenHeld(frc2::PIDCommand{
40     frc2::PIDController{dc::kStabilizationP, dc::kStabilizationI,
41                         dc::kStabilizationD},
42     // Close the loop on the turn rate
43     [this] { return m_drive.GetTurnRate(); },
44     // Setpoint is 0
45     0,
46     // Pipe the output to the turning controls
47     [this](double output) {
48         m_drive.ArcadeDrive(m_driverController.GetY(
49                             frc::GenericHID::JoystickHand::kLeftHand),
50                             output);
51     },
52     // Require the robot drive
53     {&m_drive}});

```

## 18.12 Motion Profiling through TrapezoidProfileSubsystems and TrapezoidProfileCommands

**Note:** For a description of the WPILib motion profiling features used by these command-based wrappers, see [Trapezoidal Motion Profiles in WPILib](#).

**Note:** The TrapezoidProfile command wrappers are generally intended for composition with custom or external controllers. For combining trapezoidal motion profiling with WPILib's PIDController, see [Combining Motion Profiling and PID in Command-Based](#).

When controlling a mechanism, it is often desirable to move it smoothly between two positions, rather than to abruptly change its setpoint. This is called “motion-profiling,” and is supported in WPILib through the TrapezoidProfile class (Java, C++).

To further help teams integrate motion profiling into their command-based robot projects, WPILib includes two convenience wrappers for the TrapezoidProfile class: TrapezoidProfileSubsystem, which automatically generates and executes motion profiles in its periodic() method, and the TrapezoidProfileCommand, which executes a single user-provided TrapezoidProfile.



### 18.12.1 TrapezoidProfileSubsystem

**Note:** In C++, the TrapezoidProfileSubsystem class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see [The C++ Units Library](#).

---

The TrapezoidProfileSubsystem class (Java, C++) will automatically create and execute trapezoidal motion profiles to reach the user-provided goal state. To use the TrapezoidProfileSubsystem class, users must create a subclass of it.

#### Creating a TrapezoidProfileSubsystem

When subclassing TrapezoidProfileSubsystem, users must override a single abstract method to provide functionality that the class will use in its ordinary operation:

##### useState()

Java

```
protected abstract void useState(TrapezoidProfile.State state);
```

C++

```
virtual void UseState(frc::TrapezoidProfile<Distance>::State state) = 0;
```

The `useState()` method consumes the current state of the motion profile. The TrapezoidProfileSubsystem will automatically call this method from its `periodic()` block, and pass it the motion profile state corresponding to the subsystem's current progress through the motion profile.

Users may do whatever they want with this state; a typical use case (as shown in the [Full TrapezoidProfileSubsystem Example](#)) is to use the state to obtain a setpoint and a feedforward for an external “smart” motor controller.

#### Constructor Parameters

Users must pass in a set of TrapezoidProfile.Constraints to the TrapezoidProfileSubsystem base class through the superclass constructor call of their subclass. This serves to constrain the automatically-generated profiles to a given maximum velocity and acceleration.

Users must also pass in an initial position for the mechanism.

Advanced users may pass in an alternate value for the loop period, if a non-standard main loop period is being used.

## Using a TrapezoidProfileSubsystem

Once an instance of a TrapezoidProfileSubsystem subclass has been created, it can be used by commands through the following methods:

### setGoal()

**Note:** If you wish to set the goal to a simple distance with an implicit target velocity of zero, an overload of setGoal() exists that takes a single distance value, rather than a full motion profile state.

The setGoal() method can be used to set the goal state of the TrapezoidProfileSubsystem. The subsystem will automatically execute a profile to the goal, passing the current state at each iteration to the provided *useState()* method.

Java

```
// The subsystem will execute a profile to a position of 5 and a velocity of 3.
examplePIDSubsystem.setGoal(new TrapezoidProfile.Goal(5, 3);
```

C++

```
// The subsystem will execute a profile to a position of 5 meters and a velocity of 3_mps.
examplePIDSubsystem.SetGoal({5_m, 3_mps});
```

## Full TrapezoidProfileSubsystem Example

What does a TrapezoidProfileSubsystem look like when used in practice? The following examples are taken from the ArmbotOffboard example project (Java, C++):

Java

```
8 package edu.wpi.first.wpilibj.examples.armbotoffboard.subsystems;
9
10 import edu.wpi.first.wpilibj.controller.ArmFeedforward;
11 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
12 import edu.wpi.first.wpilibj2.command.TrapezoidProfileSubsystem;
13
14 import edu.wpi.first.wpilibj.examples.armbotoffboard.Constants.ArmConstants;
15 import edu.wpi.first.wpilibj.examples.armbotoffboard.ExampleSmartMotorController;
16
17 /**
18  * A robot arm subsystem that moves with a motion profile.
19  */
20 public class ArmSubsystem extends TrapezoidProfileSubsystem {
21     private final ExampleSmartMotorController m_motor =
22         new ExampleSmartMotorController(ArmConstants.kMotorPort);
23     private final ArmFeedforward m_feedforward =
24         new ArmFeedforward(ArmConstants.kSVolts, ArmConstants.kCosVolts,
25                             ArmConstants.kVVoltSecondPerRad, ArmConstants.
26         ↪ kAVoltSecondSquaredPerRad);
```

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```

26
27  /**
28   * Create a new ArmSubsystem.
29   */
30  public ArmSubsystem() {
31      super(new TrapezoidProfile.Constraints(ArmConstants.kMaxVelocityRadPerSecond,
32      ↪kMaxAccelerationRadPerSecSquared),
33            ArmConstants.kArmOffsetRads);
34      m_motor.setPID(ArmConstants.kP, 0, 0);
35  }
36
37  @Override
38  public void useState(TrapezoidProfile.State setpoint) {
39      // Calculate the feedforward from the sepoint
40      double feedforward = m_feedforward.calculate(setpoint.position, setpoint.
41      ↪velocity);
42      // Add the feedforward to the PID output to get the motor output
43      m_motor.setSetpoint(ExampleSmartMotorController.PIDMode.kPosition, setpoint.
44      ↪position,
45                        feedforward / 12.0);
46  }
47  }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc/controller/ArmFeedforward.h>
11 #include <frc2/command/TrapezoidProfileSubsystem.h>
12 #include <units/units.h>
13
14 #include "ExampleSmartMotorController.h"
15
16 /**
17  * A robot arm subsystem that moves with a motion profile.
18  */
19 class ArmSubsystem : public frc2::TrapezoidProfileSubsystem<units::radians> {
20     using State = frc::TrapezoidProfile<units::radians>::State;
21
22     public:
23         ArmSubsystem();
24
25         void UseState(State setpoint) override;
26
27     private:
28         ExampleSmartMotorController m_motor;
29         frc::ArmFeedforward m_feedforward;
30 };

```

## C++ (Source)

```

8  #include "subsystems/ArmSubsystem.h"
9
10 #include "Constants.h"
11

```

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```

12 using namespace ArmConstants;
13 using State = frc2::TrapezoidProfile<units::radians>::State;
14
15 ArmSubsystem::ArmSubsystem()
16     : frc2::TrapezoidProfileSubsystem<units::radians>(
17         {kMaxVelocity, kMaxAcceleration}, kArmOffset),
18         m_motor(kMotorPort),
19         m_feedforward(kS, kCos, kV, kA) {
20     m_motor.SetPID(kP, 0, 0);
21 }
22
23 void ArmSubsystem::UseState(State setpoint) {
24     // Calculate the feedforward from the sepoint
25     units::volt_t feedforward =
26         m_feedforward.Calculate(setpoint.position, setpoint.velocity);
27     // Add the feedforward to the PID output to get the motor output
28     m_motor.SetSetpoint(ExampleSmartMotorController::PIDMode::kPosition,
29                         setpoint.position.to<double>(), feedforward / 12_V);
30 }

```

Using a TrapezoidProfileSubsystem with commands can be quite simple:

Java

```

63 // Move the arm to 2 radians above horizontal when the 'A' button is pressed.
64 new JoystickButton(m_driverController, Button.kA.value)
65     .whenPressed(() -> m_robotArm.setGoal(2), m_robotArm);
66
67 // Move the arm to neutral position when the 'B' button is pressed.
68 new JoystickButton(m_driverController, Button.kB.value)
69     .whenPressed(() -> m_robotArm.setGoal(Constants.ArmConstants.kArmOffsetRads),
70     m_robotArm);

```

C++

```

33 // Move the arm to 2 radians above horizontal when the 'A' button is pressed.
34 frc2::JoystickButton(&m_driverController, 1)
35     .WhenPressed([this] { m_arm.SetGoal(2_rad); }, {&m_arm});
36
37 // Move the arm to neutral position when the 'B' button is pressed.
38 frc2::JoystickButton(&m_driverController, 1)
39     .WhenPressed([this] { m_arm.SetGoal(ArmConstants::kArmOffset); },
40     {&m_arm});

```

## 18.12.2 TrapezoidProfileCommand

**Note:** In C++, the TrapezoidProfileCommand class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see [The C++ Units Library](#).

The TrapezoidProfileCommand class (Java, C++) allows users to create a command that will

execute a single TrapezoidProfile, passing its current state at each iteration to a user-defined function.

As with TrapezoidProfileSubsystem, users can create a TrapezoidProfileCommand by subclassing the TrapezoidProfileCommand class. However, as with many of the other command classes in the command-based library, users may want to save code by defining a TrapezoidProfileCommand *inline*.

## Creating a TrapezoidProfileCommand

A TrapezoidProfileCommand can be created two ways - by subclassing the TrapezoidProfileCommand class, or by defining the command *inline*. Both methods ultimately extremely similar, and ultimately the choice of which to use comes down to where the user desires that the relevant code be located.

In either case, a TrapezoidProfileCommand is created by passing the necessary parameters to its constructor (if defining a subclass, this can be done with a *super()* call):

Java

```

28  /**
29  * Creates a new TrapezoidProfileCommand that will execute the given {@link
↳TrapezoidProfile}.
30  * Output will be piped to the provided consumer function.
31  *
32  * @param profile      The motion profile to execute.
33  * @param output        The consumer for the profile output.
34  * @param requirements The subsystems required by this command.
35  */
36  public TrapezoidProfileCommand(TrapezoidProfile profile,
37                                Consumer<State> output,
38                                Subsystem... requirements) {
39      m_profile = requireNonNullParam(profile, "profile", "TrapezoidProfileCommand");
40      m_output = requireNonNullParam(output, "output", "TrapezoidProfileCommand");
41      addRequirements(requirements);
42  }

```

C++

```

36  public:
37  /**
38  * Creates a new TrapezoidProfileCommand that will execute the given
39  * TrapezoidalProfile. Output will be piped to the provided consumer function.
40  *
41  * @param profile The motion profile to execute.
42  * @param output  The consumer for the profile output.
43  */
44  TrapezoidProfileCommand(frc::TrapezoidProfile<Distance> profile,
45                          std::function<void(State)> output,
46                          std::initializer_list<Subsystem*> requirements)
47      : m_profile(profile), m_output(output) {
48      this->AddRequirements(requirements);

```

## profile

The profile parameter is the TrapezoidProfile object that will be executed by the command. By passing this in, users specify the start state, end state, and motion constraints of the profile that the command will use.

## output

The output parameter is a function (usually passed as a *lambda*) that consumes the output and setpoint of the control loop. Passing in the useOutput function in PIDCommand is functionally analogous to overriding the *useState()* function in PIDSubsystem.

## requirements

Like all inlineable commands, TrapezoidProfileCommand allows the user to specify its subsystem requirements as a constructor parameter.

## Full TrapezoidProfileCommand Example

What does a TrapezoidProfileSubsystem look like when used in practice? The following examples are taken from the DriveDistanceOffboard example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.drivedistanceoffboard.commands;
9
10 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
11 import edu.wpi.first.wpilibj2.command.TrapezoidProfileCommand;
12
13 import edu.wpi.first.wpilibj.examples.drivedistanceoffboard.Constants.DriveConstants;
14 import edu.wpi.first.wpilibj.examples.drivedistanceoffboard.subsystems.DriveSubsystem;
15
16 /**
17  * Drives a set distance using a motion profile.
18  */
19 public class DriveDistanceProfiled extends TrapezoidProfileCommand {
20     /**
21      * Creates a new DriveDistanceProfiled command.
22      *
23      * @param meters The distance to drive.
24      * @param drive The drive subsystem to use.
25      */
26     public DriveDistanceProfiled(double meters, DriveSubsystem drive) {
27         super(
28             new TrapezoidProfile(
29                 // Limit the max acceleration and velocity
30                 new TrapezoidProfile.Constraints(DriveConstants.kMaxSpeedMetersPerSecond,
31                     DriveConstants.
32                     ↪kMaxAccelerationMetersPerSecondSquared),
33                 // End at desired position in meters; implicitly starts at 0
34                 new TrapezoidProfile.State(meters, 0)),
35             // Pipe the profile state to the drive

```

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```

35     setpointState -> drive.setDriveStates(setpointState, setpointState),
36     // Require the drive
37     drive);
38     // Reset drive encoders since we're starting at 0
39     drive.resetEncoders();
40 }
41 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc2/command/CommandHelper.h>
11 #include <frc2/command/TrapezoidProfileCommand.h>
12
13 #include "subsystems/DriveSubsystem.h"
14
15 class DriveDistanceProfiled
16     : public frc2::CommandHelper<frc2::TrapezoidProfileCommand<units::meters>,
17     DriveDistanceProfiled> {
18 public:
19     DriveDistanceProfiled(units::meter_t distance, DriveSubsystem* drive);
20 };

```

## C++ (Source)

```

8  #include "commands/DriveDistanceProfiled.h"
9
10 #include "Constants.h"
11
12 using namespace DriveConstants;
13
14 DriveDistanceProfiled::DriveDistanceProfiled(units::meter_t distance,
15     DriveSubsystem* drive)
16     : CommandHelper(
17     frc::TrapezoidProfile<units::meters>{
18         // Limit the max acceleration and velocity
19         {kMaxSpeed, kMaxAcceleration},
20         // End at desired position in meters; implicitly starts at 0
21         {distance, 0_mps}},
22     // Pipe the profile state to the drive
23     [drive](auto setpointState) {
24         drive->SetDriveStates(setpointState, setpointState);
25     },
26     // Require the drive
27     {drive}) {
28     // Reset drive encoders since we're starting at 0
29     drive->ResetEncoders();
30 }

```

And, for an *inlined* example:

## Java

```

68 // Do the same thing as above when the 'B' button is pressed, but defined inline
69 new JoystickButton(m_driverController, Button.kB.value)
70     .whenPressed(

```

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```

71     new TrapezoidProfileCommand(
72         new TrapezoidProfile(
73             // Limit the max acceleration and velocity
74             new TrapezoidProfile.Constraints(
75                 DriveConstants.kMaxSpeedMetersPerSecond,
76                 DriveConstants.kMaxAccelerationMetersPerSecondSquared),
77             // End at desired position in meters; implicitly starts at 0
78             new TrapezoidProfile.State(3, 0)),
79         // Pipe the profile state to the drive
80         setpointState -> m_robotDrive.setDriveStates(
81             setpointState,
82             setpointState),
83         // Require the drive
84         m_robotDrive)
85         .beforeStarting(m_robotDrive::resetEncoders)
86         .withTimeout(10));

```

## C++

```

44 // Do the same thing as above when the 'B' button is pressed, but defined
45 // inline
46 frc2::JoystickButton(&m_driverController, 2)
47     .WhenPressed(
48         frc2::TrapezoidProfileCommand<units::meters>(
49             frc2::TrapezoidProfile<units::meters>(
50                 // Limit the max acceleration and velocity
51                 {DriveConstants::kMaxSpeed, DriveConstants::kMaxAcceleration},
52                 // End at desired position in meters; implicitly starts at 0
53                 {3_m, 0_mps}),
54             // Pipe the profile state to the drive
55             [this](auto setpointState) {
56                 m_drive.SetDriveStates(setpointState, setpointState);
57             },
58             // Require the drive
59             {&m_drive})
60             .BeforeStarting([this]() { m_drive.ResetEncoders(); })
61             .WithTimeout(10_s));
62 }

```

## 18.13 Combining Motion Profiling and PID in Command-Based

**Note:** For a description of the WPILib PID control features used by these command-based wrappers, see [PID Control in WPILib](#).

**Note:** Unlike the earlier version of `PIDController`, the 2020 `ProfiledPIDController` class runs *synchronously*, and is not handled in its own thread. Accordingly, changing its period parameter will *not* change the actual frequency at which it runs in any of these wrapper classes. Users should never modify the period parameter unless they are certain of what



they are doing.

---

A common FRC controls solution is to pair a trapezoidal motion profile for setpoint generation with a PID controller for setpoint tracking. To facilitate this, WPILib includes its own *ProfiledPIDController* class. To further aid teams in integrating this functionality into their robots, the command-based framework contains two convenience wrappers for the *ProfiledPIDController* class: *ProfiledPIDSubsystem*, which integrates the controller into a subsystem, and *ProfiledPIDCommand*, which integrates the controller into a command.

### 18.13.1 ProfiledPIDSubsystem

---

**Note:** In C++, the *ProfiledPIDSubsystem* class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see *The C++ Units Library*.

---

The *ProfiledPIDSubsystem* class (Java, C++) allows users to conveniently create a subsystem with a built-in *PIDController*. In order to use the *ProfiledPIDSubsystem* class, users must create a subclass of it.

#### Creating a ProfiledPIDSubsystem

When subclassing *ProfiledPIDSubsystem*, users must override two abstract methods to provide functionality that the class will use in its ordinary operation:

##### getMeasurement()

Java

```
protected abstract double getMeasurement();
```

C++

```
virtual double GetMeasurement() = 0;
```

The *getMeasurement* method returns the current measurement of the process variable. The *PIDSubsystem* will automatically call this method from its *periodic()* block, and pass its value to the control loop.

Users should override this method to return whatever sensor reading they wish to use as their process variable measurement.

##### useOutput()

Java

```
protected abstract void useOutput(double output, TrapezoidProfile.State setpoint);
```

C++

```
virtual void UseOutput(double output, frc::TrapezoidProfile<Distance>::State_
    ↳ setpoint) = 0;
```

The `useOutput()` method consumes the output of the PID controller, and the current setpoint state (which is often useful for computing a feedforward). The `PIDSubsystem` will automatically call this method from its `periodic()` block, and pass it the computed output of the control loop.

Users should override this method to pass the final computed control output to their subsystem's motors.

## Passing In the Controller

Users must also pass in a `ProfiledPIDController` to the `ProfiledPIDSubsystem` base class through the superclass constructor call of their subclass. This serves to specify the PID gains, the motion profile constraints, and the period (if the user is using a non-standard main robot loop period).

Additional modifications (e.g. enabling continuous input) can be made to the controller in the constructor body by calling `getController()`.

## Using a ProfiledPIDSubsystem

Once an instance of a `PIDSubsystem` subclass has been created, it can be used by commands through the following methods:

### setGoal()

**Note:** If you wish to set the goal to a simple distance with an implicit target velocity of zero, an overload of `setGoal()` exists that takes a single distance value, rather than a full motion profile state.

The `setGoal()` method can be used to set the setpoint of the `PIDSubsystem`. The subsystem will automatically track to the setpoint using the defined output:

Java

```
// The subsystem will track to a goal of 5 meters and velocity of 3 meters per second.
examplePIDSubsystem.setGoal(5, 3);
```

C++

```
// The subsystem will track to a goal of 5 meters and velocity of 3 meters per second.
examplePIDSubsystem.SetGoal({5_m, 3_mps});
```

### enable() and disable()

The `enable()` and `disable()` methods enable and disable the automatic control of the `ProfiledPIDSubsystem`. When the subsystem is enabled, it will automatically run the mo-

tion profile and the control loop and track to the goal. When it is disabled, no control is performed.

Additionally, the `enable()` method resets the internal `ProfiledPIDController`, and the `disable()` method calls the user-defined `useOutput()` method with both output and setpoint set to 0.

### Full ProfiledPIDSubsystem Example

What does a `PIDSubsystem` look like when used in practice? The following examples are taken from the ArmBot example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.armbot.subsystems;
9
10 import edu.wpi.first.wpilibj.Encoder;
11 import edu.wpi.first.wpilibj.PWMVictorSPX;
12 import edu.wpi.first.wpilibj.controller.ArmFeedforward;
13 import edu.wpi.first.wpilibj.controller.ProfiledPIDController;
14 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
15 import edu.wpi.first.wpilibj2.command.ProfiledPIDSubsystem;
16
17 import edu.wpi.first.wpilibj.examples.armbot.Constants.ArmConstants;
18
19 /**
20  * A robot arm subsystem that moves with a motion profile.
21  */
22 public class ArmSubsystem extends ProfiledPIDSubsystem {
23     private final PWMVictorSPX m_motor = new PWMVictorSPX(ArmConstants.kMotorPort);
24     private final Encoder m_encoder =
25         new Encoder(ArmConstants.kEncoderPorts[0], ArmConstants.kEncoderPorts[1]);
26     private final ArmFeedforward m_feedforward =
27         new ArmFeedforward(ArmConstants.kSVolts, ArmConstants.kCosVolts,
28             ArmConstants.kVVoltSecondPerRad, ArmConstants.
29             ↪ kAVoltSecondSquaredPerRad);
30
31     /**
32      * Create a new ArmSubsystem.
33      */
34     public ArmSubsystem() {
35         super(new ProfiledPIDController(ArmConstants.kP, 0, 0, new TrapezoidProfile.
36             ↪ Constraints(
37                 ArmConstants.kMaxVelocityRadPerSecond, ArmConstants.
38                 ↪ kMaxAccelerationRadPerSecSquared)), 0);
39         m_encoder.setDistancePerPulse(ArmConstants.kEncoderDistancePerPulse);
40         // Start arm at rest in neutral position
41         setGoal(ArmConstants.kArmOffsetRads);
42     }
43
44     @Override
45     public void useOutput(double output, TrapezoidProfile.State setpoint) {
46         // Calculate the feedforward from the sepoint
47         double feedforward = m_feedforward.calculate(setpoint.position, setpoint.
48             ↪ velocity);
49         // Add the feedforward to the PID output to get the motor output
50         m_motor.setVoltage(output + feedforward);

```

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```

47     }
48
49     @Override
50     public double getMeasurement() {
51         return m_encoder.getDistance() + ArmConstants.kArmOffsetRads;
52     }
53 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc/Encoder.h>
11 #include <frc/PWMVictorSPX.h>
12 #include <frc/controller/ArmFeedforward.h>
13 #include <frc2/command/ProfiledPIDSubsystem.h>
14 #include <units/units.h>
15
16 /**
17  * A robot arm subsystem that moves with a motion profile.
18  */
19 class ArmSubsystem : public frc2::ProfiledPIDSubsystem<units::radians> {
20     using State = frc::TrapezoidProfile<units::radians>::State;
21
22     public:
23         ArmSubsystem();
24
25         void UseOutput(double output, State setpoint) override;
26
27         units::radian_t GetMeasurement() override;
28
29     private:
30         frc::PWMVictorSPX m_motor;
31         frc::Encoder m_encoder;
32         frc::ArmFeedforward m_feedforward;
33 };

```

## C++ (Source)

```

8  #include "subsystems/ArmSubsystem.h"
9
10 #include "Constants.h"
11
12 using namespace ArmConstants;
13 using State = frc::TrapezoidProfile<units::radians>::State;
14
15 ArmSubsystem::ArmSubsystem()
16     : frc2::ProfiledPIDSubsystem<units::radians>(
17         frc::ProfiledPIDController<units::radians>(
18             kP, 0, 0, {kMaxVelocity, kMaxAcceleration})),
19         m_motor(kMotorPort),
20         m_encoder(kEncoderPorts[0], kEncoderPorts[1]),
21         m_feedforward(kS, kCos, kV, kA) {
22     m_encoder.SetDistancePerPulse(kEncoderDistancePerPulse.to<double>());
23     // Start arm in neutral position
24     SetGoal(State{kArmOffset, 0_rad_per_s});

```

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```

25 }
26
27 void ArmSubsystem::UseOutput(double output, State setpoint) {
28     // Calculate the feedforward from the setpoint
29     units::volt_t feedforward =
30         m_feedforward.Calculate(setpoint.position, setpoint.velocity);
31     // Add the feedforward to the PID output to get the motor output
32     m_motor.SetVoltage(units::volt_t(output) + feedforward);
33 }
34
35 units::radian_t ArmSubsystem::GetMeasurement() {
36     return units::radian_t(m_encoder.GetDistance()) + kArmOffset;
37 }

```

Using a ProfiledPIDSubsystem with commands can be very simple:

Java

```

63 // Move the arm to 2 radians above horizontal when the 'A' button is pressed.
64 new JoystickButton(m_driverController, Button.kA.value)
65     .whenPressed(() -> m_robotArm.setGoal(2), m_robotArm);
66
67 // Move the arm to neutral position when the 'B' button is pressed.
68 new JoystickButton(m_driverController, Button.kB.value)
69     .whenPressed(() -> m_robotArm.setGoal(Constants.ArmConstants.kArmOffsetRads),
70 m_robotArm);

```

C++

```

33 // Move the arm to 2 radians above horizontal when the 'A' button is pressed.
34 frc2::JoystickButton(&m_driverController, 1)
35     .WhenPressed([this] { m_arm.SetGoal(2_rad); }, {&m_arm});
36
37 // Move the arm to neutral position when the 'B' button is pressed.
38 frc2::JoystickButton(&m_driverController, 1)
39     .WhenPressed([this] { m_arm.SetGoal(ArmConstants::kArmOffset); },
40 {&m_arm});

```

### 18.13.2 ProfiledPIDCommand

**Note:** In C++, the ProfiledPIDCommand class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see [The C++ Units Library](#).

The ProfiledPIDCommand class (Java, C++) allows users to easily create commands with a built-in ProfiledPIDController. As with ProfiledPIDSubsystem, users can create a ProfiledPIDCommand by subclassing the ProfiledPIDCommand class. However, as with many of the other command classes in the command-based library, users may want to save code by defining it *inline*.

## Creating a PIDCommand

A `ProfiledPIDCommand` can be created two ways - by subclassing the `ProfiledPIDCommand` class, or by defining the command *inline*. Both methods ultimately extremely similar, and ultimately the choice of which to use comes down to where the user desires that the relevant code be located.

In either case, a `ProfiledPIDCommand` is created by passing the necessary parameters to its constructor (if defining a subclass, this can be done with a *super()* call):

Java

```

32  /**
33   * Creates a new PIDCommand, which controls the given output with a
  ↪ ProfiledPIDController.
34   * Goal velocity is specified.
35   *
36   * @param controller      the controller that controls the output.
37   * @param measurementSource the measurement of the process variable
38   * @param goalSource       the controller's goal
39   * @param useOutput        the controller's output
40   * @param requirements     the subsystems required by this command
41   */
42  public ProfiledPIDCommand(ProfiledPIDController controller, DoubleSupplier
  ↪ measurementSource,
43                           Supplier<State> goalSource, BiConsumer<Double, State>
  ↪ useOutput,
44                           Subsystem... requirements) {
45      requireNonNullParam(controller, "controller", "SynchronousPIDCommand");
46      requireNonNullParam(measurementSource, "measurementSource", "SynchronousPIDCommand
  ↪ ");
47      requireNonNullParam(goalSource, "goalSource", "SynchronousPIDCommand");
48      requireNonNullParam(useOutput, "useOutput", "SynchronousPIDCommand");
49
50      m_controller = controller;
51      m_useOutput = useOutput;
52      m_measurement = measurementSource;
53      m_goal = goalSource;
54      m_requirements.addAll(Set.of(requirements));
55  }

```

C++

```

39  public:
40  /**
41   * Creates a new PIDCommand, which controls the given output with a
42   * ProfiledPIDController.
43   *
44   * @param controller      the controller that controls the output.
45   * @param measurementSource the measurement of the process variable
46   * @param goalSource       the controller's goal
47   * @param useOutput        the controller's output
48   * @param requirements     the subsystems required by this command
49   */
50  ProfiledPIDCommand(frc::ProfiledPIDController<Distance> controller,
51                    std::function<Distance_t()> measurementSource,
52                    std::function<State()> goalSource,
53                    std::function<void(double, State)> useOutput,

```

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```
54         std::initializer_list<Subsystem*> requirements)
55     : m_controller{controller},
56       m_measurement{std::move(measurementSource)},
57       m_goal{std::move(goalSource)},
58       m_useOutput{std::move(useOutput)} {
59     this->AddRequirements(requirements);
```

## controller

The controller parameter is the `ProfiledPIDController` object that will be used by the command. By passing this in, users can specify the PID gains, the motion profile constraints, and the period for the controller (if the user is using a nonstandard main robot loop period).

When subclassing `ProfiledPIDCommand`, additional modifications (e.g. enabling continuous input) can be made to the controller in the constructor body by calling `getController()`.

## measurementSource

The measurementSource parameter is a function (usually passed as a *lambda*) that returns the measurement of the process variable. Passing in the measurementSource function in `ProfiledPIDCommand` is functionally analogous to overriding the *getMeasurement()* function in `ProfiledPIDSubsystem`.

When subclassing `ProfiledPIDCommand`, advanced users may further modify the measurement supplier by modifying the class's `m_measurement` field.

## goalSource

The goalSource parameter is a function (usually passed as a *lambda*) that returns the current goal state for the mechanism. If only a constant goal is needed, an overload exists that takes a constant goal rather than a supplier. Additionally, if goal velocities are desired to be zero, overloads exist that take a constant distance rather than a full profile state.

When subclassing `ProfiledPIDCommand`, advanced users may further modify the setpoint supplier by modifying the class's `m_goal` field.

## useOutput

The useOutput parameter is a function (usually passed as a *lambda*) that consumes the output and setpoint state of the control loop. Passing in the useOutput function in `ProfiledPIDCommand` is functionally analogous to overriding the *useOutput()* function in `ProfiledPIDSubsystem`.

When subclassing `ProfiledPIDCommand`, advanced users may further modify the output consumer by modifying the class's `m_useOutput` field.

## requirements

Like all inlineable commands, `ProfiledPIDCommand` allows the user to specify its subsystem requirements as a constructor parameter.

## Full ProfiledPIDCommand Example

What does a `ProfiledPIDCommand` look like when used in practice? The following examples are from the `GyroDriveCommands` example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.gyrodrivecommands.commands;
9
10 import edu.wpi.first.wpilibj.controller.ProfiledPIDController;
11 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
12 import edu.wpi.first.wpilibj2.command.ProfiledPIDCommand;
13
14 import edu.wpi.first.wpilibj.examples.gyrodrivecommands.Constants.DriveConstants;
15 import edu.wpi.first.wpilibj.examples.gyrodrivecommands.subsystems.DriveSubsystem;
16
17 /**
18  * A command that will turn the robot to the specified angle using a motion profile.
19  */
20 public class TurnToAngleProfiled extends ProfiledPIDCommand {
21     /**
22      * Turns to robot to the specified angle using a motion profile.
23      *
24      * @param targetAngleDegrees The angle to turn to
25      * @param drive               The drive subsystem to use
26      */
27     public TurnToAngleProfiled(double targetAngleDegrees, DriveSubsystem drive) {
28         super(
29             new ProfiledPIDController(DriveConstants.kTurnP, DriveConstants.kTurnI,
30                                     DriveConstants.kTurnD, new TrapezoidProfile.
31 ↪ Constraints(
32                 DriveConstants.kMaxTurnRateDegPerS,
33                 DriveConstants.kMaxTurnAccelerationDegPerSSquared)),
34             // Close loop on heading
35             drive::getHeading,
36             // Set reference to target
37             targetAngleDegrees,
38             // Pipe output to turn robot
39             (output, setpoint) -> drive.arcadeDrive(0, output),
40             // Require the drive
41             drive);
42
43         // Set the controller to be continuous (because it is an angle controller)
44         getController().enableContinuousInput(-180, 180);
45         // Set the controller tolerance - the delta tolerance ensures the robot is
46 ↪ stationary at the
47         // setpoint before it is considered as having reached the reference
48         getController()
49             .setTolerance(DriveConstants.kTurnToleranceDeg, DriveConstants.
50 ↪ kTurnRateToleranceDegPerS);
51     }

```

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```

49
50 @Override
51 public boolean isFinished() {
52     // End when the controller is at the reference.
53     return getController().atGoal();
54 }
55 }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc2/command/CommandHelper.h>
11 #include <frc2/command/ProfiledPIDCommand.h>
12
13 #include "subsystems/DriveSubsystem.h"
14
15 /**
16  * A command that will turn the robot to the specified angle using a motion
17  * profile.
18  */
19 class TurnToAngleProfiled
20     : public frc2::CommandHelper<frc2::ProfiledPIDCommand<units::radians>,
21                               TurnToAngleProfiled> {
22 public:
23     /**
24      * Turns to robot to the specified angle using a motion profile.
25      *
26      * @param targetAngleDegrees The angle to turn to
27      * @param drive               The drive subsystem to use
28      */
29     TurnToAngleProfiled(units::degree_t targetAngleDegrees,
30                         DriveSubsystem* drive);
31
32     bool IsFinished() override;
33 };

```

## C++ (Source)

```

8  #include "commands/TurnToAngleProfiled.h"
9
10 #include <frc/controller/ProfiledPIDController.h>
11
12 using namespace DriveConstants;
13
14 TurnToAngleProfiled::TurnToAngleProfiled(units::degree_t target,
15                                           DriveSubsystem* drive)
16     : CommandHelper(
17         frc::ProfiledPIDController<units::radians>(
18             kTurnP, kTurnI, kTurnD, {kMaxTurnRate, kMaxTurnAcceleration}),
19         // Close loop on heading
20         [drive] { return drive->GetHeading(); },
21         // Set reference to target
22         target,
23         // Pipe output to turn robot
24         [drive](double output, auto setpointState) {

```

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```
25         drive->ArcadeDrive(0, output);
26     },
27     // Require the drive
28     {drive}) {
29     // Set the controller to be continuous (because it is an angle controller)
30     GetController().EnableContinuousInput(-180_deg, 180_deg);
31     // Set the controller tolerance - the delta tolerance ensures the robot is
32     // stationary at the setpoint before it is considered as having reached the
33     // reference
34     GetController().SetTolerance(kTurnTolerance, kTurnRateTolerance);
35
36     AddRequirements({drive});
37 }
38
39 bool TurnToAngleProfiled::IsFinished() { return GetController().AtGoal(); }
```



## [Old] Command Based Programming

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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### 19.1 [Old] Command Based - Basics

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**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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#### 19.1.1 What is Command-Based Programming?

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**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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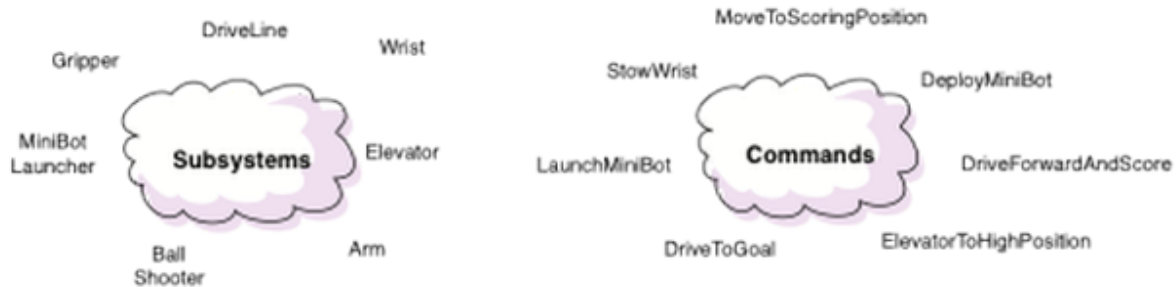
WPILib supports a method of writing programs called “Command-based programming”. Command-based programming is a design pattern to help you organize your robot programs. Some of the characteristics of robot programs that might be different from other desktop programs are:

- Activities happen over time, for example a sequence of steps to shoot a Frisbee or raise an elevator and place a tube on a goal.
- These activities occur concurrently, that is it might be desirable for an elevator, wrist and gripper to all be moving into a pickup position at the same time to increase robot performance.
- It is desirable to test the robot mechanisms and activities each individually to help debug your robot.

- Often the program needs to be augmented with additional autonomous programs at the last minute, perhaps at competitions, so easily extendable code is important.

Command-based programming supports all these goals easily to make the robot program much simpler than using some less structured technique.

### Commands and Subsystems

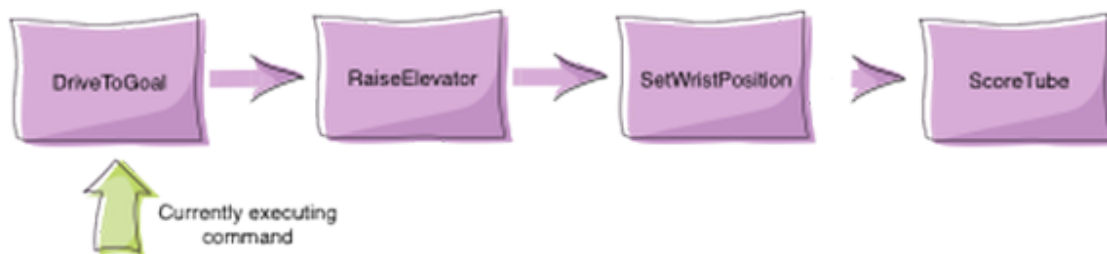


Programs based on the WPILib Command Template are organized around two fundamental concepts: **Subsystems** and **Commands**.

**Subsystems** - define the capabilities of each part of the robot and are subclasses of Subsystem.

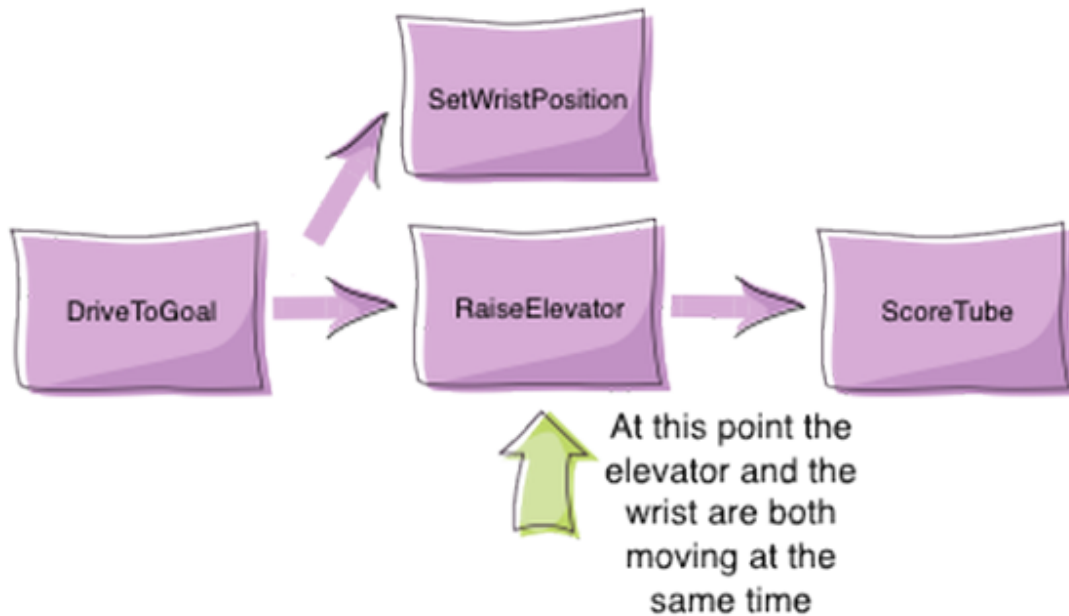
**Commands** - define the operation of the robot incorporating the capabilities defined in the subsystems. Commands are subclasses of Command or CommandGroup. Commands run when scheduled or in response to buttons being pressed or virtual buttons from the SmartDashboard.

### How Commands Work



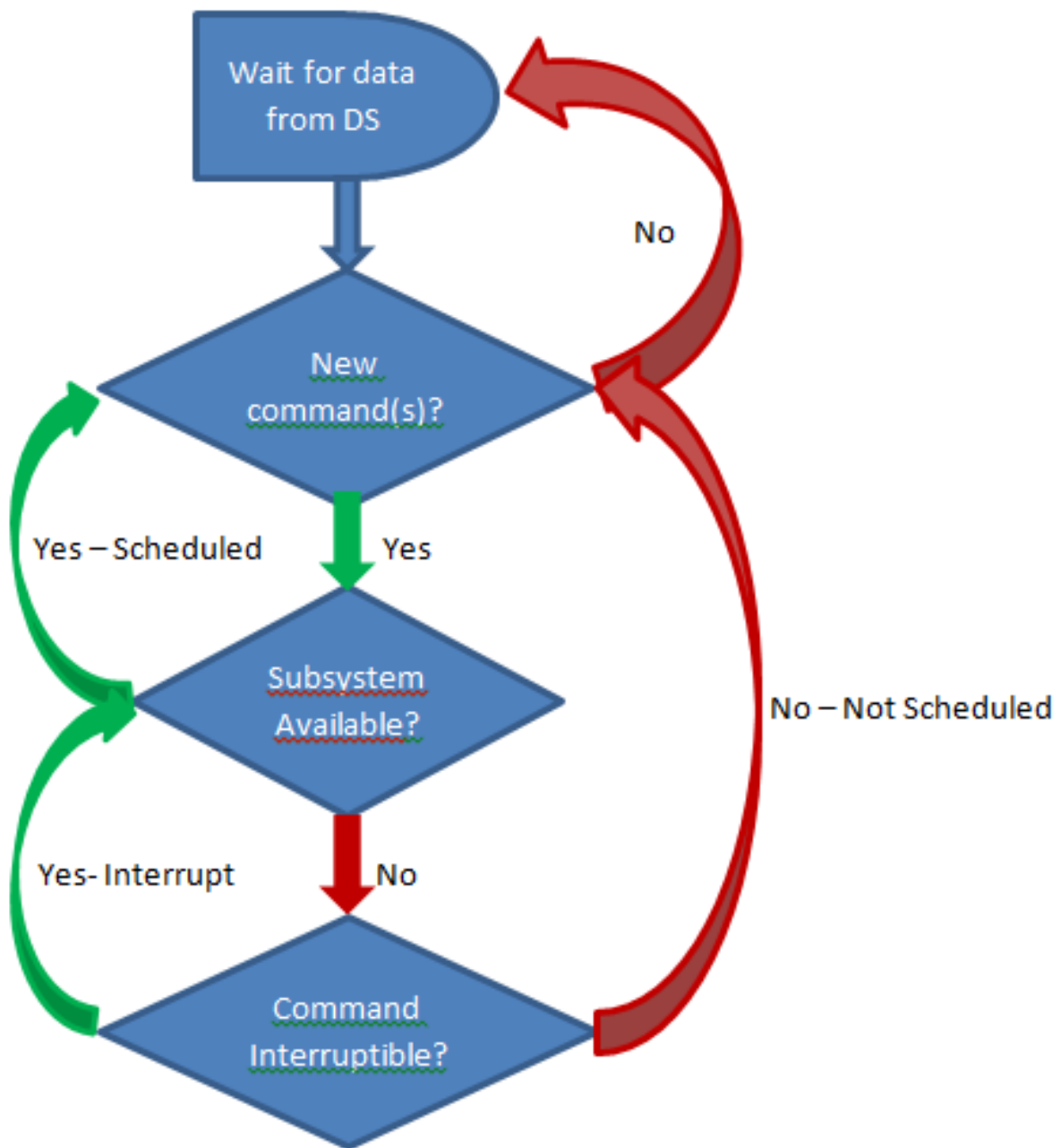
Commands let you break up the tasks of operating the robot into small chunks. Each command has an `execute()` method that does some work and an `isFinished()` method that tells if it is done. This happens on every update from the driver station or about every 20ms. Commands can be grouped together and executed sequentially, starting the next one in the group as the previous one finishes.

## Concurrency



Sometimes it is desirable to have several operations happening concurrently. In the previous example you might want to set the wrist position while the elevator is moving up. In this case, a command group can start a parallel command (or command group) running.

## How It Works - Scheduling Commands



There are three main ways commands are scheduled:

1. Manually, by calling the `start()` method on the command (*used for autonomous*)
2. Automatically by the scheduler based on *button/trigger actions* specified in the code (typically defined in the OI class but checked by the Scheduler).
3. Automatically when a previous command completes (*default commands* and *command groups*).

Each time the driver station gets new data, the periodic method of your robot program is

called. It runs a Scheduler that checks the trigger conditions to see if any commands need to be scheduled or cancelled.

When a command is scheduled, the Scheduler checks to make sure that no other commands are using the same subsystems that the new command requires. If one or more of the subsystems is currently in use, and the current command is interruptible, it will be interrupted and the new command will be scheduled. If the current command is not interruptible, the new command will fail to be scheduled.

## How It Works - Running Commands

After checking for new commands, the scheduler proceeds through the list of active commands and calls the `execute()` and `isFinished()` methods on each command. Notice that the apparent concurrent execution is done without the use of threads or tasks which would add complexity to the program. Each command simply has some code to execute (`execute` method) to move it further along towards its goal and a method (`isFinished`) that determines if the command has reached the goal. The `execute` and `isFinished` methods are just called repeatedly.

## Command Groups

More complex commands can be built up from simpler commands. For example, shooting a disc may be a long sequence of commands that are executed one after another. Maybe some of these commands in the sequence can be executed concurrently. Command groups are commands, but instead of having an `isFinished` and `execute` method, they have a list of other commands to execute. This allows more complex operations to be built up out of simpler operations, a basic principle in programming. Each of the individual smaller commands can be easily tested first, then the group can be tested. More information on command groups can be found in the [Creating groups of commands article](#).

### 19.1.2 Creating a Robot Project

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

Creating a project is detailed in [Creating a Robot Program](#). Select “Template” then your programming language then “Old Command Robot” to create a basic Command-Based Robot program. Alternately you can use RobotBuilder to create the framework of your Command-Based Robot project as detailed in [RobotBuilder](#).

When you create an Old Command Robot project or use RobotBuilder to export a project, the old command based vendor library is automatically imported.

### 19.1.3 Adding Commands and Subsystems to the Project

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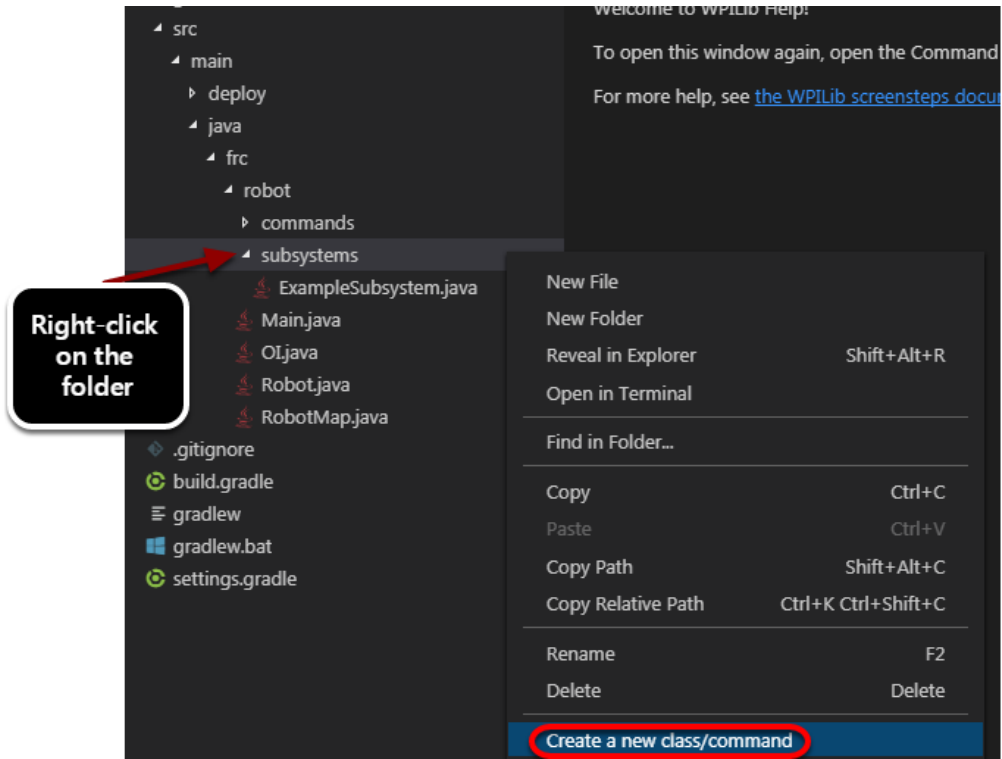
**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are



strongly encouraged to migrate to the [new command-based library](#).

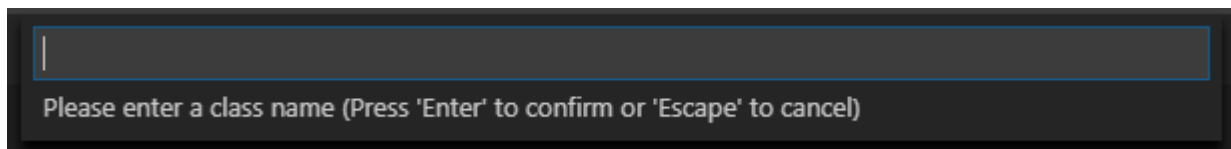
**Note:** Commands and Subsystems each are created as classes. The plugin has built-in templates for both Commands and Subsystems to make it easier for you to add them to your program.

### Adding Subsystems to the Project



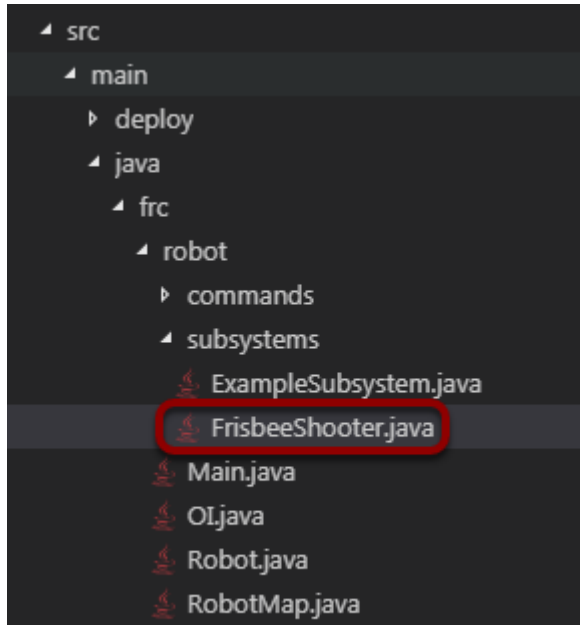
To add a subsystem, right-click on the desired folder and select **Create a new class/command** in the drop down menu. Then select **Subsystem (Old)** or **PID Subsystem (Old)**.

### Naming the Subsystem



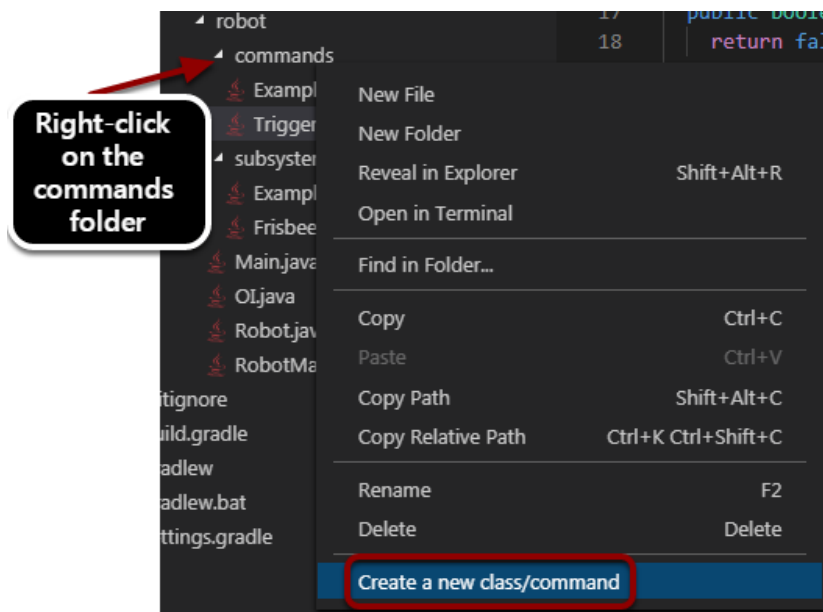
Fill in a name for the subsystem. This will become the resultant class name for the subsystem so the name has to be a valid class name for your language.

## Subsystem Created in Project



You can see the new subsystem created in the Subsystems folder in the project. To learn more about creating subsystems, see the [Simple Subsystems](#) article.

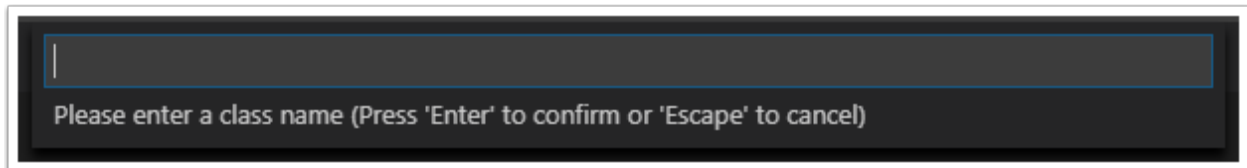
## Adding a Command to the Project



A command can be created for the project using steps similar to creating a subsystem. First right-click on the folder name in the project, then select **Create a new class/command** in the drop down menu. Then select **Command (Old)**, **Instant Command (Old)**, **TimedCommand (Old)**, **Command Group (Old)**:

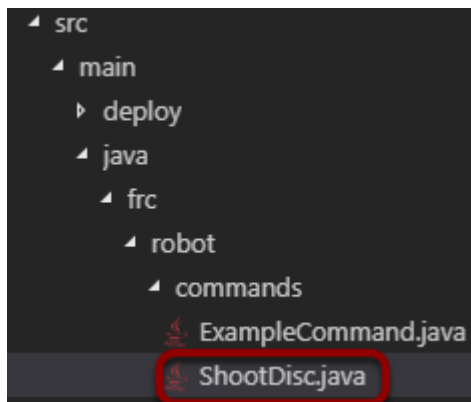
- **Command** - A basic command that operates on a subsystem
- **Instant Command** - A command that runs and completes instantly
- **Timed Command** - A command that runs for a specified time duration
- **Command Group** - A command that runs other commands

### Set the Command Name



Enter the Command name into the dialog box. This will be the class name for the Command so it must be a valid class name for your language.

### Command Created in the Project



You can see that the Command has been created in the Commands folder in the project in the Project Explorer window. To learn more about creating commands, see the [Creating Simple Commands](#) article.

## 19.1.4 Converting a Simple Autonomous Program to Command-Based

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

This document describes how to rewrite a simple autonomous into a command based autonomous. Hopefully, going through this process will help those more familiar with the older simple autonomous method understand the command based method better. By re-writing it as a command based program, there are several benefits in terms of testing and reuse. For this example, all of the logic is abstracted out into functions primarily so that the focus of this example can be on the structure.

## Initial Autonomous Code

Java

```
// Aim shooter
SetTargetAngle(); // Initialization: prepares for the action to be performed

while (!AtRightAngle()) { // Condition: keeps the loop going while it is satisfied
    CorrectAngle(); // Execution: repeatedly updates the code to try to make the
    ↪condition false
    delay(); // Delay to prevent maxing CPU
}

HoldAngle(); // End: performs any cleanup and final task before moving on to the next
↪action

// Spin up to Speed
SetTargetSpeed(); // Initialization: prepares for the action to be performed

while (!FastEnough()) { // Condition: keeps the loop going while it is satisfied
    SpeedUp(); // Execution: repeatedly updates the code to try to make the condition
    ↪false
    delay(); // Delay to prevent maxing CPU
}

HoldSpeed();

// Shoot Frisbee
Shoot(); // End: performs any cleanup and final task before moving on to the next
↪action
```

C++

```
// Aim shooter
SetTargetAngle(); // Initialization: prepares for the action to be performed

while (!AtRightAngle()) { // Condition: keeps the loop going while it is satisfied
    CorrectAngle(); // Execution: repeatedly updates the code to try to make the
    ↪condition false
    delay(); // Delay to prevent maxing CPU
}

HoldAngle(); // End: performs any cleanup and final task before moving on to the next
↪action

// Spin up to Speed
SetTargetSpeed(); // Initialization: prepares for the action to be performed

while (!FastEnough()) { // Condition: keeps the loop going while it is satisfied
    SpeedUp(); // Execution: repeatedly updates the code to try to make the condition
    ↪false
    delay(); // Delay to prevent maxing CPU
}

HoldSpeed();

// Shoot Frisbee
Shoot(); // End: performs any cleanup and final task before moving on to the next
↪action
```

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---

The code above aims a shooter, then it spins up a wheel and, finally, once the wheel is running at the desired speed, it shoots the frisbee. The code consists of three distinct actions: aim, spin up to speed and shoot the Frisbee. The first two actions follow a command pattern that consists of four parts:

1. Initialization: prepares for the action to be performed.
2. Condition: keeps the loop going while it is satisfied.
3. Execution: repeatedly updates the code to try to make the condition false.
4. End: performs any cleanup and final task before moving on to the next action.

The last action only has an explicit initialize, though depending on how you read it, it can implicitly end under a number of conditions. The most obvious one two in this case are when it's done shooting or when autonomous has ended.

## Rewriting it as Commands

Java

```
public class AutonomousCommand extends CommandGroup {  
  
    public AutonomousCommand() {  
        addSequential(new Aim());  
        addSequential(new SpinUpShooter());  
        addSequential(new Shoot());  
    }  
}
```

C++

```
#include "AutonomousCommand.h"  
  
AutonomousCommand::AutonomousCommand()  
{  
    AddSequential(new Aim());  
    AddSequential(new SpinUpShooter());  
    AddSequential(new Shoot());  
}
```

The same code can be rewritten as a CommandGroup that groups the three actions, where each action is written as it's own command. First, the command group will be written, then the commands will be written to accomplish the three actions. This code is pretty straightforward. It does the three actions sequentially, that is one after the other. Line 3 aims the robot, then line 4 spins the shooter up and, finally, line 5 actually shoots the frisbee. The `addSequential()` method sets it so that these commands run one after the other.

## The Aim Command

Java

```

public class Aim extends Command {

    public Aim() {
        requires(Robot.turret);
    }

    // Called just before this Command runs the first time
    protected void initialize() {
        SetTargetAngle();
    }

    // Called repeatedly when this Command is scheduled to run
    protected void execute() {
        CorrectAngle();
    }

    // Make this return true when this Command no longer needs to run execute()
    protected boolean isFinished() {
        return AtRightAngle();
    }

    // Called once after isFinished returns true
    protected void end() {
        HoldAngle();
    }

    // Called when another command which requires one or more of the same
    // subsystems is scheduled to run
    protected void interrupted() {
        end();
    }
}

```

C++

```

#include "Aim.h"

Aim::Aim()
{
    Requires(Robot::turret);
}

// Called just before this Command runs the first time
void Aim::Initialize()
{
    SetTargetAngle();
}

// Called repeatedly when this Command is scheduled to run
void Aim::Execute()
{
    CorrectAngle();
}

// Make this return true when this Command no longer needs to run execute()
bool Aim::IsFinished()
{

```

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```

    return AtRightAngle();
}

// Called once after isFinished returns true
void Aim::End()
{
    HoldAngle();
}

// Called when another command which requires one or more of the same
// subsystems is scheduled to run
void Aim:Interrupted()
{
    End();
}

```

As you can see, the command reflects the four parts of the action we discussed earlier. It also has the interrupted() method which will be discussed below. The other significant difference is that the condition in the isFinished() is the opposite of what you would put as the condition of the while loop, it returns true when you want to stop running the execute method as opposed to false. Initializing, executing and ending are exactly the same, they just go within their respective method to indicate what they do.

### SpinUpShooter Command

Java

```

public class SpinUpShooter extends Command {

    public SpinUpShooter() {
        requires(Robot.shooter);
    }

    // Called just before this Command runs the first time
    protected void initialize() {
        SetTargetSpeed();
    }

    // Called repeatedly when this Command is scheduled to run
    protected void execute() {
        SpeedUp();
    }

    // Make this return true when this Command no longer needs to run execute()
    protected boolean isFinished() {
        return FastEnough();
    }

    // Called once after isFinished returns true
    protected void end() {
        HoldSpeed();
    }

    // Called when another command which requires one or more of the same
    // subsystems is scheduled to run

```

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```

    protected void interrupted() {
        end();
    }
}

```

C++

```

#include "SpinUpShooter.h"

SpinUpShooter::SpinUpShooter()
{
    Requires(Robot::shooter)
}

// Called just before this Command runs the first time
void SpinUpShooter::Initialize()
{
    SetTargetSpeed();
}

// Called repeatedly when this Command is scheduled to run
void SpinUpShooter::Execute()
{
    SpeedUp();
}

// Make this return true when this Command no longer needs to run execute()
bool SpinUpShooter::IsFinished()
{
    return FastEnough();
}

// Called once after isFinished returns true
void SpinUpShooter::End()
{
    HoldSpeed();
}

// Called when another command which requires one or more of the same
// subsystems is scheduled to run
void SpinUpShooter::Interrupted()
{
    End();
}

```

The spin up shooter command is very similar to the Aim command, it's the same basic idea.

## Shoot Command

Java

```

public class Shoot extends Command {

    public Shoot() {
        requires(shooter);
    }
}

```

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```

    }

    // Called just before this Command runs the first time
    protected void initialize() {
        Shoot();
    }

    // Called repeatedly when this Command is scheduled to run
    protected void execute() {
    }

    // Make this return true when this Command no longer needs to run execute()
    protected boolean isFinished() {
        return true;
    }

    // Called once after isFinished returns true
    protected void end() {
    }

    // Called when another command which requires one or more of the same
    // subsystems is scheduled to run
    protected void interrupted() {
        end();
    }
}

```

C++

```

#include "Shoot.h"

Shoot::Shoot()
{
    Requires(Robot.shooter);
}

// Called just before this Command runs the first time
void Shoot::Initialize()
{
    Shoot();
}

// Called repeatedly when this Command is scheduled to run
void Shoot::Execute()
{
}

// Make this return true when this Command no longer needs to run execute()
bool Shoot::IsFinished()
{
    return true;
}

// Called once after isFinished returns true
void Shoot::End()
{
}

```

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```
}  
  
// Called when another command which requires one or more of the same  
// subsystems is scheduled to run  
void Shoot::Interrupted()  
{  
    End();  
}
```

The shoot command is the same basic transformation yet again, however it is set to end immediately. In CommandBased programming, it is better to have its `isFinished` method return true when the act of shooting is finished, but this is a more direct translation of the original code.

## Benefits of Command-Based

Why bother re-writing the code as CommandBased? Writing the code in the CommandBased style offers a number of benefits:

- **Re-Usability** - You can reuse the same command in teleop and multiple autonomous modes. They all reference the same code, so if you need to tweak it to tune it or fix it, you can do it in one place without having to make the same edits in multiple places.
- **Testability** - You can test each part using tools such as the ShuffleBoard to test parts of the autonomous. Once you put them together, you'll have more confidence that each piece works as desired.
- **Parallelization** - If you wanted this code to aim and spin up the shooter at the same time, it's trivial with CommandBased programming. Just use `AddParallel()` instead of `AddSequential()` when adding the Aim command and now aiming and spinning up will happen simultaneously.
- **Interruptibility** - Commands are interruptible, this provides the ability to exit a command early, a task that is much harder in the equivalent while loop based code.

## 19.2 [Old] Command Based - Subsystems

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**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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### 19.2.1 Simple Subsystems

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

Subsystems are the parts of your robot that are independently controlled like collectors, shooters, drive bases, elevators, arms, wrists, grippers, etc. Each subsystem is coded as an instance of the Subsystem class. Subsystems should have methods that define the operation of the actuators and sensors but not more complex behavior that happens over time.

### Creating a Subsystem

Java

```
import edu.wpi.first.wpilibj.DigitalInput;
import edu.wpi.first.wpilibj.Victor;
import edu.wpi.first.wpilibj.command.Subsystem;

/**
 * The claw subsystem is a simple system with a motor for opening and closing.
 * If using stronger motors, you should probably use a sensor so that the motors
 * don't stall.
 */
public class Claw extends Subsystem {
    private final Victor m_motor = new Victor(7);
    private final DigitalInput m_contact = new DigitalInput(5);

    /**
     * Create a new claw subsystem.
     */
    public Claw() {
        super();
    }

    @Override
    public void initDefaultCommand() {
    }

    /**
     * Set the claw motor to move in the open direction.
     */
    public void open() {
        m_motor.set(-1);
    }

    /**
     * Set the claw motor to move in the close direction.
     */
    @Override
    public void close() {
        m_motor.set(1);
    }

    /**
     * Stops the claw motor from moving.
     */
    public void stop() {
        m_motor.set(0);
    }
}
```

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```

    * Return true when the robot is grabbing an object hard enough to trigger
    * the limit switch.
    */
    public boolean isGrabbing() {
        return m_contact.get();
    }
}

```

C++

```

#include "subsystems/Claw.h"

Claw::Claw() : frc::Subsystem("Claw") {
    // Let's show everything on the LiveWindow
    AddChild("Motor", m_motor);
}

void Claw::InitDefaultCommand() {}

/**
 * Set the claw motor to move in the open direction.
 */
void Claw::Open() { m_motor.Set(-1); }

/**
 * Set the claw motor to move in the close direction.
 */
void Claw::Close() { m_motor.Set(1); }

/**
 * Stops the claw motor from moving.
 */
void Claw::Stop() { m_motor.Set(0); }

/**
 * Return true when the robot is grabbing an object hard enough to trigger
 * the limit switch.
 */
bool Claw::IsGripping() { return m_contact.Get(); }

```

This is an example of a fairly straightforward subsystem that operates a claw on a robot. The claw mechanism has a single motor to open or close the claw and no sensors (not necessarily a good idea in practice, but works for the example). The idea is that the open and close operations are simply timed. There are three methods, `open()`, `close()`, and `stop()` that operate the claw motor. Notice that there is not specific code that actually checks if the claw is opened or closed. The open method gets the claw moving in the open direction and the close method gets the claw moving in the close direction. Use a command to control the timing of this operation to make sure that the claw opens and closes for a specific period of time.

## Operating the Claw with a Command

Java

```
package org.usfirst.frc.team1.robot.commands;

import edu.wpi.first.wpilibj.command.Command;
import org.usfirst.frc.team1.robot.Robot;

public class OpenClaw extends Command {

    public OpenClaw() {
        requires(Robot.claw);
        setTimeout(.9);
    }

    protected void initialize() {
        Robot.claw.open()
    }

    protected void execute() {

    }

    protected boolean isFinished() {
        return isTimedOut();
    }

    protected void end() {
        Robot.claw.stop();
    }

    protected void interrupted() {
        end();
    }
}
```

C++

```
#include "commands/OpenClaw.h"

#include "Robot.h"

OpenClaw::OpenClaw() : frc::Command("OpenClaw") {
    Requires(&Robot::claw);
    SetTimeout(1);
}

// Called just before this Command runs the first time
void OpenClaw::Initialize() { Robot::claw.Open(); }

// Make this return true when this Command no longer needs to run execute()
bool OpenClaw::IsFinished() { return IsTimedOut(); }

// Called once after isFinished returns true
void OpenClaw::End() { Robot::claw.Stop(); }
```

Commands provide the timing of the subsystems operations. Each command would do a different operation with the subsystem, the Claw in this case. The commands provides the timing for opening or closing. Here is an example of a simple Command that controls the opening of the claw. Notice that a timeout is set for this command (0.9 seconds) to time the opening of the claw and a check for the time in the `isFinished()` method. You can find more details in the article about [using commands](#).

## 19.2.2 PIDSubsystems for built-in PID Control

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the *new command-based library*.

**Note:** If a mechanism uses a sensor for feedback, then most often a PID controller will be used to control the motor speed or position. Examples of subsystems that might use PID control are: elevators with potentiometers to track the height, shooters with encoders to measure the speed, wrists with potentiometers to measure the joint angle, etc.

There is a PIDController class built into WPILib, but to simplify its use for command based programs there is a PIDSubsystem. A PIDSubsystem is a normal subsystem with the PIDController built in and exposes the required methods for operation.

### Controlling the Angle of a Wrist Joint

In this example you can see the basic elements of a PIDSubsystem for the wrist joint:

Java

```
package org.usfirst.frc.team1.robot.subsystems;
import edu.wpi.first.wpilibj.*;
import edu.wpi.first.wpilibj.command.PIDSubsystem;
import org.usfirst.frc.team1.robot.RobotMap;

public class Wrist extends PIDSubsystem { // This system extends PIDSubsystem

    Victor motor = RobotMap.wristMotor;
    AnalogInput pot = RobotMap.wristPot();

    public Wrist() {
        super("Wrist", 2.0, 0.0, 0.0); // The constructor passes a name for the
        ↪ subsystem and the P, I and D constants that are used when computing the motor output
        setAbsoluteTolerance(0.05);
        getPIDController().setContinuous(false);
    }

    public void initDefaultCommand() {
    }

    protected double returnPIDInput() {
        return pot.getAverageVoltage(); // returns the sensor value that is providing
        ↪ the feedback for the system
    }

    protected void usePIDOutput(double output) {
        motor.pidWrite(output); // this is where the computed output value from the
        ↪ PIDController is applied to the motor
    }
}
```

C++

```
#include "subsystems/Wrist.h"

#include <frc/smartdashboard/SmartDashboard.h>

Wrist::Wrist() : frc::PIDSubsystem("Wrist", kP_real, 0.0, 0.0) {
#ifdef SIMULATION // Check for simulation and update PID values
    GetPIDController()->SetPID(kP_simulation, 0, 0, 0);
#endif
    SetAbsoluteTolerance(2.5);
}

void Wrist::InitDefaultCommand() {}

void Wrist::Log() {
    // frc::SmartDashboard::PutData("Wrist Angle", &m_pot);
}

double Wrist::ReturnPIDInput() { return m_pot.Get(); }

void Wrist::UsePIDOutput(double d) { m_motor.Set(d); }
```

## 19.3 [Old] Command Based - Commands

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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### 19.3.1 Creating Simple Commands

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

This article describes the basic format of a Command and walks through an example of creating a command to drive your robot with Joysticks.

#### Basic Command Format

To implement a command, a number of methods are overridden from the WPILib Command class. Most of the methods are boiler plate and can often be ignored, but are there for maximum flexibility when you need it. There a number of parts to this basic command class:

Java

```

public class MyCommandName extends Command {

    /*
     * 1. Constructor - Might have parameters for this command such as target
     ↪ positions of devices. Should also set the name of the command for debugging
     ↪ purposes.
     * This will be used if the status is viewed in the dashboard. And the command
     ↪ should require (reserve) any devices it might use.
     */
    public MyCommandName() {
        super("MyCommandName");
        requires(elevator);
    }

    // initialize() - This method sets up the command and is called immediately
    ↪ before the command is executed for the first time and every subsequent time it is
    ↪ started .
    // Any initialization code should be here.
    protected void initialize() {

    }

    /*
     * execute() - This method is called periodically (about every 20ms) and does
     ↪ the work of the command. Sometimes, if there is a position a
     * subsystem is moving to, the command might set the target position for the
     ↪ subsystem in initialize() and have an empty execute() method.
     */
    protected void execute() {

    }

    // Make this return true when this Command no longer needs to run execute()
    protected boolean isFinished() {
        return false;
    }
}

```

## C++

```

#include "MyCommandName.h"

/*
 * 1. Constructor - Might have parameters for this command such as target
     ↪ positions of devices. Should also set the name of the command for debugging
     ↪ purposes.
     * This will be used if the status is viewed in the dashboard. And the command
     ↪ should require (reserve) any devices it might use.
     */
MyCommandName::MyCommandName() : CommandBase("MyCommandName")
{
    Requires(Elevator);
}

// initialize() - This method sets up the command and is called immediately before
     ↪ the command is executed for the first time and
// every subsequent time it is started . Any initialization code should be here.
void MyCommandName::Initialize()
{

```

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```

}

/*
 *   execute() - This method is called periodically (about every 20ms) and does the
 *   ↪work of the command. Sometimes, if there is a position a
 *   ↪subsystem is moving to, the command might set the target position for the
 *   ↪subsystem in initialize() and have an empty execute() method.
 */
void MyCommandName::Execute()
{
}

bool MyCommandName::IsFinished()
{
    return false;
}

void MyCommandName::End()
{
}

// Make this return true when this Command no longer needs to run execute()
void MyCommandName::Interrupted()
{
}

```

## Simple Command Example

This example illustrates a simple command that will drive the robot using tank drive with values provided by the joysticks.

Java

```

public class DriveWithJoysticks extends Command {

    public DriveWithJoysticks() {
        requires(drivetrain); // drivetrain is an instance of our Drivetrain subsystem
    }

    protected void initialize() {
    }

    /*
     *   execute() - In our execute method we call a tankDrive method we have created
     *   ↪in our subsystem. This method takes two speeds as a parameter which we get from
     *   ↪methods in the OI class.
     *   ↪These methods abstract the joystick objects so that if we want to change how
     *   ↪we get the speed later we can do so without modifying our commands
     *   ↪(for example, if we want the joysticks to be less sensitive, we can multiply
     *   ↪them by .5 in the getLeftSpeed method and leave our command the same).
     */
    protected void execute() {
        drivetrain.tankDrive(oi.getLeftSpeed(), oi.getRightSpeed());
    }
}

```

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```

    /*
     * isFinished - Our isFinished method always returns false meaning this command
     ↪ never completes on it's own. The reason we do this is that this command will be set
     ↪ as the default command for the subsystem. This means that whenever the subsystem is
     ↪ not running another command, it will run this command. If any other command is
     ↪ scheduled it will interrupt this command, then return to this command when the
     ↪ other command completes.
    */
    protected boolean isFinished() {
        return false;
    }

    protected void end() {
    }

    protected void interrupted() {
    }
}

```

C++

```

#include "DriveWithJoysticks.h"
#include "RobotMap.h"

DriveWithJoysticks::DriveWithJoysticks() : CommandBase("DriveWithJoysticks")
{
    Requires(Robot::drivetrain); // Drivetrain is our instance of the drive system
}

// Called just before this Command runs the first time
void DriveWithJoysticks::Initialize()
{
}

/*
 * execute() - In our execute method we call a tankDrive method we have created
 ↪ in our subsystem. This method takes two speeds as a parameter which we get from
 ↪ methods in the OI class.
 * These methods abstract the joystick objects so that if we want to change how
 ↪ we get the speed later we can do so without modifying our commands
 * (for example, if we want the joysticks to be less sensitive, we can multiply
 ↪ them by .5 in the getLeftSpeed method and leave our command the same).
*/
void DriveWithJoysticks::Execute()
{
    Robot::drivetrain->Drive(Robot::oi->GetLeftSpeed(), Robot::oi->GetRightSpeed());
}

/*
 * isFinished - Our isFinished method always returns false meaning this command
 ↪ never completes on it's own. The reason we do this is that this command will be set
 ↪ as the default command for the subsystem. This means that whenever the subsystem is
 ↪ not running another command, it will run this command. If any other command is
 ↪ scheduled it will interrupt this command, then return to this command when the
 ↪ other command completes.
*/

```

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```

bool DriveWithJoysticks::IsFinished()
{
    return false;
}

void DriveWithJoysticks::End()
{
    Robot::drivetrain->Drive(0, 0);
}

// Called when another command which requires one or more of the same
// subsystems is scheduled to run
void DriveWithJoysticks::Interrupted()
{
    End();
}

```

### 19.3.2 Creating Groups of Commands

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

**Note:** Once you have created commands to operate the mechanisms in your robot, they can be grouped together to get more complex operations. These groupings of commands are called CommandGroups and are easily defined as shown in this article.

### Complex Operations

Java

```

public class PlaceSoda extends CommandGroup {

    public PlaceSoda() {
        addSequential(new SetElevatorSetpoint(Elevator.TABLE_HEIGHT));
        addSequential(new SetWristSetpoint(Wrist.PICKUP));
        addSequential(new OpenClaw());
    }
}

```

C++

```

#include "PlaceSoda.h"
#include "Elevator.h"
#include "Wrist.h"

PlaceSoda::PlaceSoda()
{

```

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```

AddSequential(new SetElevatorSetpoint(Elevator::TABLE_HEIGHT));
AddSequential(new SetWristSetpoint(Wrist::PICKUP));
AddSequential(new OpenClaw());
}

```

This is an example of a command group that places a soda can on a table. To accomplish this, (1) the robot elevator must move to the TABLE\_HEIGHT, then (2) set the wrist angle, then (3) open the claw. All of these tasks must run sequentially to make sure that the soda can isn't dropped. The addSequential() method takes a command (or a command group) as a parameter and will execute them one after another when this command is scheduled.

## Running Commands in Parallel

Java

```

public class PrepareToGrab extends CommandGroup {

    public PrepareToGrab() {
        addParallel(new SetWristSetpoint(Wrist.PICKUP));
        addParallel(new SetElevatorSetpoint(Elevator.BOTTOM));
        addParallel(new OpenClaw());
    }
}

```

C++

```

#include "PrepareToGrab.h"
#include "Wrist.h"
#include "Elevator.h"

PrepareToGrab::PrepareToGrab()
{
    AddParallel(new SetWristSetpoint(Wrist::PICKUP));
    AddParallel(new SetElevatorSetpoint(Elevator::BOTTOM));
    AddParallel(new OpenClaw());
}

```

To make the program more efficient, often it is desirable to run multiple commands at the same time. In this example, the robot is getting ready to grab a soda can. Since the robot isn't holding anything, all the joints can move at the same time without worrying about dropping anything. Here all the commands are run in parallel so all the motors are running at the same time and each completes whenever the isFinished() method is called. The commands may complete out of order. The steps are: (1) move the wrist to the pickup setpoint, then (2) move the elevator to the floor pickup position, and (3) open the claw

## Mixing Parallel and Sequential Commands

Java

```

public class Grab extends CommandGroup {

    public Grab() {

```

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```

        addSequential(new CloseClaw());
        addParallel(new SetElevatorSetpoint(Elevator.STOW));
        addSequential(new SetWristSetpoint(Wrist.STOW));
    }
}

```

C++

```

#include "Grab.h"
#include "Elevator.h"
#include "Wrist.h"

Grab::Grab()
{
    AddSequential(new CloseClaw());
    AddParallel(new SetElevatorSetpoint(Elevator::STOW));
    AddSequential(new SetWristSetpoint(Wrist::STOW));
}

```

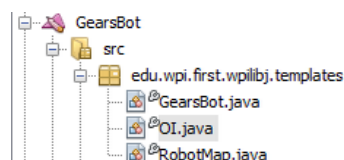
Often there are some parts of a command group that must complete before other parts run. In this example, a soda can is grabbed, then the elevator and wrist can move to their stowed positions. In this case, the wrist and elevator have to wait until the can is grabbed, then they can operate independently. The first command (1) `CloseClaw` grabs the soda and nothing else runs until it is finished since it is sequential, then the (2) elevator and (3) wrist move at the same time.

### 19.3.3 Running Commands on Joystick Input

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

**Note:** You can cause commands to run when joystick buttons are pressed, released, or continuously while the button is held down. This is extremely easy to do only requiring a few lines of code.

#### The OI Class



```

21 public class OI {
22     // Create the joystick and of the 8 buttons on it
23     Joystick leftJoy = new Joystick(1);
24     Button button1 = new JoystickButton(leftJoy, 1),
25         button2 = new JoystickButton(leftJoy, 2),

```

The command based template contains a class called OI, located in `OI.java`, where **Operator Interface** behaviors are typically defined.

## Create the Joystick object and JoystickButton Objects

Java

```
public class OI {
    // Create the joystick and the 8 buttons on it
    Joystick leftJoy = new Joystick(0);
    Button button1 = new JoystickButton(leftJoy, 1),
        button2 = new JoystickButton(leftJoy, 2),
        button3 = new JoystickButton(leftJoy, 3),
        button4 = new JoystickButton(leftJoy, 4),
        button5 = new JoystickButton(leftJoy, 5),
        button6 = new JoystickButton(leftJoy, 6),
        button7 = new JoystickButton(leftJoy, 7),
        button8 = new JoystickButton(leftJoy, 8);
}
```

C++

```
OI::OI()
{
    joy = new Joystick(0);

    JoystickButton* button1 = new JoystickButton(joy, 1),
        button2 = new JoystickButton(joy, 2),
        button3 = new JoystickButton(joy, 3),
        button4 = new JoystickButton(joy, 4),
        button5 = new JoystickButton(joy, 5),
        button6 = new JoystickButton(joy, 6),
        button7 = new JoystickButton(joy, 7),
        button8 = new JoystickButton(joy, 8);
}
```

In this example there is a Joystick object connected as Joystick 0. Then 8 buttons are defined on that joystick to control various aspects of the robot. This is especially useful for testing although generating buttons on SmartDashboard is another alternative for testing commands.

## Associate the Buttons with Commands

Java

```
public OI() {
    button1.whenPressed(new PrepareToGrab());
    button2.whenPressed(new Grab());
    button3.whenPressed(new DriveToDistance(0.11));
    button4.whenPressed(new PlaceSoda());
    button6.whenPressed(new DriveToDistance(0.2));
    button8.whenPressed(new Stow());

    button7.whenPressed(new SodaDelivery());
}
```

C++

```
button1->WhenPressed(new PrepareToGrab());
button2->WhenPressed(new Grab());
button3->WhenPressed(new DriveToDistance(0.11));
button4->WhenPressed(new PlaceSoda());
button6->WhenPressed(new DriveToDistance(0.2));
button8->WhenPressed(new Stow());

button7->WhenPressed(new SodaDelivery());
```

In this example most of the joystick buttons from the previous code fragment are associated with commands. When the associated button is pressed the command is run. This is an excellent way to create a teleop program that has buttons to do particular actions.

### Other Options

In addition to the `whenPressed()` condition showcased above, there are a few other conditions you can use to link buttons to commands:

- Commands can run when a button is released by using `whenReleased()` instead of `whenPressed()`.
- Commands can run continuously while the button is depressed by calling `whileHeld()`.
- Commands can be toggled when a button is pressed using `toggleWhenPressed()`.
- A command can be canceled when a button is pressed using `cancelWhenPressed()`.

Additionally commands can be triggered by arbitrary conditions of your choosing by using the `Trigger` class instead of `Button`. Triggers (and Buttons) are usually polled every 20ms or whenever the scheduler is called.

### 19.3.4 Running Commands during Autonomous

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

---

**Note:** Once commands are defined they can run in either the teleop or autonomous part of the program. In fact, the power of the command based programming approach is that you can reuse the same commands in either place. If the robot has a command that can shoot Frisbees during autonomous with camera aiming and accurate shooting, there is no reason not to use it to help the drivers during the teleop period of the game.

---

Java

```
public class SodaDelivery extends CommandGroup {

    public SodaDelivery() {
        addSequential(new PrepareToGrab());
        addSequential(new Grab());
        addSequential(new DriveToDistance(0.11));
    }
}
```

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```

        addSequential(new PlaceSoda());
        addSequential(new DriveToDistance(0.2));
        addSequential(new Stow());
    }
}

```

C++

```

#include "PlaceSoda.h"

PlaceSoda::PlaceSoda()
{
    AddSequential(new PrepareToGrab());
    AddSequential(new Grab());
    AddSequential(new DriveToDistance(0.11));
    AddSequential(new PlaceSoda());
    AddSequential(new DriveToDistance(0.2));
    AddSequential(new Stow());
}

```

Our robot must do the following tasks during the autonomous period: pick up a soda can off the floor then drive a set distance from a table and deliver the can there. The process consists of:

1. Prepare to grab (move elevator, wrist, and gripper into position)
2. Grab the soda can
3. Drive to a distance from the table indicated by an ultrasonic rangefinder
4. Place the soda
5. Back off to a distance from the rangefinder
6. Re-stow the gripper

To do these tasks there are 6 commands that are executed sequentially as shown in this example (note that some of these, such as PlaceSoda are other command groups).

## Setting the Command to Run during Autonomous

Java

```

public class Robot extends TimedRobot {
    Command autonomousCommand;

    /**
     * This function is run when the robot is first started up and should be
     * used for any initialization code.
     */
    public void robotInit() {
        oi = new OI();
        // instantiate the command used for the autonomous period
        autonomousCommand = new SodaDelivery();
    }

    public void autonomousInit() {

```

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```

    // schedule the autonomous command (example)
    if (autonomousCommand != null) autonomousCommand.start();
}

/**
 * This function is called periodically during autonomous
 */
public void autonomousPeriodic() {
    Scheduler.getInstance().run();
}

```

C++

```

Command* autonomousCommand;

class Robot: public TimedRobot {

    /**
     * This function is run when the robot is first started up and should be
     * used for any initialization code.
     */
    void RobotInit()
    {
        // instantiate the command used for the autonomous period
        autonomousCommand = new SodaDelivery();
        oi = new OI();
    }

    void AutonomousInit()
    {
        // schedule the autonomous command (example)
        if(autonomousCommand != NULL) autonomousCommand->Start();
    }
    /**
     * This function is called periodically during autonomous
     */
    void AutonomousPeriodic()
    {
        Scheduler::GetInstance()->Run();
    }
}

```

To get the SodaDelivery command to run as the Autonomous program,

1. Instantiate it in the RobotInit() method. RobotInit() is called only once when the robot starts so it is a good time to create the command instance.
2. Start it during the AutonomousInit() method. AutonomousInit() is called once at the start of the autonomous period so we schedule the command there.
3. Be sure the scheduler is called repeatedly during the AutonomousPeriodic() method. AutonomousPeriodic() is called (nominally) every 20ms so that is a good time to run the scheduler which makes a pass through all the currently scheduled commands.

### 19.3.5 Default Commands

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

In some cases you may have a subsystem which you want to always be running a command no matter what. So what do you do when the command you are currently running ends? That's where default commands come in.

#### The Default Command

Each subsystem may, but is not required to, have a default command which is scheduled whenever the subsystem is idle (the command currently requiring the system completes). The most common example of a default command is a command for the drivetrain that implements the normal joystick control. This command may be interrupted by other commands for specific maneuvers ("precision mode", automatic alignment/targeting, etc.) but after any command requiring the drivetrain completes the joystick command would be scheduled again.

#### Setting the Default Command

Java

```
public class ExampleSubsystem extends Subsystem {

    // Put methods for controlling this subsystem
    // here. Call these from Commands.

    public void initDefaultCommand() {
        // Set the default command for a subsystem here.
        setDefaultCommand(new MyDefaultCommand());
    }
}
```

C++

```
#include "ExampleSubsystem.h"

ExampleSubsystem::ExampleSubsystem()
{
    // Put methods for controlling this subsystem
    // here. Call these from Commands.
}

ExampleSubsystem::InitDefaultCommand()
{
    // Set the default command for a subsystem here.
    SetDefaultCommand(new MyDefaultCommand());
}
```

All subsystems should contain a method called `initDefaultCommand()` which is where you will set the default command if desired. If you do not wish to have a default command, simply

leave this method blank. If you do wish to set a default command, call `setDefaultCommand` from within this method, passing in the command to be set as the default.

### 19.3.6 Synchronizing Two Commands

---

**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

---

Commands can be nested inside of command groups to create more complex commands. The simpler commands can be added to the command groups to either run sequentially (each command finishing before the next starts) or in parallel (the command is scheduled, and the next command is immediately scheduled also). Occasionally there are times where you want to make sure that two parallel command complete before moving onto the next command. This article describes how to do that.

#### CommandGroup with Sequential and Parallel Commands

Java

```
public class CoopBridgeAutonomous extends CommandGroup {

    public CoopBridgeAutonomous() {
        //SmartDashboard.putDouble("Camera Time", 5.0);
        addSequential(new SetTipperState(BridgeTipper.READY_STATE)); // 1
        addParallel(new SetVirtualSetpoint(SetVirtualSetpoint.HYBRID_LOCATION)); // 2
        addSequential(new DriveToBridge()); // 3
        addParallel(new ContinuousCollect());
        addSequential(new SetTipperState(BridgeTipper.DOWN_STATE));

        // addParallel(new WaitThenShoot());

        addSequential(new TurnToTargetLowPassFilterHybrid(4.0));
        addSequential(new FireSequence());
        addSequential(new MoveBallToShooter(true));
    }
}
```

C++

```
#include "CoopBridgeAutonomous.h"

CoopBridgeAutonomous::CoopBridgeAutonomous()
{
    // SmartDashboard->PutDouble("Camera Time", 5.0);
    AddSequential(new SetTipperState(READY_STATE);
    AddParallel(new SetVirtualSetpoint(HYBRID_LOCATION);
    AddSequential(new DriveToBridge());
    AddParallel(new ContinuousCollect());
    AddSequential(new SetTipperState(DOWN_STATE));

    // addParallel(new WaitThenShoot());
```

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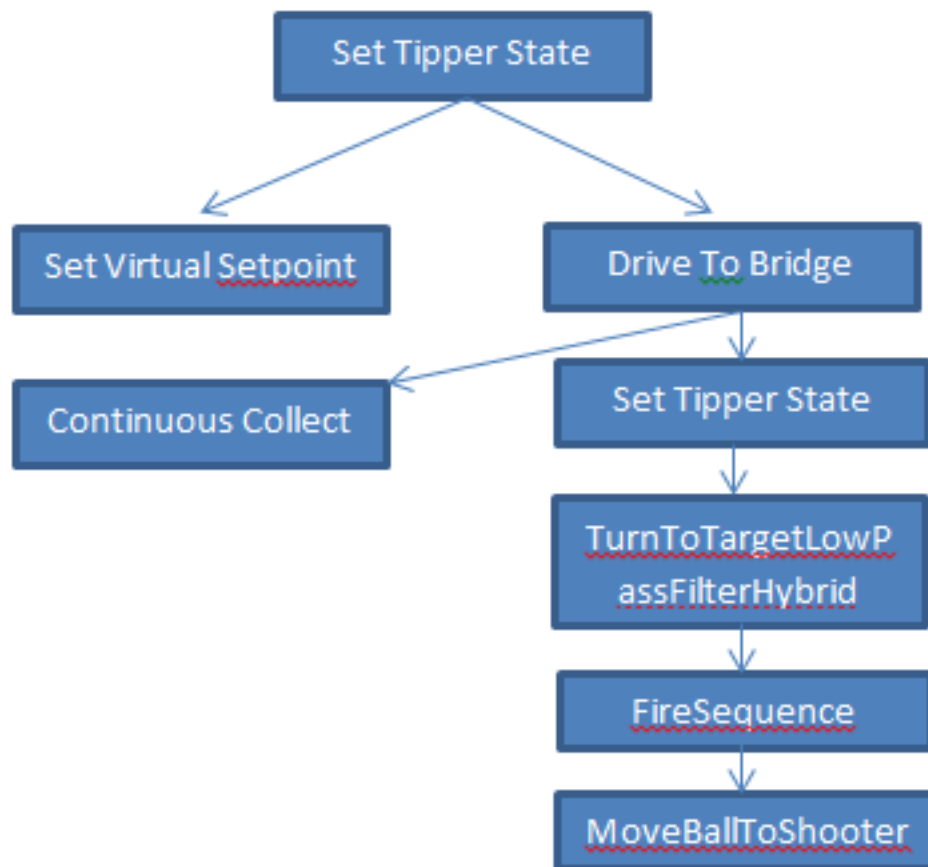
```

AddSequential(new TurnToTargetLowPassFilterHybrid(4.0));
AddSequential(new FireSequence());
AddSequential(new MoveBallToShooter(true));
}

```

In this example some commands are added in parallel and others are added sequentially to the CommandGroup CoopBridgeAutonomous (1). The first command “SetTipperState” is added and completes before the SetVirtualSetpoint command starts (2). Before SetVirtualSetpoint command completes, the DriveToBridge command is immediately scheduled because of the SetVirtualSetpoint is added in parallel (3). This example might give you an idea of how commands are scheduled.

### Example Flowchart

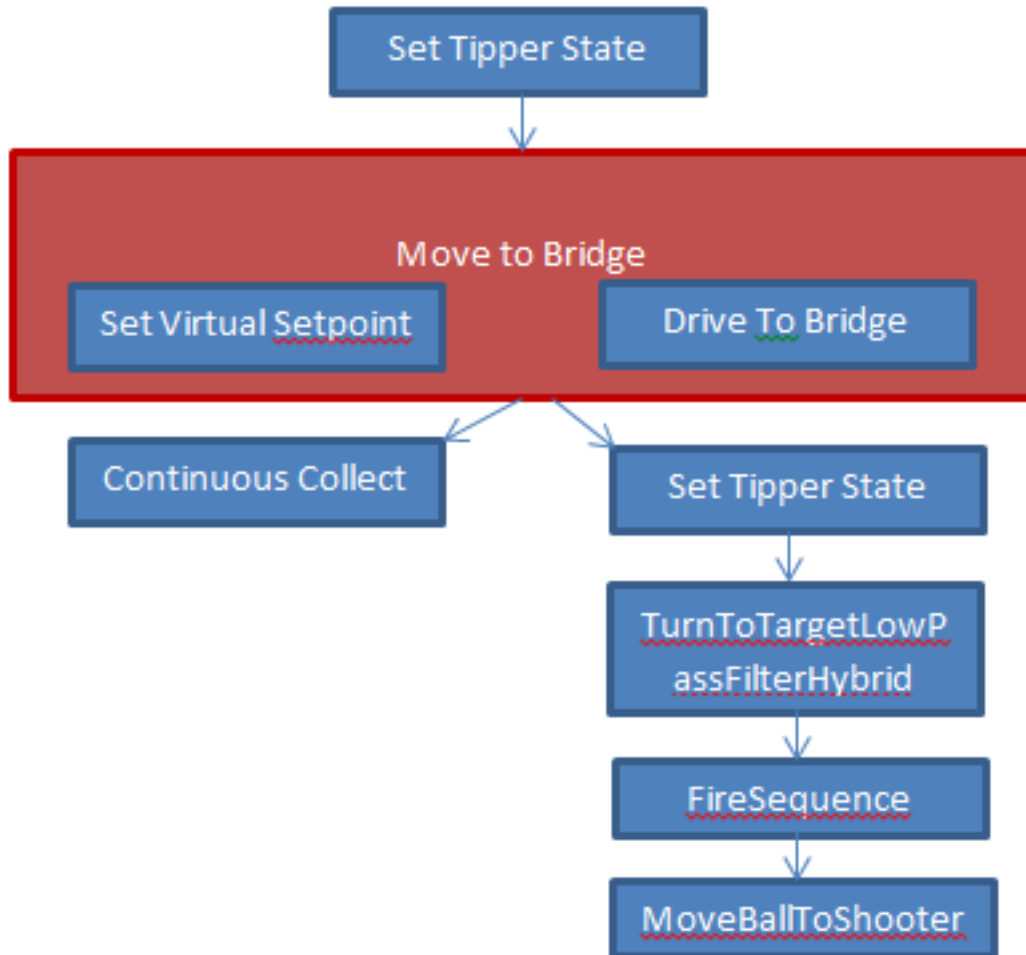


**Note:** There is no dependency coming from the commands scheduled using “Add Parallel” either or both of these commands could still be running when the MoveBallToShooter command is reached.

Here is the code shown above represented as a flowchart. Any command in the main sequence (the sequence on the right here) that requires a subsystem in use by a parallel command will cause the parallel command to be canceled. For example, if the FireSequence required a sub-

system in use by SetVirtualSetpoint, the SetVirtualSetpoint command will be canceled when FireSequence is scheduled.

### Waiting for a Command



If there are two commands that need to complete before the following commands are scheduled, they can be put into a command group by themselves, adding both in parallel. Then that command group can be scheduled sequentially from an enclosing command group. When a command group is scheduled sequentially, the commands inside it will all finish before the next outer command is scheduled. In this way you can be sure that an action consisting of multiple parallel commands has completed before going on to the next command.

In this example you can see that the addition of a command group "Move to Bridge" containing the **Set Virtual Setpoint** and **Drive to Bridge** commands forces both to complete before the next commands are scheduled.

### 19.3.7 Scheduling Commands

---

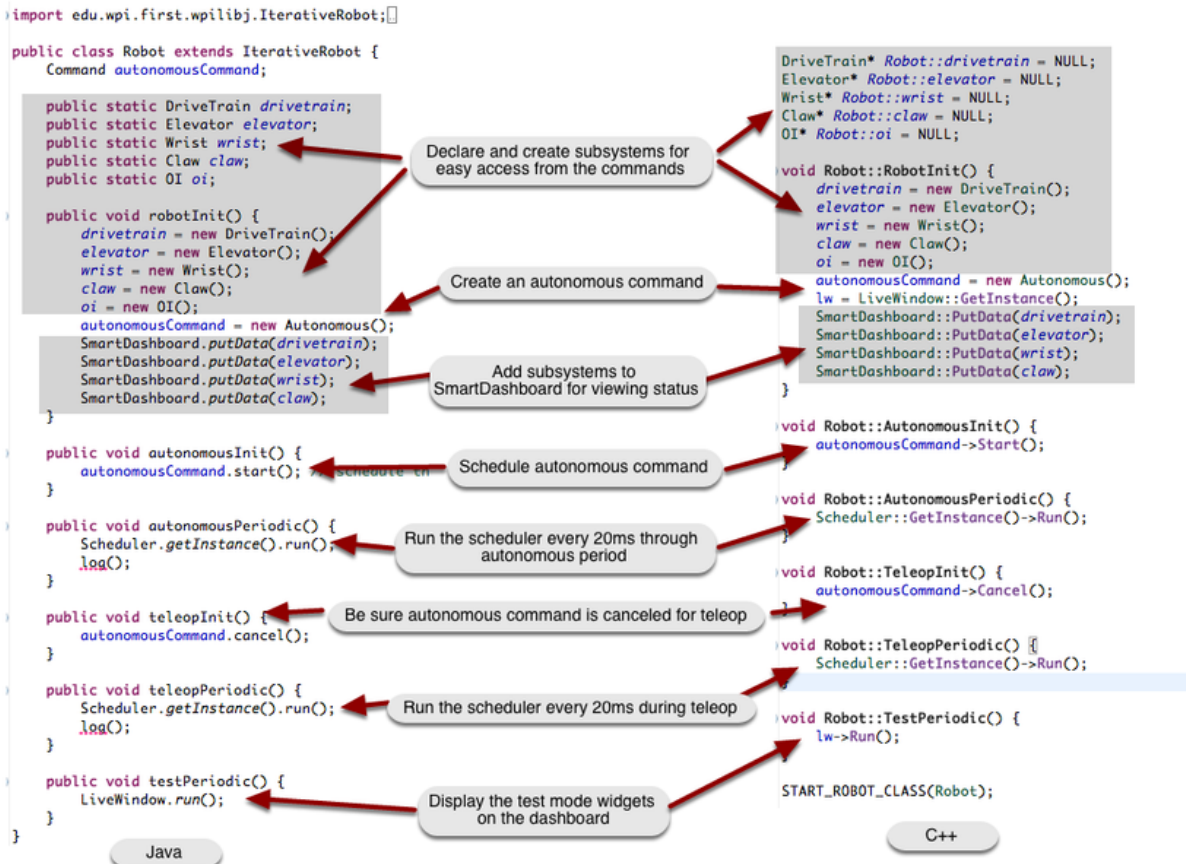
**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the *new command-based library*.

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Commands are scheduled to run based on a number of factors such as triggers, default commands when no other running commands require a subsystem, a prior command in a group finishes, button presses, autonomous period starting, etc. Although many commands may be running virtually at the same time, there is only a single thread (the main robot thread). This is to reduce the complexity of synchronization between threads. There are threads that run in the system for systems like PID loops, communications, etc. but those are all self contained with very little interaction requiring complex synchronization. This makes the system much more robust and predictable.

This is accomplished by a class called Scheduler. It has a `run()` method that is called periodically (typically every 20ms in response to a driver station update) that tries to make progress on every command that is currently running. This is done by calling the `execute()` method on the command followed by the `isFinished()` method. If `isFinished()` returns true, the command is marked to be removed from execution on the next pass through the scheduler. So if there are a number of commands all scheduled to run at the same time, then every time the `Scheduler.run()` method is called, each of the active commands `execute()` and `isFinished()` methods are called. This has the same effect as using multiple threads.

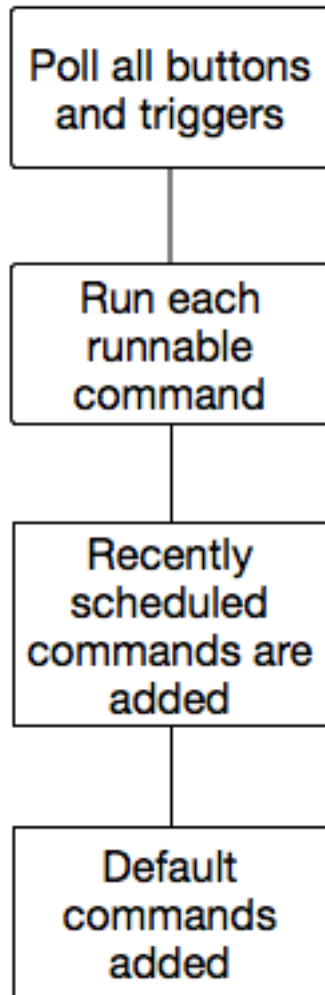
## Command-Based Program Anatomy



This shows a typical command-based Robot program and all the code needed to ensure that commands are scheduled correctly. The `Scheduler.run` method causes one pass through the scheduler which will let each currently active command run through its `execute()` and `isFinished()` methods. Ignore the `log()` methods in the Java example.

## Command Life Cycle

### Scheduler.run()



The work in command-based programs occurs whenever the Scheduler.Run (C++) or Scheduler.run (Java) method is called. This is typically called on each driver station update which occurs every 20 ms or 50 times per second. The pseudo code illustrates what happens on each call to the run method.

1. Buttons and triggers are polled to see if the associated commands should be scheduled. If the trigger is true, the command is added to a list of commands that should be scheduled.
2. Loop through the list of all the commands that are currently runnable and call their execute and isFinished methods. Commands where the isFinished method returns true are removed from the list of currently running commands.
3. Loop through all the commands that have been scheduled to run in the previous steps. Those commands are added to the list of running commands.



4. Default commands are added for each subsystem that currently has no commands running that require that subsystem.

### Optimizing Command Groups

Java

```
public class Pickup extends CommandGroup {
    public Pickup() {
        addSequential(new CloseClaw());
        addParallel(new SetWristSetpoint(-45));
        addSequential(new SetElevatorSetpoint(0.25));
    }
}
```

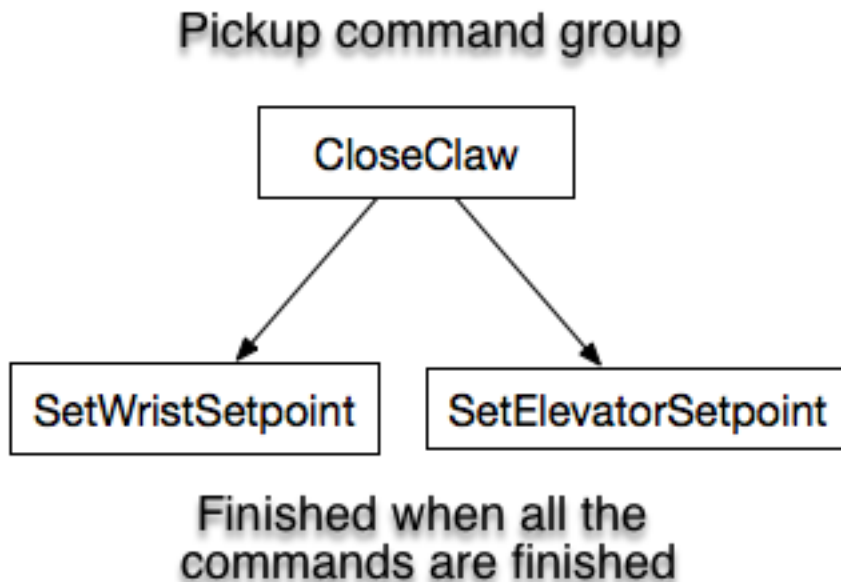
C++

```
Pickup::Pickup() : CommandGroup("Pickup") {
    AddSequential(new CloseClaw());
    AddParallel(new SetWristSetpoint(-45));
    AddSequential(new SetElevatorSetpoint(0.25));
}
```

Once you have working commands that operate the mechanisms on your robot you can combine those commands into groups to make more complex actions. Commands can be added to command groups to execute sequentially or in parallel. Sequential commands wait until they are finished (`isFinished` method returns true) before running the next command in the group. Parallel commands start running, then immediately schedule the next command in the group.

It is important to notice that the commands are added to the group in the constructor. The command group is simply a list of command instances that run when scheduled and any parameters that are passed to the commands are evaluated during the constructor for the group.

Imagine that in a robot design, there is a claw, attached to a wrist joint and all of those on an elevator. When picking up something, the claw needs to close first before either the elevator or wrist can move otherwise the object may slip out of the claw. In the example shown above the `CloseClaw` command will be scheduled first. After it is finished (the claw is closed), the wrist will move to its setpoint and in parallel, the elevator will move. This gets both the elevator and wrist moving simultaneously optimizing the time required to complete the task.

**When do command groups finish?**

A command group finishes when all the commands started in that group finish. This is true regardless of the type of commands that are added to the group. For example, if a number of commands are added in parallel and sequentially, the group is finished when all the commands added to the group are finished. As each command is added to a command group, it is put on a list. As those child commands finish, they are taken off the list. The command group is finished when the list of child commands is empty.

In the Pickup command shown in the example above, the command is finished when CloseClaw, SetWristSetpoint, and SetElevatorSetpoint all finish. It doesn't matter that some of the commands are sequential and some parallel.

**Schedule a Command within a Running Command**

Commands can be scheduled by calling the `start()` method (Java) or `Start()` method (C++) on a command instance. This will cause the command to be added to the currently running set of commands in the scheduler. This is often useful when a program needs to conditionally schedule one command or another. The newly scheduled command will be added to a list of new commands on this pass through the run method of the scheduler and actually will run the first time on the next pass through the run method. Newly created commands are never executed in the same call to the scheduler run method, always queued for the next call which usually occurs 20ms later.

**Removing all Commands from the Scheduler**

Java

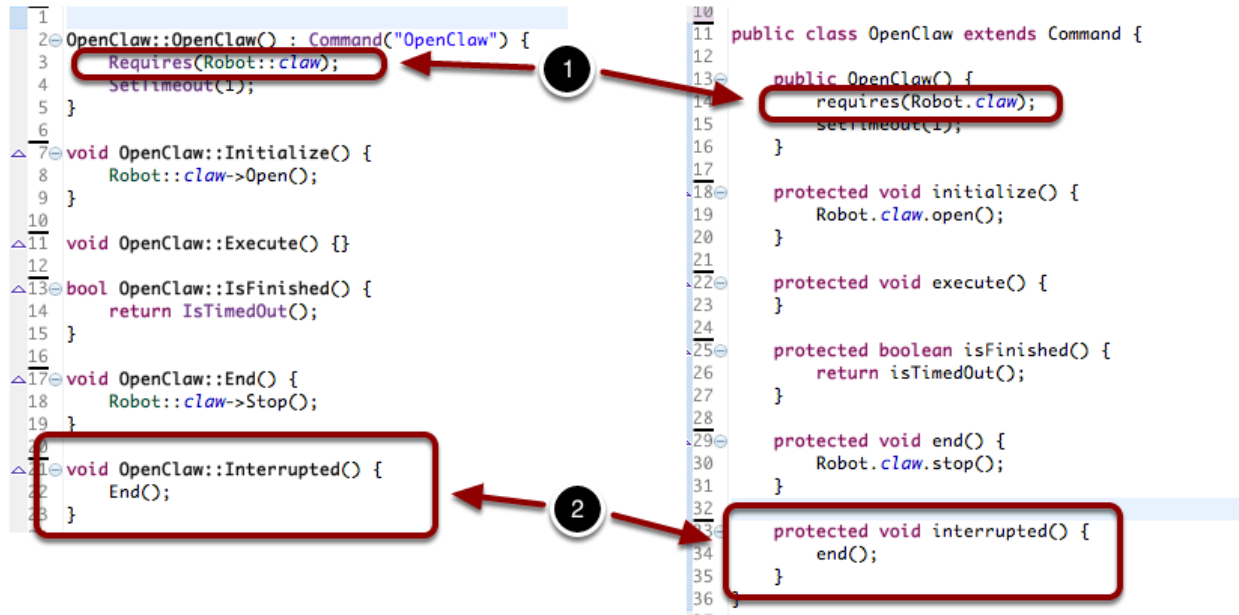
```
Scheduler.getInstance().removeAll();
```

C++

```
Scheduler::RemoveAll();
```

It is occasionally useful to make sure that there are no running commands in the scheduler. To remove all running commands use the `Scheduler.removeAll()` method (Java) or `Scheduler::RemoveAll()` method (C++). This will cause all currently running to have their `interrupted()` method (Java) or `Interrupted()` method (C++) called. Commands that have not yet started will have their `end()` method (Java) or `End()` method (C++) called.

### The “requires” method



If you have multiple commands that use the same subsystem it makes sense that they don't run at the same time. For example, if there is a Claw subsystem with `OpenClaw` and `CloseClaw` commands, they can't both run at the same time. Each command that uses the Claw subsystem declares that by 1 calling the `requires()` method (Java) or `Requires()` method (C++). When one of the commands is running, say from a joystick button press, and you try to run another command that also requires the Claw, the second one preempts the first one. Suppose that `OpenClaw` was running, and you press the button to run the `CloseClaw` command. The `OpenClaw` command is interrupted - 2 its `interrupted` method is called on the next run cycle and the `CloseClaw` command is scheduled. If you think about it, this is almost always the desired behavior. If you pressed a button to start opening the claw and you change your mind and want to close it, it makes sense for the `OpenClaw` command to be stopped and the `CloseClaw` to be started.

A command may require many subsystems, for example a complex autonomous sequence might use a number of subsystems to complete its task.

Command groups automatically require all the subsystems for each of the commands in the group. There is no need to call the `requires` method for a group.

### How are the requirements of a group evaluated?

The subsystems that a command group requires is the union of the set of subsystems that are required for all of the child commands. If a 4 commands are added to a group, then the group will require all of the subsystems required by each of the 4 commands in the group. For example, if are three commands scheduled in a group - the first requires subsystem A, the second requires subsystem B, and the third requires subsystems C and D. The group will require subsystems A, B, C, and D. If another command is started, say from a joystick button, that requires either A, B, C, or D it will interrupt the entire group including any parallel or sequential commands that might be running from that group.

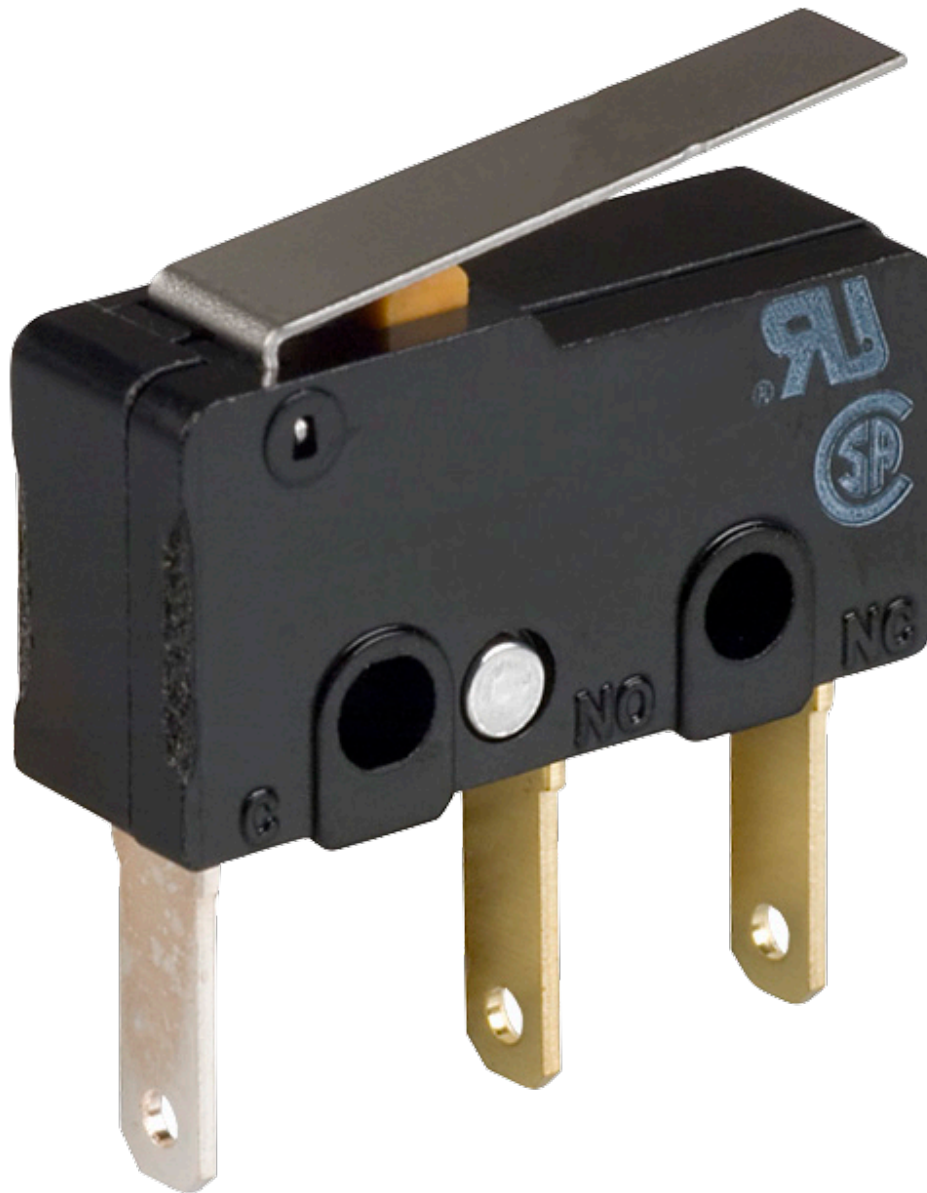
### 19.3.8 Using Limit Switches to Control Behavior

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**Important:** This documentation describes the use of the legacy command-based library. While this documentation has been preserved to help teams that have yet to do so, teams are strongly encouraged to migrate to the [new command-based library](#).

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Limit switches are often used to control mechanisms on robots. While limit switches are simple to use, they only can sense a single position of a moving part. This makes them ideal for ensuring that movement doesn't exceed some limit but not so good at controlling the speed of the movement as it approaches the limit. For example, a rotational shoulder joint on a robot arm would best be controlled using a potentiometer or an absolute encoder, the limit switch could make sure that if the potentiometer ever failed, the limit switch would stop the robot from going to far and causing damage.

**Values Provided**

Limit switches can have “normally opened” or “normally closed” outputs. The usual way of wiring the switch is between a digital input signal connection and ground. The digital input has pull-up resistors that will make the input be high (1 value) when the switch is open, but when the switch closes the value goes to 0 since the input is now connected to ground. The switch shown here has both normally open and normally closed outputs.

**Polling - Waiting for a Switch to Close**

Java

```

import edu.wpi.first.wpilibj.DigitalInput;
import edu.wpi.first.wpilibj.SampleRobot;
import edu.wpi.first.wpilibj.Timer;

public class RobotTemplate extends SampleRobot {

    DigitalInput limitSwitch;

    public void robotInit() {
        limitSwitch = new DigitalInput(1);
    }

    public void operatorControl() {
        // more code here
        while (limitSwitch.get()) {
            Timer.delay(10);
        }
    }
}

```

C++

```

#include "RobotTemplate.h"
#include "frc/DigitalInput.h"

RobotTemplate::RobotTemplate()
{
    DigitalInput* limitSwitch;
}

void RobotTemplate::RobotInit()
{
    limitSwitch = new DigitalInput(1);
}

void RobotTemplate::operatorControl()
{
    while(limitSwitch->Get())
    {
        Wait(10);
    }
}

```

You can write a very simple piece of code that just reads the limit switch over and over again waiting until it detects that its value transitions from 1 (opened) to 0 (closed). While this works, it's usually impractical for the program to be able to just wait for the switch to operate and not be doing anything else, like responding to joystick input. This example shows the fundamental use of the switch, but while the program is waiting, nothing else is happening.

### Operating until Limit Closed

Java

```

package edu.wpi.first.wpilibj.templates.commands;

```

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```
public class ArmUp extends CommandBase {
    public ArmUp() {

        protected void initialize() {
            arm.armUp();
        }

        protected void execute() {

        }

        protected boolean isFinished() {
            return arm.isSwitchSet();
        }

        protected void end() {
            arm.armStop();
        }

        protected void interrupted() {
            end();
        }
    }
}
```

C++

```
#include "ArmUp.h"

ArmUp::ArmUp()
{

}

void ArmUp::Initialize()
{
    arm.ArmUp();
}

void ArmUp::Execute()
{

}

void ArmUp::IsFinished()
{
    return arm.isSwitchSet();
}

void ArmUp::End()
{
    arm.ArmStop();
}

void ArmUp::Interrupted()
{
    End();
}
```

Commands call their `execute()` and `isFinished()` methods about 50 times per second, or at a rate of every 20ms. A command that will operate a motor until the limit switch is closed can read the digital input value in the `isFinished()` method and return true when the switch changes to the correct state. Then the command can stop the motor.

**Important:** Remember, the mechanism (an Arm in this case) has some inertia and won't stop immediately so it's important to make sure things don't break while the arm is slowing.

## Counter to detect Switch Close

Java

```
package edu.wpi.first.wpilibj.templates.subsystems;
import edu.wpi.first.wpilibj.Counter;
import edu.wpi.first.wpilibj.DigitalInput;
import edu.wpi.first.wpilibj.SpeedController;
import edu.wpi.first.wpilibj.Victor;
import edu.wpi.first.wpilibj.command.Subsystem;
public class Arm extends Subsystem {

    DigitalInput limitSwitch = new DigitalInput(1);
    SpeedController armMotor = new Victor(1);
    Counter counter = new Counter(limitSwitch);

    public boolean isSwitchSet() {
        return counter.get() > 0;
    }

    public void initializeCounter() {
        counter.reset();
    }

    public void armUp() {
        armMotor.set(0.5);
    }

    public void armDown() {
        armMotor.set(-0.5);
    }

    public void armStop() {
        armMotor.set(0.0);
    }
    protected void initDefaultCommand() {
    }
}
```

C++

```
#include "Arm.h"
#include "frc/Counter.h"
#include "frc/DigitalInput.h"
#include "frc/SpeedController.h"
#include "frc/Victor.h"
```

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```

DigitalInput* limitSwitch;
SpeedController* armMotor;
Counter* counter;

Arm::Arm()
{
    limitSwitch = new DigitalInput(1);
    armMotor = new Victor(1);
    counter = new Counter(limitSwitch);
}

bool Arm::IsSwitchSet()
{
    return counter->Get() >0;
}

void Arm::InitializeCounter()
{
    counter->Reset();
}

void Arm::ArmUp()
{
    armMotor->Set(.5);
}

void Arm::ArmDown()
{
    armMotor->Set(-0.5);
}

void Arm::ArmStop()
{
    armMotor->Set(0);
}

void InitDefaultCommand()
{
}

```

It's possible that a limit switch might close then open again as a mechanism moves past the switch. If the closure is fast enough the program might not notice that the switch closed. An alternative method of catching the switch closing is use a Counter object. Since counters are implemented in hardware, it will be able to capture the closing of the fastest switches and increment it's count. Then the program can simply notice that the count has increased and take whatever steps are needed to do the operation.

Above is a subsystem that uses a counter to watch the limit switch and wait for the value to change. When it does, the counter will increment and that can be watched in a command.

### Using a Command with a Counter to detect Limit Switch Close

Java

```

package edu.wpi.first.wpilibj.templates.commands;

public class ArmUp extends CommandBase {

    public ArmUp() {

    }

    protected void initialize() {
        arm.initializeCounter();
        arm.armUp();
    }

    protected void execute() {

    }

    protected boolean isFinished() {
        return arm.isSwitchSet();
    }

    protected void end() {
        arm.armStop();
    }

    protected void interrupted() {
        end();
    }

}

```

C++

```

#include "ArmUp.h"

ArmUp::ArmUp()
{
}

void ArmUp::Initialize()
{
    arm.InitializeCounter();
    arm.ArmUp();
}

void ArmUp::Execute()
{
}

bool ArmUp::IsFinished()
{
    return arm->IsSwitchSet();
}

void ArmUp::End()
{
    arm->ArmStop();
}

void ArmUp::Interrupted()

```

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```
{  
    End();  
}
```

This command initializes the counter in the above subsystem then starts the motor moving. It then tests the counter value in the `isFinished()` method waiting for it to count the limit switch changing. When it does, the arm is stopped. By using a hardware counter, a switch that might close then open very quickly can still be caught by the program.

## Kinematics and Odometry

### 20.1 Introduction to Kinematics and The Chassis Speeds Class

#### 20.1.1 What is kinematics?

The brand new kinematics suite contains classes for differential drive, swerve drive, and mecanum drive kinematics and odometry. The kinematics classes help convert between a universal `ChassisSpeeds` object, containing linear and angular velocities for a robot to usable speeds for each individual type of drivetrain i.e. left and right wheel speeds for a differential drive, four wheel speeds for a mecanum drive, or individual module states (speed and angle) for a swerve drive.

#### 20.1.2 What is odometry?

Odometry involves using sensors on the robot to create an estimate of the position of the robot on the field. In FRC, these sensors are typically several encoders (the exact number depends on the drive type) and a gyroscope to measure robot angle. The odometry classes utilize the kinematics classes along with periodic user inputs about speeds (and angles in the case of swerve) to create an estimate of the robot's location on the field.

#### 20.1.3 The Chassis Speeds Class

The `ChassisSpeeds` object is essential to the new WPILib kinematics and odometry suite. The `ChassisSpeeds` object represents the speeds of a robot chassis. This struct has three components:

- `vx`: The velocity of the robot in the x (forward) direction.
- `vy`: The velocity of the robot in the y (sideways) direction. (Positive values mean the robot is moving to the left).
- `omega`: The angular velocity of the robot in radians per second.

**Note:** A non-holonomic drivetrain (i.e. a drivetrain that cannot move sideways, ex: a differential drive) will have a  $v_y$  component of zero because of its inability to move sideways.

---

### 20.1.4 Constructing a ChassisSpeeds object

The constructor for the ChassisSpeeds object is very straightforward, accepting three arguments for  $v_x$ ,  $v_y$ , and  $\omega$ . In Java,  $v_x$  and  $v_y$  must be in meters per second. In C++, the units library may be used to provide a linear velocity using any linear velocity unit.

Java

```
// The robot is moving at 3 meters per second forward, 2 meters
// per second to the right, and rotating at half a rotation per
// second counterclockwise.
var speeds = new ChassisSpeeds(3.0, -2.0, Math.PI);
```

C++

```
// The robot is moving at 3 meters per second forward, 2 meters
// per second to the right, and rotating at half a rotation per
// second counterclockwise.
frc::ChassisSpeeds speeds{3.0_mps, -2.0_mps,
    units::radians_per_second_t(wpi::math::pi)};
```

### 20.1.5 Creating a ChassisSpeeds Object from Field-Relative Speeds

A ChassisSpeeds object can also be created from a set of field-relative speeds when the robot angle is given. This converts a set of desired velocities relative to the field (for example, toward the opposite alliance station and toward the right field boundary) to a ChassisSpeeds object which represents speeds that are relative to the robot frame. This is useful for implementing field-oriented controls for a swerve or mecanum drive robot.

The static ChassisSpeeds.fromFieldRelativeSpeeds (Java) / ChassisSpeeds::FromFieldRelativeSpeeds (C++) method can be used to generate the ChassisSpeeds object from field-relative speeds. This method accepts the  $v_x$  (relative to the field),  $v_y$  (relative to the field),  $\omega$ , and the robot angle.

Java

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
ChassisSpeeds speeds = ChassisSpeeds.fromFieldRelativeSpeeds(
    2.0, 2.0, Math.PI / 2.0, Rotation2d.fromDegrees(45.0));
```

C++

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
```

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```
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
frc::ChassisSpeeds speeds = frc::ChassisSpeeds::FromFieldRelativeSpeeds(
    2_mps, 2_mps, units::radians_per_second_t(wpi::math::pi / 2.0), Rotation2d(45_deg));
```

**Note:** The angular velocity is not explicitly stated to be “relative to the field” because the angular velocity is the same as measured from a field perspective or a robot perspective.

## 20.2 Differential Drive Kinematics

The `DifferentialDriveKinematics` class is a useful tool that converts between a `ChassisSpeeds` object and a `DifferentialDriveWheelSpeeds` object, which contains velocities for the left and right sides of a differential drive robot.

### 20.2.1 Constructing the Kinematics Object

The `DifferentialDriveKinematics` object accepts one constructor argument, which is the track width of the robot. This represents the distance between the two sets of wheels on a differential drive.

**Note:** In Java, the track width must be in meters. In C++, the units library can be used to pass in the track width using any length unit.

### 20.2.2 Converting Chassis Speeds to Wheel Speeds

The `toWheelSpeeds(ChassisSpeeds speeds)` (Java) / `ToWheelSpeeds(ChassisSpeeds speeds)` (C++) method should be used to convert a `ChassisSpeeds` object to a `DifferentialDriveWheelSpeeds` object. This is useful in situations where you have to convert a linear velocity ( $v_x$ ) and an angular velocity ( $\omega$ ) to left and right wheel velocities.

Java

```
// Creating my kinematics object: track width of 27 inches
DifferentialDriveKinematics kinematics =
    new DifferentialDriveKinematics(Units.inchesToMeters(27.0));

// Example chassis speeds: 2 meters per second linear velocity,
// 1 radian per second angular velocity.
var chassisSpeeds = new ChassisSpeeds(2.0, 0, 1.0);

// Convert to wheel speeds
DifferentialDriveWheelSpeeds wheelSpeeds = kinematics.toWheelSpeeds(chassisSpeeds);

// Left velocity
double leftVelocity = wheelSpeeds.leftMetersPerSecond;
```

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```
// Right velocity
double rightVelocity = wheelSpeeds.rightMetersPerSecond;
```

C++

```
// Creating my kinematics object: track width of 27 inches
frc::DifferentialDriveKinematics kinematics{27_in};

// Example chassis speeds: 2 meters per second linear velocity,
// 1 radian per second angular velocity.
frc::ChassisSpeeds chassisSpeeds{2_mps, 0_mps, 1_rad_per_s};

// Convert to wheel speeds. Here, we can use C++17's structured bindings
// feature to automatically split the DifferentialDriveWheelSpeeds
// struct into left and right velocities.
auto [left, right] = kinematics.ToWheelSpeeds(chassisSpeeds);
```

### 20.2.3 Converting Wheel Speeds to Chassis Speeds

One can also use the kinematics object to convert individual wheel speeds (left and right) to a singular ChassisSpeeds object. The `toChassisSpeeds(DifferentialDriveWheelSpeeds speeds)` (Java)/`ToChassisSpeeds(DifferentialDriveWheelSpeeds speeds)` (C++) method should be used to achieve this.

Java

```
// Creating my kinematics object: track width of 27 inches
DifferentialDriveKinematics kinematics =
    new DifferentialDriveKinematics(Units.inchesToMeters(27.0));

// Example differential drive wheel speeds: 2 meters per second
// for the left side, 3 meters per second for the right side.
var wheelSpeeds = new DifferentialDriveWheelSpeeds(2.0, 3.0);

// Convert to chassis speeds.
ChassisSpeeds chassisSpeeds = kinematics.toChassisSpeeds(wheelSpeeds);

// Linear velocity
double linearVelocity = chassisSpeeds.vxMetersPerSecond;

// Angular velocity
double angularVelocity = chassisSpeeds.omegaRadiansPerSecond;
```

C++

```
// Creating my kinematics object: track width of 27 inches
frc::DifferentialDriveKinematics kinematics{27_in};

// Example differential drive wheel speeds: 2 meters per second
// for the left side, 3 meters per second for the right side.
frc::DifferentialDriveWheelSpeeds wheelSpeeds{2_mps, 3_mps};

// Convert to chassis speeds. Here we can use C++17's structured bindings
```

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```
// feature to automatically split the ChassisSpeeds struct into its 3 components.
// Note that because a differential drive is non-holonomic, the vy variable
// will be equal to zero.
auto [linearVelocity, vy, angularVelocity] = kinematics.ToChassisSpeeds(wheelSpeeds);
```

## 20.3 Differential Drive Odometry

A user can use the differential drive kinematics classes in order to perform *odometry*. WPILib contains a `DifferentialDriveOdometry` class that can be used to track the position of a differential drive robot on the field.

**Note:** Because this method only uses encoders and a gyro, the estimate of the robot's position on the field will drift over time, especially as your robot comes into contact with other robots during gameplay. However, odometry is usually very accurate during the autonomous period.

### 20.3.1 Creating the Odometry Object

The `DifferentialDriveOdometry` class requires one mandatory argument and one optional argument. The mandatory argument is the angle reported by your gyroscope (as a `Rotation2d`). The optional argument is the starting pose of your robot on the field (as a `Pose2d`). By default, the robot will start at  $x = 0$ ,  $y = 0$ ,  $\theta = 0$ .

**Note:** 0 degrees / radians represents the robot angle when the robot is facing directly toward your opponent's alliance station. As your robot turns to the left, your gyroscope angle should increase. By default, WPILib gyros exhibit the opposite behavior, so you should negate the gyro angle.

**Important:** The encoder positions must be reset to zero before constructing the `DifferentialDriveOdometry` class.

Java

```
// Creating my odometry object. Here,
// our starting pose is 5 meters along the long end of the field and in the
// center of the field along the short end, facing forward.
DifferentialDriveOdometry m_odometry = new DifferentialDriveOdometry(
    getGyroHeading(), new Pose2d(5.0, 13.5, new Rotation2d()));
```

C++

```
// Creating my odometry object. Here,
// our starting pose is 5 meters along the long end of the field and in the
// center of the field along the short end, facing forward.
frc::DifferentialDriveOdometry m_odometry{GetGyroHeading(),
    frc::Pose2d{5_m, 13.5_m, 0_rad}};
```



### 20.3.2 Updating the Robot Pose

The update method can be used to update the robot's position on the field. This method must be called periodically, preferably in the `periodic()` method of a *Subsystem*. The update method returns the new updated pose of the robot. This method takes in the gyro angle of the robot, along with the left encoder distance and right encoder distance.

---

**Note:** The encoder distances in Java must be in meters. In C++, the units library can be used to represent the distance using any linear distance unit. If the robot is moving forward in a straight line, **both** distances (left and right) must be positive.

---

Java

```
@Override
public void periodic() {
    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    var gyroAngle = Rotation2d.fromDegrees(-m_gyro.getAngle());

    // Update the pose
    m_pose = m_odometry.update(gyroAngle, m_leftEncoder.getDistance(), m_rightEncoder.
        ↪getDistance());
}
```

C++

```
void Periodic() override {
    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    frc::Rotation2d gyroAngle{units::degree_t(-m_gyro.GetAngle())};

    // Update the pose
    m_pose = m_odometry.Update(gyroAngle, m_leftEncoder.GetDistance(), m_rightEncoder.
        ↪GetDistance());
}
```

### 20.3.3 Resetting the Robot Pose

The robot pose can be reset via the `resetPose` method. This method accepts two arguments – the new field-relative pose and the current gyro angle.

---

**Important:** If at any time, you decide to reset your gyroscope, the `resetPose` method **MUST** be called with the new gyro angle. Furthermore, the encoders must also be reset to zero when resetting the pose.

---

---

**Note:** A full example of a differential drive robot with odometry is available here: [C++ / Java](#).

---

In addition, the `GetPose` (C++) / `getPoseMeters` (Java) methods can be used to retrieve the current robot pose without an update.

## 20.4 Swerve Drive Kinematics

The `SwerveDriveKinematics` class is a useful tool that converts between a `ChassisSpeeds` object and several `SwerveModuleState` objects, which contains velocities and angles for each swerve module of a swerve drive robot.

### 20.4.1 The swerve module state class

The `SwerveModuleState` class contains information about the velocity and angle of a singular module of a swerve drive. The constructor for a `SwerveModuleState` takes in two arguments, the velocity of the wheel on the module, and the angle of the module.

---

**Note:** In Java, the velocity of the wheel must be in meters per second. In C++, the units library can be used to provide the velocity using any linear velocity unit.

---



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**Note:** An angle of 0 corresponds to the modules facing forward.

---

### 20.4.2 Constructing the kinematics object

The `SwerveDriveKinematics` class accepts a variable number of constructor arguments, with each argument being the location of a swerve module relative to the robot center (as a `Translation2d`). The number of constructor arguments corresponds to the number of swerve modules.

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**Note:** A swerve drive must have 2 or more modules.

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**Note:** In C++, the class is templated on the number of modules. Therefore, when constructing a `SwerveDriveKinematics` object as a member variable of a class, the number of modules must be passed in as a template argument. For example, for a typical swerve drive with four modules, the kinematics object must be constructed as follows: `frc::SwerveDriveKinematics<4>m_kinematics{...}`.

---

The locations for the modules must be relative to the center of the robot. Positive x values represent moving toward the front of the robot whereas positive y values represent moving toward the left of the robot.

Java

```
// Locations for the swerve drive modules relative to the robot center.
Translation2d m_frontLeftLocation = new Translation2d(0.381, 0.381);
Translation2d m_frontRightLocation = new Translation2d(0.381, -0.381);
Translation2d m_backLeftLocation = new Translation2d(-0.381, 0.381);
Translation2d m_backRightLocation = new Translation2d(-0.381, -0.381);

// Creating my kinematics object using the module locations
SwerveDriveKinematics m_kinematics = new SwerveDriveKinematics(
```

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```
m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation, m_backRightLocation
);
```

C++

```
// Locations for the swerve drive modules relative to the robot center.
frc::Translation2d m_frontLeftLocation{0.381_m, 0.381_m};
frc::Translation2d m_frontRightLocation{0.381_m, -0.381_m};
frc::Translation2d m_backLeftLocation{-0.381_m, 0.381_m};
frc::Translation2d m_backRightLocation{-0.381_m, -0.381_m};

// Creating my kinematics object using the module locations.
frc::SwerveDriveKinematics<4> m_kinematics{
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation,
    m_backRightLocation};
```

### 20.4.3 Converting chassis speeds to module states

The `toSwerveModuleStates(ChassisSpeeds speeds)` (Java)/`ToSwerveModuleStates(ChassisSpeeds speeds)` (C++) method should be used to convert a `ChassisSpeeds` object to an array of `SwerveModuleState` objects. This is useful in situations where you have to convert a forward velocity, sideways velocity, and an angular velocity into individual module states.

The elements in the array that is returned by this method are the same order in which the kinematics object was constructed. For example, if the kinematics object was constructed with the front left module location, front right module location, back left module location, and the back right module location in that order, the elements in the array would be the front left module state, front right module state, back left module state, and back right module state in that order.

Java

```
// Example chassis speeds: 1 meter per second forward, 3 meters
// per second to the left, and rotation at 1.5 radians per second
// counterclockwise.
ChassisSpeeds speeds = new ChassisSpeeds(1.0, 3.0, 1.5);

// Convert to module states
SwerveModuleState[] moduleStates = kinematics.toSwerveModuleStates(speeds);

// Front left module state
SwerveModuleState frontLeft = moduleStates[0];

// Front right module state
SwerveModuleState frontRight = moduleStates[1];

// Back left module state
SwerveModuleState backLeft = moduleStates[2];

// Back right module state
SwerveModuleState backRight = moduleStates[3];
```

C++

```
// Example chassis speeds: 1 meter per second forward, 3 meters
// per second to the left, and rotation at 1.5 radians per second
// counterclockwise.
frc::ChassisSpeeds speeds{1_mps, 3_mps, 1.5_rad_per_s};

// Convert to module states. Here, we can use C++17's structured
// bindings feature to automatically split up the array into its
// individual SwerveModuleState components.
auto [fl, fr, bl, br] = kinematics.ToSwerveModuleStates(speeds);
```

## Field-oriented drive

*Recall* that a `ChassisSpeeds` object can be created from a set of desired field-oriented speeds. This feature can be used to get module states from a set of desired field-oriented speeds.

Java

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
ChassisSpeeds speeds = ChassisSpeeds.fromFieldRelativeSpeeds(
    2.0, 2.0, Math.PI / 2.0, Rotation2d.fromDegrees(45.0));

// Now use this in our kinematics
SwerveModuleState[] moduleStates = kinematics.toSwerveModuleStates(speeds);
```

C++

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
frc::ChassisSpeeds speeds = frc::ChassisSpeeds::FromFieldRelativeSpeeds(
    2_mps, 2_mps, units::radians_per_second_t(wpi::math::pi / 2.0), Rotation2d(45_deg));

// Now use this in our kinematics
auto [fl, fr, bl, br] = kinematics.ToSwerveModuleStates(speeds);
```

## Using custom centers of rotation

Sometimes, rotating around one specific corner might be desirable for certain evasive maneuvers. This type of behavior is also supported by the WPILib classes. The same `ToSwerveModuleStates()` method accepts a second parameter for the center of rotation (as a `Translation2d`). Just like the wheel locations, the `Translation2d` representing the center of rotation should be relative to the robot center.

**Note:** Because all robots are a rigid frame, the provided  $v_x$  and  $v_y$  velocities from the `ChassisSpeeds` object will still apply for the entirety of the robot. However, the  $\omega$  from the `ChassisSpeeds` object will be measured from the center of rotation.

For example, one can set the center of rotation on a certain module and if the provided ChassisSpeeds object has a vx and vy of zero and a non-zero omega, the robot will appear to rotate around that particular swerve module.

#### 20.4.4 Converting module states to chassis speeds

One can also use the kinematics object to convert an array of SwerveModuleState objects to a singular ChassisSpeeds object. The toChassisSpeeds(SwerveModuleState... states) (Java) / ToChassisSpeeds(SwerveModuleState... states) (C++) method can be used to achieve this.

Java

```
// Example module states
var frontLeftState = new SwerveModuleState(23.43, Rotation2d.fromDegrees(-140.19));
var frontRightState = new SwerveModuleState(23.43, Rotation2d.fromDegrees(-39.81));
var backLeftState = new SwerveModuleState(54.08, Rotation2d.fromDegrees(-109.44));
var backRightState = new SwerveModuleState(54.08, Rotation2d.fromDegrees(-70.56));

// Convert to chassis speeds
ChassisSpeeds chassisSpeeds = kinematics.toChassisSpeeds(
    frontLeftState, frontRightState, backLeftState, backRightState);

// Getting individual speeds
double forward = chassisSpeeds.vxMetersPerSecond;
double sideways = chassisSpeeds.vyMetersPerSecond;
double angular = chassisSpeeds.omegaRadiansPerSecond;
```

C++

```
// Example module States
frc::SwerveModuleState frontLeftState{23.43_mps, Rotation2d(-140.19_deg)};
frc::SwerveModuleState frontRightState{23.43_mps, Rotation2d(-39.81_deg)};
frc::SwerveModuleState backLeftState{54.08_mps, Rotation2d(-109.44_deg)};
frc::SwerveModuleState backRightState{54.08_mps, Rotation2d(-70.56_deg)};

// Convert to chassis speeds. Here, we can use C++17's structured bindings
// feature to automatically break up the ChassisSpeeds struct into its
// three components.
auto [forward, sideways, angular] = kinematics.ToChassisSpeeds(
    frontLeftState, frontRightState, backLeftState, backRightState);
```

### 20.5 Swerve Drive Odometry

A user can use the swerve drive kinematics classes in order to perform *odometry*. WPILib contains a SwerveDriveOdometry class that can be used to track the position of a swerve drive robot on the field.

---

**Note:** Because this method only uses encoders and a gyro, the estimate of the robot's position on the field will drift over time, especially as your robot comes into contact with other robots during gameplay. However, odometry is usually very accurate during the autonomous period.

---

### 20.5.1 Creating the odometry object

The `SwerveDriveOdometry<int NumModules>` class requires one template argument (only C++), two mandatory arguments, and one optional argument. The template argument (only C++) is an integer representing the number of swerve modules. The mandatory arguments are the kinematics object that represents your swerve drive (in the form of a `SwerveDriveKinematics` class) and the angle reported by your gyroscope (as a `Rotation2d`). The third optional argument is the starting pose of your robot on the field (as a `Pose2d`). By default, the robot will start at  $x = 0$ ,  $y = 0$ ,  $\theta = 0$ .

**Note:** 0 degrees / radians represents the robot angle when the robot is facing directly toward your opponent's alliance station. As your robot turns to the left, your gyroscope angle should increase. By default, WPILib gyros exhibit the opposite behavior, so you should negate the gyro angle.

Java

```
// Locations for the swerve drive modules relative to the robot center.
Translation2d m_frontLeftLocation = new Translation2d(0.381, 0.381);
Translation2d m_frontRightLocation = new Translation2d(0.381, -0.381);
Translation2d m_backLeftLocation = new Translation2d(-0.381, 0.381);
Translation2d m_backRightLocation = new Translation2d(-0.381, -0.381);

// Creating my kinematics object using the module locations
SwerveDriveKinematics m_kinematics = new SwerveDriveKinematics(
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation, m_backRightLocation
);

// Creating my odometry object from the kinematics object. Here,
// our starting pose is 5 meters along the long end of the field and in the
// center of the field along the short end, facing forward.
SwerveDriveOdometry m_odometry = new SwerveDriveOdometry(m_kinematics,
    getGyroHeading(), new Pose2d(5.0, 13.5, new Rotation2d()));
```

C++

```
// Locations for the swerve drive modules relative to the robot center.
frc::Translation2d m_frontLeftLocation{0.381_m, 0.381_m};
frc::Translation2d m_frontRightLocation{0.381_m, -0.381_m};
frc::Translation2d m_backLeftLocation{-0.381_m, 0.381_m};
frc::Translation2d m_backRightLocation{-0.381_m, -0.381_m};

// Creating my kinematics object using the module locations.
frc::SwerveDriveKinematics<4> m_kinematics{
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation,
    m_backRightLocation};

// Creating my odometry object from the kinematics object. Here,
// our starting pose is 5 meters along the long end of the field and in the
// center of the field along the short end, facing forward.
frc::SwerveDriveOdometry<4> m_odometry{m_kinematics, GetGyroHeading(),
    frc::Pose2d{5_m, 13.5_m, 0_rad}};
```

## 20.5.2 Updating the robot pose

The update method of the odometry class updates the robot position on the field. The update method takes in the gyro angle of the robot, along with a series of module states (speeds and angles) in the form of a `SwerveModuleState` each. It is important that the order in which you pass the `SwerveModuleState` objects is the same as the order in which you created the kinematics object.

This update method must be called periodically, preferably in the `periodic()` method of a *Subsystem*. The update method returns the new updated pose of the robot.

Java

```
@Override
public void periodic() {
    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    var gyroAngle = Rotation2d.fromDegrees(-m_gyro.getAngle());

    // Update the pose
    m_pose = m_odometry.update(gyroAngle, m_frontLeftModule.getState(), m_
    ↪ frontRightModule.getState(),
        m_backLeftModule.getState(), m_backRightModule.getState());
}
```

C++

```
void Periodic() override {
    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    frc::Rotation2d gyroAngle{units::degree_t(-m_gyro.GetAngle())};

    // Update the pose
    m_pose = m_odometry.Update(gyroAngle, m_frontLeftModule.GetState(), m_
    ↪ frontRightModule.GetState(),
        m_backLeftModule.GetState(), m_backRightModule.GetState());
}
```

## 20.5.3 Resetting the Robot Pose

The robot pose can be reset via the `resetPose` method. This method accepts two arguments – the new field-relative pose and the current gyro angle.

---

**Important:** If at any time, you decide to reset your gyroscope, the `resetPose` method **MUST** be called with the new gyro angle.

---

---

**Note:** The implementation of `getState()` / `GetState()` above is left to the user. The idea is to get the module state (speed and angle) from each module. For a full example, see here: [C++](#) / [Java](#).

---

In addition, the `GetPose (C++) / getPoseMeters (Java)` methods can be used to retrieve the current robot pose without an update.

## 20.6 Mecanum Drive Kinematics

The `MecanumDriveKinematics` class is a useful tool that converts between a `ChassisSpeeds` object and a `MecanumDriveWheelSpeeds` object, which contains velocities for each of the four wheels on a mecanum drive.

### 20.6.1 Constructing the Kinematics Object

The `MecanumDriveKinematics` class accepts four constructor arguments, with each argument being the location of a wheel relative to the robot center (as a `Translation2d`). The order for the arguments is front left, front right, back left, and back right. The locations for the wheels must be relative to the center of the robot. Positive x values represent moving toward the front of the robot whereas positive y values represent moving toward the left of the robot.

Java

```
// Locations of the wheels relative to the robot center.
Translation2d m_frontLeftLocation = new Translation2d(0.381, 0.381);
Translation2d m_frontRightLocation = new Translation2d(0.381, -0.381);
Translation2d m_backLeftLocation = new Translation2d(-0.381, 0.381);
Translation2d m_backRightLocation = new Translation2d(-0.381, -0.381);

// Creating my kinematics object using the wheel locations.
MecanumDriveKinematics m_kinematics = new MecanumDriveKinematics(
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation, m_backRightLocation
);
```

C++

```
// Locations of the wheels relative to the robot center.
frc::Translation2d m_frontLeftLocation{0.381_m, 0.381_m};
frc::Translation2d m_frontRightLocation{0.381_m, -0.381_m};
frc::Translation2d m_backLeftLocation{-0.381_m, 0.381_m};
frc::Translation2d m_backRightLocation{-0.381_m, -0.381_m};

// Creating my kinematics object using the wheel locations.
frc::MecanumDriveKinematics m_kinematics{
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation,
    m_backRightLocation};
```

### 20.6.2 Converting Chassis Speeds to Wheel Speeds

The `toWheelSpeeds(ChassisSpeeds speeds) (Java) / ToWheelSpeeds(ChassisSpeeds speeds) (C++)` method should be used to convert a `ChassisSpeeds` object to a `MecanumDriveWheelSpeeds` object. This is useful in situations where you have to convert a forward velocity, sideways velocity, and an angular velocity into individual wheel speeds.

Java



```
// Example chassis speeds: 1 meter per second forward, 3 meters
// per second to the left, and rotation at 1.5 radians per second
// counterclockwise.
ChassisSpeeds speeds = new ChassisSpeeds(1.0, 3.0, 1.5);

// Convert to wheel speeds
MecanumDriveWheelSpeeds wheelSpeeds = kinematics.toWheelSpeeds(speeds);

// Get the individual wheel speeds
double frontLeft = wheelSpeeds.frontLeftMetersPerSecond
double frontRight = wheelSpeeds.frontRightMetersPerSecond
double backLeft = wheelSpeeds.rearLeftMetersPerSecond
double backRight = wheelSpeeds.rearRightMetersPerSecond
```

C++

```
// Example chassis speeds: 1 meter per second forward, 3 meters
// per second to the left, and rotation at 1.5 radians per second
// counterclockwise.
frc::ChassisSpeeds speeds{1_mps, 3_mps, 1.5_rad_per_s};

// Convert to wheel speeds. Here, we can use C++17's structured
// bindings feature to automatically split up the MecanumDriveWheelSpeeds
// struct into it's individual components
auto [fl, fr, bl, br] = kinematics.ToWheelSpeeds(speeds);
```

### Field-oriented drive

*Recall* that a `ChassisSpeeds` object can be created from a set of desired field-oriented speeds. This feature can be used to get wheel speeds from a set of desired field-oriented speeds.

Java

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
ChassisSpeeds speeds = ChassisSpeeds.fromFieldRelativeSpeeds(
    2.0, 2.0, Math.PI / 2.0, Rotation2d.fromDegrees(45.0));

// Now use this in our kinematics
MecanumDriveWheelSpeeds wheelSpeeds = kinematics.toWheelSpeeds(speeds);
```

C++

```
// The desired field relative speed here is 2 meters per second
// toward the opponent's alliance station wall, and 2 meters per
// second toward the left field boundary. The desired rotation
// is a quarter of a rotation per second counterclockwise. The current
// robot angle is 45 degrees.
frc::ChassisSpeeds speeds = frc::ChassisSpeeds::FromFieldRelativeSpeeds(
    2_mps, 2_mps, units::radians_per_second_t(wpi::math::pi / 2.0), Rotation2d(45_deg));

// Now use this in our kinematics
auto [fl, fr, bl, br] = kinematics.ToWheelSpeeds(speeds);
```

## Using custom centers of rotation

Sometimes, rotating around one specific corner might be desirable for certain evasive maneuvers. This type of behavior is also supported by the WPILib classes. The same `ToWheelSpeeds()` method accepts a second parameter for the center of rotation (as a `Translation2d`). Just like the wheel locations, the `Translation2d` representing the center of rotation should be relative to the robot center.

**Note:** Because all robots are a rigid frame, the provided `vx` and `vy` velocities from the `ChassisSpeeds` object will still apply for the entirety of the robot. However, the `omega` from the `ChassisSpeeds` object will be measured from the center of rotation.

For example, one can set the center of rotation on a certain wheel and if the provided `ChassisSpeeds` object has a `vx` and `vy` of zero and a non-zero `omega`, the robot will appear to rotate around that particular wheel.

### 20.6.3 Converting wheel speeds to chassis speeds

One can also use the kinematics object to convert a `MecanumDriveWheelSpeeds` object to a singular `ChassisSpeeds` object. The `toChassisSpeeds(MecanumDriveWheelSpeeds speeds)` (Java) / `ToChassisSpeeds(MecanumDriveWheelSpeeds speeds)` (C++) method can be used to achieve this.

Java

```
// Example wheel speeds
var wheelSpeeds = new MecanumDriveWheelSpeeds(-17.67, 20.51, -13.44, 16.26);

// Convert to chassis speeds
ChassisSpeeds chassisSpeeds = kinematics.toChassisSpeeds(wheelSpeeds);

// Getting individual speeds
double forward = chassisSpeeds.vxMetersPerSecond;
double sideways = chassisSpeeds.vyMetersPerSecond;
double angular = chassisSpeeds.omegaRadiansPerSecond;
```

C++

```
// Example wheel speeds
frc::MecanumDriveWheelSpeeds wheelSpeeds{-17.67_mps, 20.51_mps, -13.44_mps, 16.26_mps}
↪;

// Convert to chassis speeds. Here, we can use C++17's structured bindings
// feature to automatically break up the ChassisSpeeds struct into its
// three components.
auto [forward, sideways, angular] = kinematics.ToChassisSpeeds(wheelSpeeds);
```

## 20.7 Mecanum Drive Odometry

A user can use the mecanum drive kinematics classes in order to perform *odometry*. WPILib contains a `MecanumDriveOdometry` class that can be used to track the position of a mecanum drive robot on the field.

**Note:** Because this method only uses encoders and a gyro, the estimate of the robot's position on the field will drift over time, especially as your robot comes into contact with other robots during gameplay. However, odometry is usually very accurate during the autonomous period.

### 20.7.1 Creating the odometry object

The `MecanumDriveOdometry` class requires two mandatory arguments and one optional argument. The mandatory arguments are the kinematics object that represents your mecanum drive (in the form of a `MecanumDriveKinematics` class) and the angle reported by your gyroscope (as a `Rotation2d`). The third optional argument is the starting pose of your robot on the field (as a `Pose2d`). By default, the robot will start at  $x = 0$ ,  $y = 0$ ,  $\theta = 0$ .

**Note:** 0 degrees / radians represents the robot angle when the robot is facing directly toward your opponent's alliance station. As your robot turns to the left, your gyroscope angle should increase. By default, WPILib gyros exhibit the opposite behavior, so you should negate the gyro angle.

Java

```
// Locations of the wheels relative to the robot center.
Translation2d m_frontLeftLocation = new Translation2d(0.381, 0.381);
Translation2d m_frontRightLocation = new Translation2d(0.381, -0.381);
Translation2d m_backLeftLocation = new Translation2d(-0.381, 0.381);
Translation2d m_backRightLocation = new Translation2d(-0.381, -0.381);

// Creating my kinematics object using the wheel locations.
MecanumDriveKinematics m_kinematics = new MecanumDriveKinematics(
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation, m_backRightLocation
);

// Creating my odometry object from the kinematics object. Here,
// our starting pose is 5 meters along the long end of the field and in the
// center of the field along the short end, facing forward.
MecanumDriveOdometry m_odometry = new MecanumDriveOdometry(m_kinematics,
    getGyroHeading(), new Pose2d(5.0, 13.5, new Rotation2d()));
```

C++

```
// Locations of the wheels relative to the robot center.
frc::Translation2d m_frontLeftLocation{0.381_m, 0.381_m};
frc::Translation2d m_frontRightLocation{0.381_m, -0.381_m};
frc::Translation2d m_backLeftLocation{-0.381_m, 0.381_m};
frc::Translation2d m_backRightLocation{-0.381_m, -0.381_m};

// Creating my kinematics object using the wheel locations.
frc::MecanumDriveKinematics m_kinematics{
    m_frontLeftLocation, m_frontRightLocation, m_backLeftLocation,
    m_backRightLocation};

// Creating my odometry object from the kinematics object. Here,
// our starting pose is 5 meters along the long end of the field and in the
```

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```
// center of the field along the short end, facing forward.
frc::MecanumDriveOdometry m_odometry{m_kinematics, GetGyroHeading(),
    frc::Pose2d{5_m, 13.5_m, 0_rad}};
```

## 20.7.2 Updating the robot pose

The update method of the odometry class updates the robot position on the field. The update method takes in the gyro angle of the robot, along with a `MecanumDriveWheelSpeeds` object representing the speed of each of the 4 wheels on the robot. This update method must be called periodically, preferably in the `periodic()` method of a *Subsystem*. The update method returns the new updated pose of the robot.

**Note:** The `MecanumDriveWheelSpeeds` class in Java must be constructed with each wheel speed in meters per second. In C++, the units library must be used to represent your wheel speeds.

Java

```
@Override
public void periodic() {
    // Get my wheel speeds
    var wheelSpeeds = new MecanumDriveWheelSpeeds(
        m_frontLeftEncoder.getRate(), m_frontRightEncoder.getRate(),
        m_backLeftEncoder.getRate(), m_backRightEncoder.getRate());

    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    var gyroAngle = Rotation2d.fromDegrees(-m_gyro.getAngle());

    // Update the pose
    m_pose = m_odometry.update(gyroAngle, wheelSpeeds);
}
```

C++

```
void Periodic() override {
    // Get my wheel speeds
    frc::MecanumDriveWheelSpeeds wheelSpeeds{
        units::meters_per_second_t(m_frontLeftEncoder.GetRate()),
        units::meters_per_second_t(m_frontRightEncoder.GetRate()),
        units::meters_per_second_t(m_backLeftEncoder.GetRate()),
        units::meters_per_second_t(m_backRightEncoder.GetRate())};

    // Get my gyro angle. We are negating the value because gyros return positive
    // values as the robot turns clockwise. This is not standard convention that is
    // used by the WPILib classes.
    frc::Rotation2d gyroAngle{units::degree_t(-m_gyro.GetAngle())};

    // Update the pose
    m_pose = m_odometry.Update(gyroAngle, wheelSpeeds);
}
```

### 20.7.3 Resetting the Robot Pose

The robot pose can be reset via the `resetPose` method. This method accepts two arguments – the new field-relative pose and the current gyro angle.

---

**Important:** If at any time, you decide to reset your gyroscope, the `resetPose` method **MUST** be called with the new gyro angle.

---

---

**Note:** A full example of a mecanum drive robot with odometry is available here: [C++ / Java](#).

---

In addition, the `GetPose` (C++) / `getPoseMeters` (Java) methods can be used to retrieve the current robot pose without an update.

## 21.1 What is NetworkTables

NetworkTables is an implementation of a distributed “dictionary”. That is named values are created either on the robot, driver station, or potentially an attached coprocessor, and the values are automatically distributed to all the other participants. For example, a driver station laptop might receive camera images over the network, perform some vision processing algorithm, and come up with some values to sent back to the robot. The values might be an X, Y, and Distance. By writing these results to NetworkTable values called “X”, “Y”, and “Distance” they can be read by the robot shortly after being written. Then the robot can act upon them.

NetworkTables can be used by programs on the robot in either C++, Java or LabVIEW and is built into each version of WPILib.

### 21.1.1 Network tables organization

Data is organized in NetworkTables in a hierarchy much like a directory on disk with folders and files. For any instance of NetworkTables there can be multiple values and subtables that may be nested in whatever way fits the data organization desired. Subtables actually are represented as a long key with slashes (/) separating the nested subtable and value key names. Each value has a key associated with it that is used to retrieve the value. For example, you might have a table called **datatable** as shown in the following examples. Within a **datatable** there are two keys, X and Y and their associated values. The OutlineViewer is a good utility for exploring the values stored in NetworkTables while a program is running.

Data types for NetworkTables are either boolean, numeric, or string. Numeric values are written as double precision values. In addition you can have arrays of any of those types to ensure that multiple data items are delivered consistently. There is also the option of storing raw data which can be used for representing structured data.

There are some default tables that are created automatically when the program starts up:

Table name	Use
/Smart-Dash-board	Used to store values written to the SmartDashboard or Shuffleboard using the SmartDashboard.put() set of methods.
/LiveWin-dow	Used to store Test mode (Test on the Driver Station) values. Typically these are Subsystems and the associated sensors and actuators.
/FMSInfo	Information about the currently running match that comes from the Driver Station and the Field Management System

### 21.1.2 Writing a simple NetworkTable program

The NetworkTables classes are instantiated automatically when your program starts. To access the instance of NetworkTables do call methods to read and write the getDefault() method can be used to get the default instance.

Java

```
package edu.wpi.first.wpilibj.templates;

import edu.wpi.first.wpilibj.TimedRobot;
import edu.wpi.first.networktables.NetworkTable;
import edu.wpi.first.networktables.NetworkTableEntry;
import edu.wpi.first.networktables.NetworkTableInstance;

public class EasyNetworkTableExample extends TimedRobot {
    NetworkTableEntry xEntry;
    NetworkTableEntry yEntry;

    public void robotInit() {
        //Get the default instance of NetworkTables that was created automatically
        //when your program starts
        NetworkTableInstance inst = NetworkTableInstance.getDefault();

        //Get the table within that instance that contains the data. There can
        //be as many tables as you like and exist to make it easier to organize
        //your data. In this case, it's a table called datatable.
        NetworkTable table = inst.getTable("datatable");

        //Get the entries within that table that correspond to the X and Y values
        //for some operation in your program.
        xEntry = table.getEntry("X");
        yEntry = table.getEntry("Y");
    }

    double x = 0;
    double y = 0;

    public void teleopPeriodic() {
        //Using the entry objects, set the value to a double that is constantly
        //increasing. The keys are actually "/datatable/X" and "/datatable/Y".
        //If they don't already exist, the key/value pair is added.
        xEntry.setDouble(x);
        yEntry.setDouble(y);
        x += 0.05;
    }
}
```

(continues on next page)

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```

        y += 1.0;
    }
}

```

C++

```

#include "TimedRobot.h"
#include "networktables/NetworkTable.h"
#include "networktables/NetworkTableEntry.h"
#include "networktables/NetworkTableInstance.h"

class EasyNetworkExample : public frc::TimedRobot {
public:
    nt::NetworkTableEntry xEntry;
    nt::NetworkTableEntry yEntry;

    void RobotInit() {
        auto inst = nt::NetworkTableInstance::GetDefault();
        auto table = inst.GetTable("datatable");
        xEntry = table->GetEntry("X");
        yEntry = table->GetEntry("Y");
    }

    double x = 0;
    double y = 0;

    void TeleopPeriodic() {
        xEntry.SetDouble(x);
        yEntry.SetDouble(y);
        x += 0.05;
        y += 0.05;
    }
}

START_ROBOT_CLASS(EasyNetworkExample)

```

The values for X and Y can be easily viewed using the OutlineViewer program that shows the NetworkTables hierarchy and all the values associated with each key.

**Note:** Actually network tables has a flat namespace for the keys. Having tables and subtables is an abstraction to make it easier to organize your data. So for a table called "SmartDashboard" and a key named "xValue", it is really a single key called "/SmartDashboard/xValue". The hierarchy is not actually represented in the distributed data, only keys with prefixes that are the contained table.

## 21.2 Listening for value changes

A common use case for NetworkTables is where a program on the Driver Station generates values that need to be sent to the robot. For example, imagine that some image processing code running on the Driver Station computes the heading and distance to a goal and sends those values to the robot. In this case it might be desirable for the robot program to be



notified when new values arrive from the Driver Station. NetworkTables provides facilities to do that.

### 21.2.1 Using a NetworkTable EntryListener

One of the more common cases for NetworkTables is waiting for a value to change on the robot. This is called an EntryListener because it notifies the robot program when a network table entry (single value) changes. The following code shows how to do this.

Java

```
package networktablesdesktopclient;

import edu.wpi.first.networktables.EntryListenerFlags;
import edu.wpi.first.networktables.NetworkTable;
import edu.wpi.first.networktables.NetworkTableEntry;
import edu.wpi.first.networktables.NetworkTableInstance;

public class TableEntryListenerExample {

    public static void main(String[] args) {
        new TableEntryListenerExample().run();
    }

    public void run() {
        //get the default instance of NetworkTables
        NetworkTableInstance inst = NetworkTableInstance.getDefault();

        //get a reference to the subtable called "datatable"
        NetworkTable table = inst.getTable("datatable");

        //get a reference to key in "datatable" called "Y"
        NetworkTableEntry yEntry = table.getEntry("Y");
        inst.startClientTeam(190);

        //add an entry listener for changed values of "X", the lambda ("->" operator)
        //defines the code that should run when "X" changes
        table.addEntryListener("X", (table, key, entry, value, flags) -> {
            System.out.println("X changed value: " + value.getValue());
        }, EntryListenerFlags.kNew | EntryListenerFlags.kUpdate);

        //add an entry listener for changed values of "Y", the lambda ("->" operator)
        //defines the code that should run when "Y" changes
        yEntry.addListener(event -> {
            System.out.println("Y changed value: " + value.getValue());
        }, EntryListenerFlags.kNew | EntryListenerFlags.kUpdate);

        try {
            Thread.sleep(10000);
        } catch (InterruptedException ex) {
            System.out.println("Interrupted");
            Thread.currentThread().interrupt();
            return;
        }
    }
}
```

## 21.3 Creating a client-side program

If all you need to do is have your robot program communicate with GRIP or a dashboard running on the Driver Station laptop, then the previous examples of writing robot programs are sufficient. But if you would like to write some custom client code that would run on the drivers station or on a coprocessor then you need to know how to build Network Tables programs for those (non-roboRIO) platforms.

A basic client program looks like the following example.

Java

```
import edu.wpi.first.networktables.NetworkTable;
import edu.wpi.first.networktables.NetworkTableEntry;
import edu.wpi.first.networktables.NetworkTableInstance;

public class NetworkTablesDesktopClient {
    public static void main(String[] args) {
        new NetworkTablesDesktopClient().run();
    }

    public void run() {
        NetworkTableInstance inst = NetworkTableInstance.getDefault();
        NetworkTable table = inst.getTable("datatable");
        NetworkTableEntry xEntry = table.getEntry("x");
        NetworkTableEntry yEntry = table.getEntry("y");
        inst.startClientTeam(TEAM); // where TEAM=190, 294, etc, or use inst.startClient(
        ↪ "hostname") or similar
        inst.startDSClient(); // recommended if running on DS computer; this gets the
        ↪ robot IP from the DS
        while (true) {
            try {
                Thread.sleep(1000);
            } catch (InterruptedException ex) {
                System.out.println("interrupted");
                return;
            }
            double x = xEntry.getDouble(0.0);
            double y = yEntry.getDouble(0.0);
            System.out.println("X: " + x + " Y: " + y);
        }
    }
}
```

In this example an instance of NetworkTables is created and a NetworkTableEntry is created to reference the values of “x” and “y” from a table called “datatable”.

Then this instance is started as a NetworkTable client with the team number (the roboRIO is always the server). Additionally, if the program is running on the Driver Station computer, by using the startDSClient() method, NetworkTables will get the robot IP address from the Driver Station.

Then this sample program simply loops once a second and gets the values for x and y and prints them on the console. In a more realistic program, the client might be processing or generating values for the robot to consume.

### 21.3.1 Building the program

When building and running the program you will need some additional libraries to include with your client-side program. These are:

<https://frcmaven.wpi.edu/artifactory/release/edu/wpi/first/ntcore/ntcore-java/> (ntcore java files)

<https://frcmaven.wpi.edu/artifactory/release/edu/wpi/first/ntcore/ntcore-jni/> (ntcore native libs for all desktop platforms)

<https://frcmaven.wpi.edu/artifactory/release/edu/wpi/first/wpiutil/wpiutil-java/> (wpiutil java files)

---

**Note:** The desktop platform jar is for Windows, macOS, and Linux.

---

### Building using Gradle

The dependencies above can be added to the dependencies block in a `build.gradle` file. The `ntcore-java` and `wpiutil-java` libraries are required at compile-time and the JNI dependencies are required at runtime. The JNI dependencies for all supported platforms should be added to the `build.gradle` if cross-platform support for the application is desired.

First, the FRC Maven repository should be added to the `repositories` block. Note that this is not required if you are using the GradleRIO plugin with your application.

```
repositories {  
    maven { url "https://frcmaven.wpi.edu/artifactory/release/" }  
}
```

Then, the dependencies can be added to the dependencies block. Here, `VERSION` should be replaced with the latest version number of the following dependencies. This usually corresponds to the version number of the latest WPILib release.

```
dependencies {  
    // Add ntcore-java  
    compile "edu.wpi.first.ntcore:ntcore-java:VERSION"  
  
    // Add wpiutil-java  
    compile "edu.wpi.first.wpiutil:wpiutil-java:VERSION"  
  
    // Add ntcore-jni for runtime. We are adding all supported platforms  
    // so that our application will work on all supported platforms.  
    runtime "edu.wpi.first.ntcore:ntcore-jni:VERSION:windowsx86"  
    runtime "edu.wpi.first.ntcore:ntcore-jni:VERSION:windowsx86-64"  
    runtime "edu.wpi.first.ntcore:ntcore-jni:VERSION:linuxx86-64"  
    runtime "edu.wpi.first.ntcore:ntcore-jni:VERSION:osxx86-64"  
}
```

## 21.4 Creating multiple instances of NetworkTables

This feature is mainly useful for coprocessors and unit testing. It allows a single program to be a member of two completely independent NetworkTables “networks” that contain completely

different (and unrelated) sets of tables. For most general usage, you should use tables within the single instance, as all current dashboard programs can only connect to a single NT server at a time.

Normally the “default” instance is set up on the robot as a server, and used for communication with the dashboard program running on your driver station computer. This is what the SmartDashboard and LiveWindow classes use.

If you had a coprocessor and wanted to have a set of tables that’s shared only between the coprocessor and the robot, you could set up a separate instance in the robot code that acts as a client (or a server) and connect the coprocessor to it, and those tables will NOT be sent to the dashboard.

Similarly, if you wanted to do unit testing of your robot program’s NT communications, you could set up your unit tests such that they create a separate client instance (still within the same program) and have it connect to the server instance that the main robot code is running.

Another example might be having two completely separate dashboard programs. You could set up two networktables server instances in your robot program (on different TCP ports of course), set up different tables on each one, and have each dashboard connect to a different server instance. Each dashboard would only see the tables on its instance.

## 21.5 Listening for subtable creation

Java

```
package networktablesdesktopclient;

import edu.wpi.first.networktables.NetworkTable;
import edu.wpi.first.networktables.NetworkTableInstance;

public class SubTableListenerExample {

    public static void main(String[] args) {
        new SubTableListenerExample().run();
    }

    public void run() {
        NetworkTableInstance inst = NetworkTableInstance.getDefault();
        NetworkTable table = inst.getTable("datatable");
        inst.startClientTeam(190);

        table.addSubTableListener((parent, name, table) -> {
            System.out.println("Parent: " + parent + " Name: " + name);
        }, false);

        try {
            Thread.sleep(100000);
        } catch (InterruptedException ex) {
            System.out.println("Interrupted!");
        }
    }
}
```

In this example a listener is defined that listens for creation of subtables one level down from the listener. That is subtables with the key “/datatable/<any-table-name>”. This will

fire the callback for each existing subtable, then continue to listen for new subtables created immediately below “datatable” in this case.

## 22.1 roboRIO Web Dashboard

The roboRIO web dashboard is a webpage built into the roboRIO that can be used for checking status and updating settings of the roboRIO.

Unlike the 2015-2018 roboRIO web dashboard, the 2019 web dashboard does not use SilverLight. Users may encounter issues using IE (compatibility) or Edge (mDNS site access). Alternate browsers such as Google Chrome or Mozilla Firefox are recommended for the best experience.

---

**Note:** The roboRIO web dashboard was been re-written for 2019. All CAN configuration functionality has been removed. Configuration of CAN devices should be done with software provided by the device vendor. For CTRE devices previously serviced using the webdashboard, the appropriate software is [CTRE Phoenix Tuner](#).

---

### 22.1.1 Opening the WebDash



To open the web dashboard, open a web browser and enter the address of the roboRIO into the address bar (172.22.11.2 for USB, or “roboRIO-####-FRC.local where #### is your team number, with no leading zeroes, for either interface). See this document for more details about mDNS and roboRIO networking: [IP Configurations](#)

### 22.1.2 System Configuration Tab

The home screen of the web dashboard is the System Configuration tab which has 5 main sections:

1. Navigation Bar - This section allows you to navigate to different sections of the web dashboard. The different pages accessible through this navigation bar are discussed below.
2. System Settings - This section contains information about the System Settings. The Hostname field should not be modified manually, instead use the roboRIO Imaging tool

**172.22.11.2: System Configuration**



Save

**Settings**

Hostname	roboRIO-1-FRC
IP Address	0.0.0.0 (Ethernet) 172.22.11.2 (Ethernet)
DNS Name	
Vendor	National Instruments
Model	roboRIO
Serial Number	030498A9
Firmware Version	6.0.0f1
Operating System	NI Linux Real-Time ARMv7-A 4.9.47-rt37-ni-6.0.0f1
Status	Running
System Start Time	Mon Nov 19 2018 14:16:34 GMT-0500 (Eastern Standard Time)
Image Title	roboRIO Image
Image Version	FRC_roboRIO_2019_v12
Comments	<div></div>
Locale	English
VISA Resource Name	system

Update Firmware

**Startup Settings**

☐ Force Safe Mode

☒ Enable Console Out

☐ Disable RT Startup App

☐ Disable FPGA Startup App

☒ Enable Secure Shell Server (sshd)

☒ LabVIEW Project Access

## 172.22.11.2: System Configuration

1

Save

Settings 2

Hostname	roboRIO-1-FRC
IP Address	0.0.0.0 (Ethernet) 172.22.11.2 (Ethernet)
DNS Name	
Vendor	National Instruments
Model	roboRIO
Serial Number	030498A9
Firmware Version	6.0.0f1
Operating System	NI Linux Real-Time ARMv7-A 4.9.47-rt37-ni-6.0.0f1
Status	Running
System Start Time	Mon Nov 19 2018 14:16:34 GMT-0500 (Eastern Standard Time)
Image Title	roboRIO Image
Image Version	FRC_roboRIO_2019_v12
Comments	
Locale	English
VISA Resource Name	system

Update Firmware

Startup Settings 3


- ☐ Force Safe Mode
- ☒ Enable Console Out
- ☐ Disable RT Startup App
- ☐ Disable FPGA Startup App
- ☒ Enable Secure Shell Server (ssh)
- ☒ LabVIEW Project Access



to set the Hostname based on your team number. This section contains information such as the device IP, firmware version and image version.

3. Startup Settings - This section contains Startup settings for the roboRIO. These are described in the sub-step below
4. System Resources (not pictured) - This section provides a snapshot of system resources such as memory and CPU load.

### Startup Settings



The screenshot shows a window titled "Startup Settings" with a list of six checkboxes. The first checkbox, "Force Safe Mode", is unchecked. The second, "Enable Console Out", is checked. The third, "Disable RT Startup App", is unchecked. The fourth, "Disable FPGA Startup App", is unchecked. The fifth, "Enable Secure Shell Server (sshd)", is checked. The sixth, "LabVIEW Project Access", is checked.

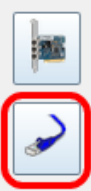
Setting	Default
Force Safe Mode	Unchecked
Enable Console Out	Checked
Disable RT Startup App	Unchecked
Disable FPGA Startup App	Unchecked
Enable Secure Shell Server (sshd)	Checked
LabVIEW Project Access	Checked

- Force Safe Mode - Forces the controller into Safe Mode. This can be used with troubleshooting imaging issues, but it is recommended to use the Reset button on the roboRIO to put the device into Safe Mode instead (with power already applied, hold the reset button for 5 seconds). **Default is unchecked.**
- Enable Console Out - This enables the on-board RS232 port to be used as a Console output. It is recommended to leave this enabled unless you are using this port to talk to a serial device (note that this port uses RS232 levels and should not be connected to many microcontrollers which use TTL levels). **Default is checked.**
- Disable RT Startup App - Checking this box disables code from running at startup. This may be used for troubleshooting if you find the roboRIO is unresponsive to new program download. Default is unchecked
- Disable FPGA Startup App - **This box should not be checked.**
- Enable Secure Shell Server (sshd) - **It is recommended to leave this box checked.** This setting enables SSH which is a way to remotely access a console on the roboRIO. Unchecking this box will prevent C++ and Java teams from loading code onto the roboRIO.
- LabVIEW Project Access -\*\* It is recommended to leave this box checked.\*\* This setting allows LabVIEW projects to access the roboRIO.

### 22.1.3 Network Configuration

This page shows the configuration of the roboRIO's network adapters. **It is not recommended to change any settings on this page.** For more information on roboRIO networking see this article: [IP Configurations](#)

**172.22.11.2: Network Configuration**



Save

**Ethernet Adapter eth0**

**Settings**

MAC Address	00:80:2F:30:49:8A
Configure IPv4 Address	<input type="text" value="DHCP or Link Local"/>
IPv4 Address	0.0.0.0
Subnet Mask	0.0.0.0
Gateway	0.0.0.0
DNS Server	0.0.0.0
Current Link Speed	10Mbit/Half Duplex
Preferred Link Speed	<input type="text" value="Autonegotiate"/>

**Ethernet Adapter usb0**

**Settings**

MAC Address	00:80:2F:40:49:8A
Configure IPv4 Address	DHCP Only
IPv4 Address	172.22.11.2
Subnet Mask	255.255.255.248
Gateway	0.0.0.0
DNS Server	0.0.0.0
Current Link Speed	Autonegotiate
Preferred Link Speed	Autonegotiate

## 22.2 roboRIO FTP

---

**Note:** The roboRIO has both SFTP and anonymous FTP enabled. This article describes how to use each to access the roboRIO file system.

---

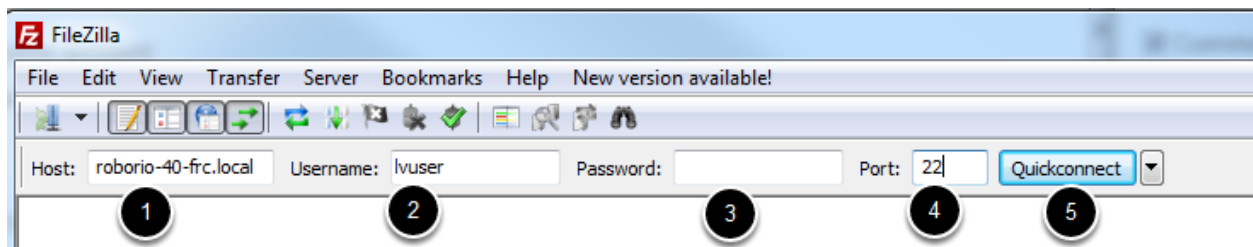
### 22.2.1 SFTP

SFTP is the recommended way to access the roboRIO file system. Because you will be using the same account that your program will run under, files copied over should always have permissions compatible with your code.

#### Software

There are a number of freely available programs for SFTP. This article will discuss using FileZilla. You can either download and install [FileZilla](#) before proceeding or extrapolate the directions below to your SFTP client of choice.

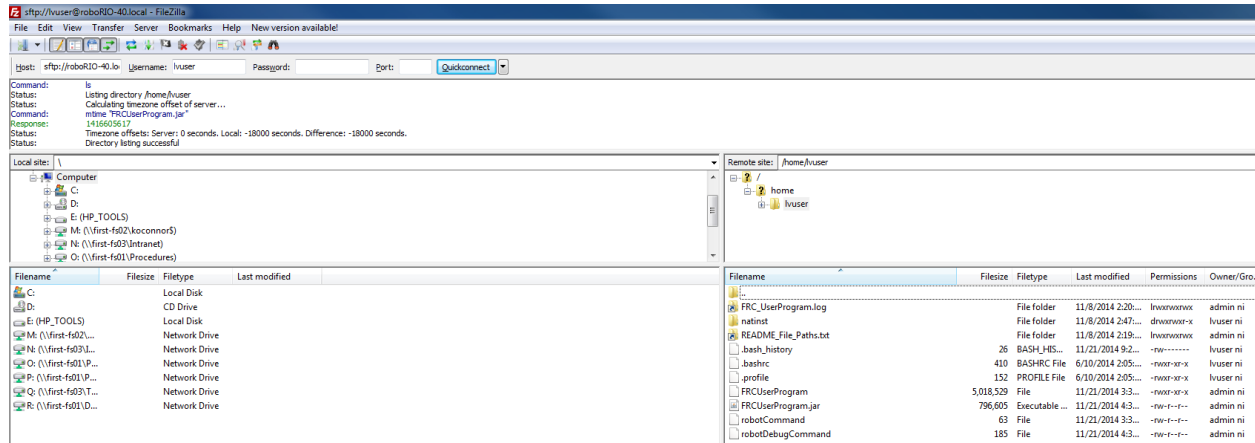
#### Connecting to the roboRIO



To connect to your roboRIO:

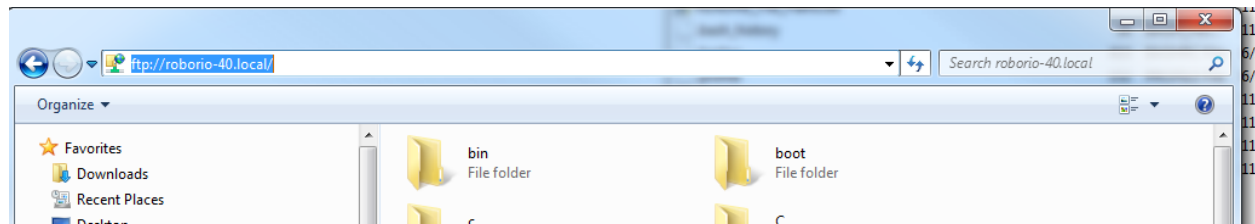
1. Enter the mDNS name (roboRIO-TEAM-frc.local) in the “Host” box
2. Enter “lvuser” in the Username box (this is the account your program runs under)
3. Leave the Password box blank
4. Enter “22” in the port box (the SFTP default port)
5. Click Quickconnect

## Browsing the roboRIO filesystem



After connecting to the roboRIO, Filezilla will open to the `\home\lvuser` directory. The right pane is the remote system (the roboRIO), the left pane is the local system (your computer). The top section of each pane shows you the hierarchy to the current directory you are browsing, the bottom pane shows contents of the directory. To transfer files, simply click and drag from one side to the other. To create directories on the roboRIO, right click and select “Create Directory”.

### 22.2.2 FTP



The roboRIO also has anonymous FTP enabled. It is recommended to use SFTP as described above, but depending on what you need FTP may work in a pinch with no additional software required. To FTP to the roboRIO, open a Windows Explorer window (on Windows 7, you can click Start->My Computer). In the address bar, type `ftp://roboRIO-TEAM-frc.local` and press enter. You can now browse the roboRIO file system just like you would browse files on your computer.

## 22.3 roboRIO User Accounts and SSH

**Note:** This document contains advanced topics not required for typical FRC programming

The roboRIO image contains a number of accounts, this article will highlight the two used for FRC and provide some detail about their purpose. It will also describe how to connect to the roboRIO over SSH.

### 22.3.1 roboRIO User Accounts

The roboRIO image contains a number of user accounts, but there are two of primary interest for FRC.

#### Admin

The “admin” account has root access to the system and can be used to manipulate OS files or settings. Teams should take caution when using this account as it allows for the modification of settings and files that may corrupt the operating system of the roboRIO. The credentials for this account are:

Username: admin

Password:

---

**Note:** The password is intentionally blank.

---

#### Lvuser

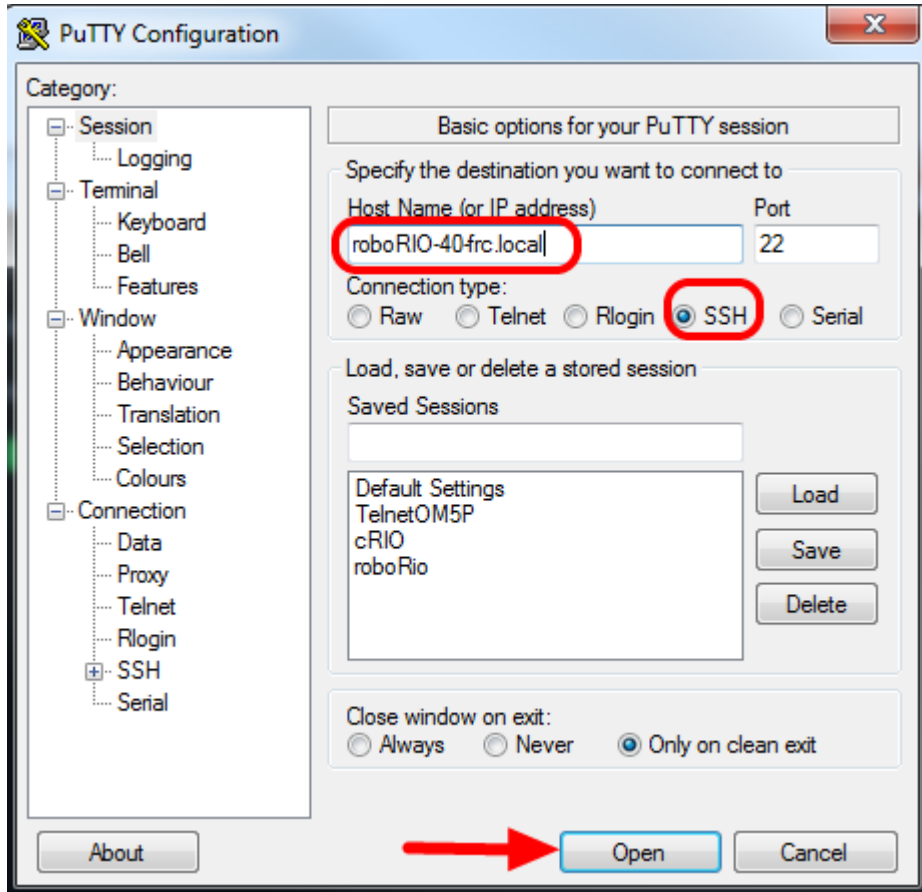
The “lvuser” account is the account used to run user code for all three languages. The credentials for this account should not be changed. Teams may wish to use this account (via ssh or sftp) when working with the roboRIO to ensure that any files or settings changes are being made on the same account as their code will run under.

**Danger:** Changing the default ssh passwords for either “lvuser” or “admin” will prevent C++ and Java teams from uploading code.

### 22.3.2 SSH

SSH (Secure SHell) is a protocol used for secure data communication. When broadly referred to regarding a Linux system (such as the one running on the roboRIO) it generally refers to accessing the command line console using the SSH protocol. This can be used to execute commands on the remote system. A free client which can be used for SSH is PuTTY: <https://www.chiark.greenend.org.uk/~sgtatham/putty/latest.html>

## Open Putty



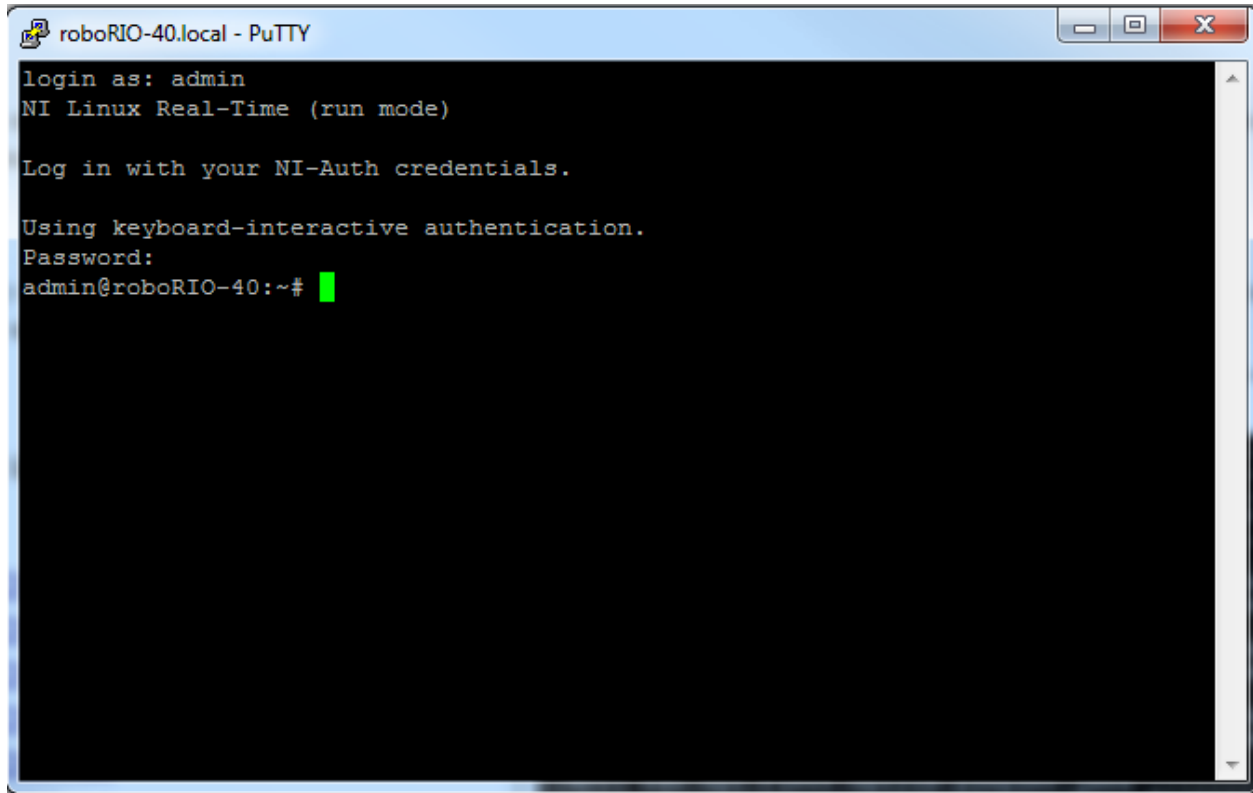
Open Putty (clicking OK at any security prompt). Then set the following settings:

1. Host Name: roboRIO-TEAM-frc.local (where TEAM is your team number, example shows team 40)
2. Connection Type: SSH

Other settings can be left at defaults. Click Open to open the connection. If you see a prompt about SSH keys, click OK.

If you are connected over USB you can use 172.22.11.2 as the hostname. If your roboRIO is set to a static IP you can use that IP as the hostname if connected over Ethernet/wireless.

## Log In



```
login as: admin
NI Linux Real-Time (run mode)

Log in with your NI-Auth credentials.

Using keyboard-interactive authentication.
Password:
admin@roboRIO-40:~#
```

When you see the prompt, enter the desired username (see above for description) then press enter. At the password prompt press enter (password for both accounts is blank).

## 22.4 roboRIO Brownout and Understanding Current Draw

In order to help maintain battery voltage to preserve itself and other control system components such as the radio during high current draw events, the roboRIO contains a staged brownout protection scheme. This article describes this scheme, provides information about proactively planning for system current draw, and describes how to use the new functionality of the PDP as well as the DS Log File Viewer to understand brownout events if they do happen on your robot.

### 22.4.1 roboRIO Brownout Protection

The roboRIO uses a staged brownout protection scheme to attempt to preserve the input voltage to itself and other control system components in order to prevent device resets in the event of large current draws pulling the battery voltage dangerously low.

#### Stage 1 - 6v output drop

#### Voltage Trigger - 6.8V

When the voltage drops below 6.8V, the 6V output on the PWM pins will start to drop.

## Stage 2 - Output Disable

### Voltage Trigger - 6.3V

When the voltage drops below 6.3V, the controller will enter the brownout protection state. The following indicators will show that this condition has occurred:

- Power LED on the roboRIO will turn Amber
- Background of the voltage display on the Driver Station will turn red
- Mode display on the Driver Station will change to Voltage Brownout
- The CAN/Power tab of the DS will increment the 12V fault counter by 1.
- The DS will record a brownout event in the DS log.

The controller will take the following steps to attempt to preserve the battery voltage:

- PWM outputs will be disabled. For PWM outputs which have set their neutral value (all speed controllers in WPILib) a single neutral pulse will be sent before the output is disabled.
- 6V, 5V, 3.3V User Rails disabled (This includes the 6V outputs on the PWM pins, the 5V pins in the DIO connector bank, the 5V pins in the Analog bank, the 3.3V pins in the SPI and I2C bank and the 5V and 3.3V pins in the MXP bank)
- GPIO configured as outputs go to High-Z
- Relay Outputs are disabled (driven low)
- CAN-based motor controllers are sent an explicit disable command

**The controller will remain in this state until the voltage rises to greater than 7.5V or drops below the trigger for the next stage of the brownout**

## Stage 3 - Device Blackout

### Voltage Trigger - 4.5V

Below 4.5V the device may blackout. The exact voltage may be lower than this and depends on the load on the device.

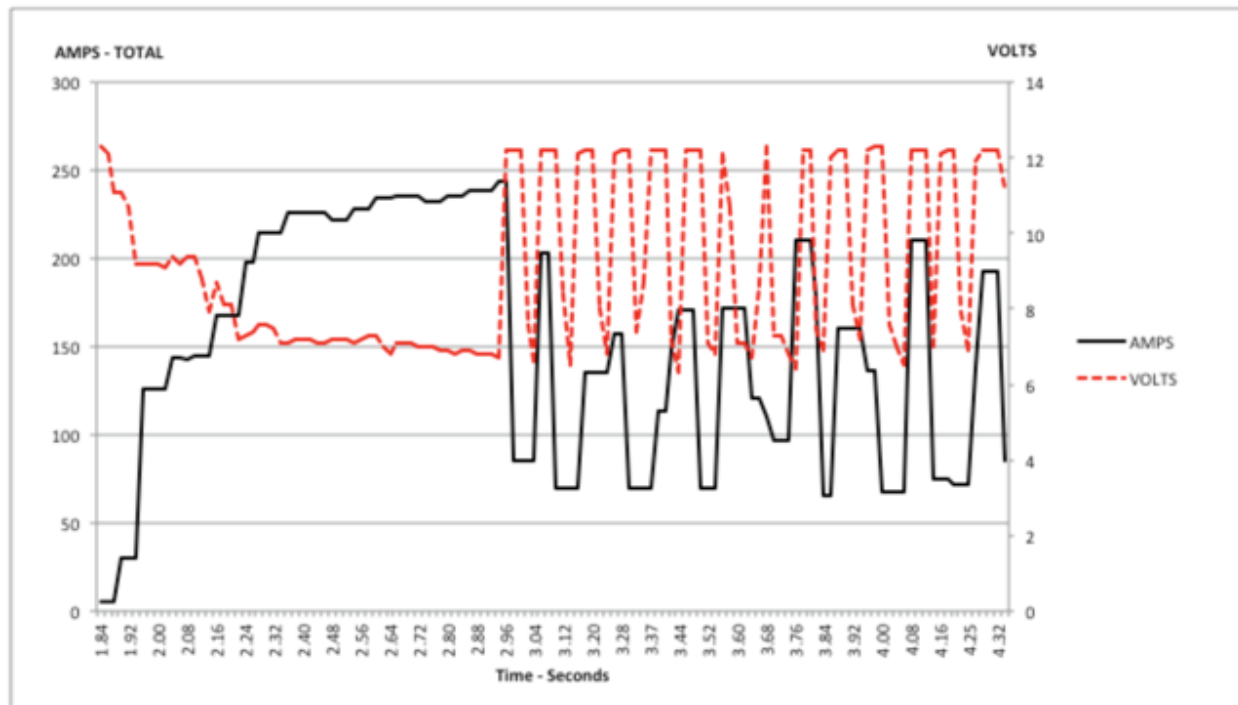
**The controller will remain in this state until the voltage rises above 4.65V when the device will begin the normal boot sequence.**

## 22.4.2 Avoiding Brownout - Proactive Current Draw Planning

The key to avoiding a brownout condition is to proactively plan for the current draw of your robot. The best way to do this is to create some form of power budget. This can be a complex document that attempts to quantify both estimated current draw and time in an effort to most completely understand power usage and therefore battery state at the end of a match, or it can be a simple inventory of current usage. To do this:



PLOT 1 – AMPS and VOLTS v. Time – 2.5 Second Window



1. Establish the max “sustained” current draw (with sustained being loosely defined here as not momentary). This is probably the most difficult part of creating the power budget. The exact current draw a battery can sustain while maintaining a voltage of 7+ volts is dependent on a variety of factors such as battery health and state of charge. As shown in the [NP18-12 data sheet](#), the terminal voltage chart gets very steep as state of charge decreases, especially as current draw increases. This datasheet shows that at 3CA continuous load (54A) a brand new battery can be continuously run for over 6 minutes while maintaining a terminal voltage of over 7V. As shown in the image above (used with permission from [Team 234s Drive System Testing document](#)), even with a fresh battery, drawing 240A for more than a second or two is likely to cause an issue. This gives us some bounds on setting our sustained current draw. For the purposes of this exercise, we’ll set our limit at 180A.
2. List out the different functions of your robot such as drivetrain, manipulator, main game mechanism, etc.
3. Start assigning your available current to these functions. You will likely find that you run out pretty quickly. Many teams gear their drivetrain to have enough torque to slip their wheels at 40-50A of current draw per motor. If we have 4 motors on the drivetrain, that eats up most, or even exceeds, our power budget! This means that we may need to put together a few scenarios and understand what functions can (and need to be) be used at the same time. In many cases, this will mean that you really need to limit the current draw of the other functions if/while your robot is maxing out the drivetrain (such as trying to push something). Benchmarking the “driving” current requirements of a drivetrain for some of these alternative scenarios is a little more complex, as it depends on many factors such as number of motors, robot weight, gearing, and efficiency. Current numbers for other functions can be done by calculating the power required to complete the function and estimating efficiency (if the mechanism has not been designed) or by determining the torque load on the motor and using the torque-current curve to determine the current draw of the motors.

4. If you have determined mutually exclusive functions in your analysis, consider enforcing the exclusion in software. You may also use the current monitoring of the PDP (covered in more detail below) in your robot program to provide output limits or exclusions dynamically (such as don't run a mechanism motor when the drivetrain current is over X or only let the motor run up to half output when the drivetrain current is over Y).

### **22.4.3 Measuring Current Draw using the PDP**

The FRC Driver Station works in conjunction with the roboRIO and PDP to extract logged data from the PDP and log it on your DS PC. A viewer for this data is still under development.

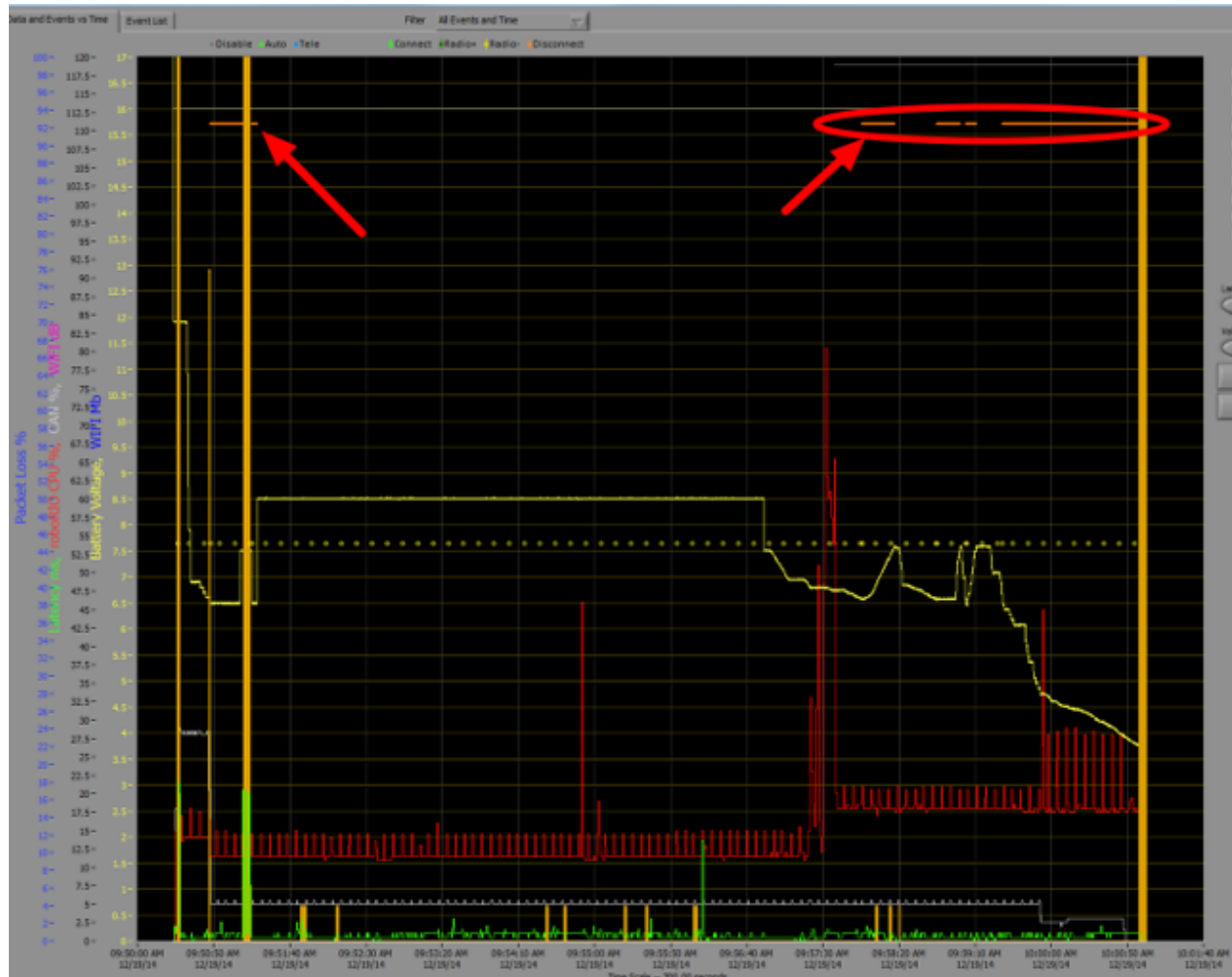
In the meantime, teams can use their robot code and manual logging, a LabVIEW front panel or the SmartDashboard to visualize current draw on their robot as mechanisms are developed. In LabVIEW, you can read the current on a PDP channel using the PDP Channel Current VI found on the Power pallet. For C++ and Java teams, use the `PowerDistributionPanel` class as described in the Power Distribution Panel article. Plotting this information over time (easiest with a LV Front Panel or with the SmartDashboard by using a Graph indicator can provide information to compare against and update your power budget or can locate mechanisms which do not seem to be performing as expected (due to incorrect load calculation, incorrect efficiency assumptions, or mechanism issues such as binding).

### **22.4.4 Identifying Brownouts**

The easiest way to identify a brownout is by clicking on the CAN\Power tab of the DS and checking the 12V fault count. Alternately, you can review the Driver Station Log after the fact using the Driver Station Log Viewer. The log will identify brownouts with a bright orange line, such as in the image above (note that these brownouts were induced with a benchtop supply and may not reflect the duration and behavior of brownouts on a typical FRC robot).

## **22.5 Recovering a roboRIO using Safe Mode**

Occasionally a roboRIO may become corrupted to the point that it cannot be recovered using the normal boot and imaging process. Booting the roboRIO into Safe Mode may allow the device to be successfully re-imaged.



### 22.5.1 Booting into Safe Mode



To boot the roboRIO into Safe Mode:

1. Apply power to the roboRIO
2. Press and hold the Reset button until the Status LED lights up (~5 seconds) then release the Reset button
3. The roboRIO will boot in Safe Mode (indicated by the Status LED flashing in groups of 3)

### 22.5.2 Recovering the roboRIO

The roboRIO can now be imaged by using the roboRIO Imaging Tool as described in [Imaging your roboRIO](#).

### **22.5.3 About Safe Mode**

In Safe Mode, the roboRIO boots a separate copy of the operating system into a RAM Disk. This allows you to recover the roboRIO even if the normal copy of the OS is corrupted. While in Safe Mode, any changes made to the OS (such as changes made by accessing the device via SSH or Serial) will not persist to the normal copy of the OS stored on disk.

## Advanced Controls

This section covers advanced control features in WPILib, such as various feedback/feedforward control algorithms and trajectory following.

### 23.1 Advanced Controls Introduction

#### 23.1.1 Control System Basics

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**Note:** This article is taken out of [Controls Engineering in FRC](#) by Tyler Veness with permission.

---

Control systems are all around us and we interact with them daily. A small list of ones you may have seen includes heaters and air conditioners with thermostats, cruise control and the anti-lock braking system (ABS) on automobiles, and fan speed modulation on modern laptops. Control systems monitor or control the behavior of systems like these and may consist of humans controlling them directly (manual control), or of only machines (automatic control).

How can we prove closed-loop controllers on an autonomous car, for example, will behave safely and meet the desired performance specifications in the presence of uncertainty? Control theory is an application of algebra and geometry used to analyze and predict the behavior of systems, make them respond how we want them to, and make them robust to disturbances and uncertainty.

Controls engineering is, put simply, the engineering process applied to control theory. As such, it's more than just applied math. While control theory has some beautiful math behind it, controls engineering is an engineering discipline like any other that is filled with trade-offs. The solutions control theory gives should always be sanity checked and informed by our performance specifications. We don't need to be perfect; we just need to be good enough to meet our specifications.

#### Nomenclature

Most resources for advanced engineering topics assume a level of knowledge well above that which is necessary. Part of the problem is the use of jargon. While it efficiently communicates

ideas to those within the field, new people who aren't familiar with it are lost.

The system or collection of actuators being controlled by a control system is called the *plant*. A controller is used to drive the plant from its current state to some desired state (the reference). Controllers which don't include information measured from the plant's output are called open-loop controllers.

Controllers which incorporate information fed back from the plant's output are called closed-loop controllers or feedback controllers.

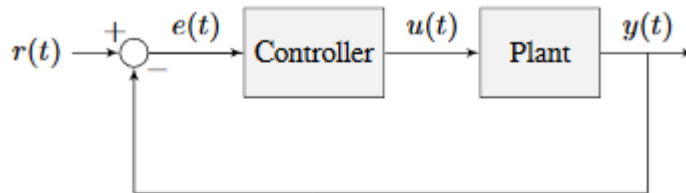


Figure 1.1: Control system nomenclature for a closed-loop system

$r(t)$	reference	$u(t)$	control input
$e(t)$	error	$y(t)$	output

**Note:** The input and output of a system are defined from the plant's point of view. The negative feedback controller shown is driving the difference between the reference and output, also known as the error, to zero.

### What is Gain?

*Gain* is a proportional value that shows the relationship between the magnitude of an input signal to the magnitude of an output signal at steady-state. Many systems contain a method by which the gain can be altered, providing more or less "power" to the system.

The figure below shows a system with a hypothetical input and output. Since the output is twice the amplitude of the input, the system has a gain of two.

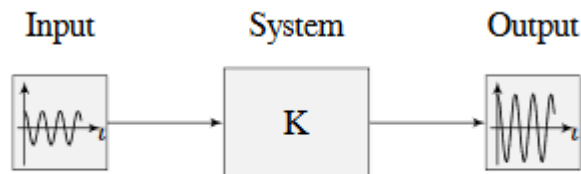


Figure 1.2: Demonstration of system with a gain of  $K = 2$

## Block Diagrams

When designing or analyzing a control system, it is useful to model it graphically. Block diagrams are used for this purpose. They can be manipulated and simplified systematically.

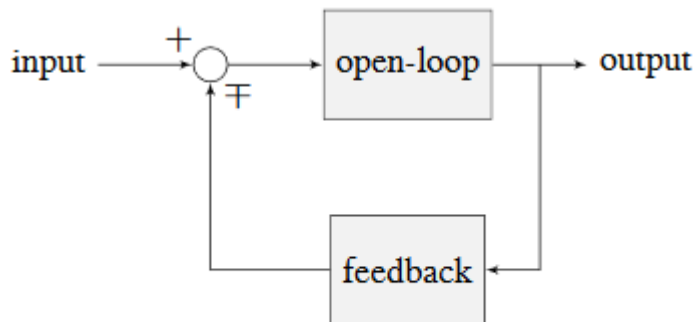


Figure 1.3: Block diagram with nomenclature

The open-loop gain is the total gain from the sum node at the input (the circle) to the output branch. This would be the system's gain if the feedback loop was disconnected. The feedback gain is the total gain from the output back to the input sum node. A sum node's output is the sum of its inputs.

The below figure is a block diagram with more formal notation in a feedback configuration.

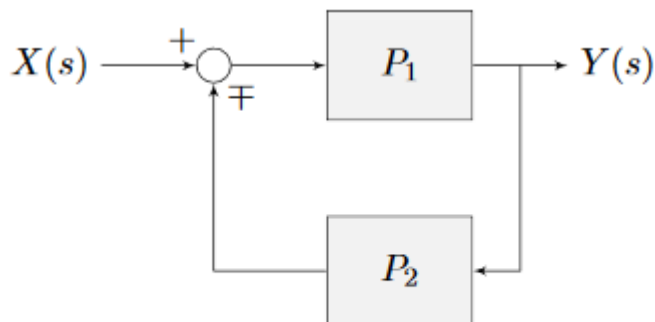


Figure 1.4: Feedback block diagram

$\mp$  means “minus or plus” where a minus represents negative feedback.

## Why Feedback Control?

Let's say we are controlling a DC brushed motor. With just a mathematical model and knowledge of all the current states of the system (i.e., angular velocity), we can predict all future states given the future voltage inputs. Why then do we need feedback control? If the system is disturbed in any way that isn't modeled by our equations, like a load was applied, or voltage sag in the rest of the circuit caused the commanded voltage to not match the applied voltage, the angular velocity of the motor will deviate from the model over time.

To combat this, we can take measurements of the system and the environment to detect this deviation and account for it. For example, we could measure the current position and estimate an angular velocity from it. We can then give the motor corrective commands as well as steer



our model back to reality. This feedback allows us to account for uncertainty and be robust to it.

### 23.1.2 Introduction to PID

The PID controller is a commonly used feedback controller consisting of proportional, integral, and derivative terms, hence the name. This article will build up the definition of a PID controller term by term while trying to provide some intuition for how each of them behaves.

First, we'll get some nomenclature for PID controllers out of the way. The *reference* is called the setpoint (the desired position) and the *output* is called the *process variable* (the measured position). Below are some common variable naming conventions for relevant quantities.

$r(t)$	<i>setpoint</i>	$u(t)$	<i>control input</i>
$e(t)$	<i>error</i>	$y(t)$	<i>output</i>

The *error*  $e(t)$  is  $r(t) - y(t)$ .

For those already familiar with PID control, this book's interpretation won't be consistent with the classical intuition of "past", "present", and "future" error. We will be approaching it from the viewpoint of modern control theory with proportional controllers applied to different physical quantities we care about. This will provide a more complete explanation of the derivative term's behavior for constant and moving *setpoints*.

The proportional term drives the position error to zero, the derivative term drives the velocity error to zero, and the integral term accumulates the area between the *setpoint* and *output* plots over time (the integral of position *error*) and adds the current total to the *control input*. We'll go into more detail on each of these.

#### Proportional Term

The *Proportional* term drives the position error to zero.

$$u(t) = K_p e(t)$$

where  $K_p$  is the proportional gain and  $e(t)$  is the error at the current time  $t$ .

The below figure shows a block diagram for a *system* controlled by a P controller.

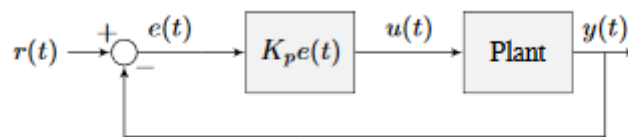


Figure 2.1: P controller block diagram

Proportional gains act like a "software-defined springs" that pull the *system* toward the desired position. Recall from physics that we model springs as  $F = -kx$  where  $F$  is the force applied,  $k$  is a proportional constant, and  $x$  is the displacement from the equilibrium point. This can be written another way as  $F = k(0 - x)$  where 0 is the equilibrium point. If we let

the equilibrium point be our feedback controller's *setpoint*, the equations have a one to one correspondence.

$$F = k(r - x)$$

$$u(t) = K_p e(t) = K_p(r(t) - y(t))$$

so the “force” with which the proportional controller pulls the *system's output* toward the *setpoint* is proportional to the *error*, just like a spring.

## Derivative Term

The *Derivative* term drives the velocity error to zero.

$$u(t) = K_p e(t) + K_d \frac{de}{dt}$$

where  $K_p$  is the proportional gain,  $K_d$  is the derivative gain, and  $e(t)$  is the error at the current time  $t$ .

The below figure shows a block diagram for a *system* controlled by a PD controller.

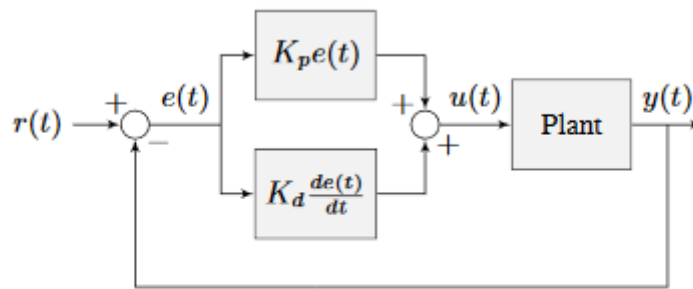


Figure 2.2: PD controller block diagram

A PD controller has a proportional controller for position ( $K_p$ ) and a proportional controller for velocity ( $K_d$ ). The velocity *setpoint* is implicitly provided by how the position *setpoint* changes over time. To prove this, we will rearrange the equation for a PD controller.

$$u_k = K_p e_k + K_d \frac{e_k - e_{k-1}}{dt}$$

where  $u_k$  is the *control input* at timestep  $k$  and  $e_k$  is the *error* at timestep  $k$ .  $e_k$  is defined as  $e_k = r_k - x_k$  where  $r_k$  is the *setpoint* and  $x_k$  is the current *state* at timestep  $k$ .

$$u_k = K_p(r_k - x_k) + K_d \frac{(r_k - x_k) - (r_{k-1} - x_{k-1})}{dt}$$

$$u_k = K_p(r_k - x_k) + K_d \frac{r_k - x_k - r_{k-1} + x_{k-1}}{dt}$$

$$u_k = K_p(r_k - x_k) + K_d \frac{r_k - r_{k-1} - x_k + x_{k-1}}{dt}$$

$$u_k = K_p(r_k - x_k) + K_d \frac{(r_k - r_{k-1}) - (x_k - x_{k-1})}{dt}$$

$$u_k = K_p(r_k - x_k) + K_d \left( \frac{r_k - r_{k-1}}{dt} - \frac{x_k - x_{k-1}}{dt} \right)$$

Notice how  $\frac{r_k - r_{k-1}}{dt}$  is the velocity of the *setpoint*. By the same reason,  $\frac{x_k - x_{k-1}}{dt}$  is the *system's* velocity at a given timestep. That means the  $K_d$  term of the PD controller is driving the estimated velocity to the *setpoint* velocity.

If the *setpoint* is constant, the implicit velocity *setpoint* is zero, so the  $K_d$  term slows the *system* down if it's moving. This acts like a “software-defined damper”. These are commonly seen on door closers, and their damping force increases linearly with velocity.

## Integral Term

**Important:** Integral gain is generally not recommended for FRC use. There are better approaches to fix *steady-state error* like using feedforwards or constraining when the integral control acts using other knowledge of the *system*.

The *Integral* term accumulates the area between the *setpoint* and *output* plots over time (i.e., the integral of position *error*) and adds the current total to the *control input*. Accumulating the area between two curves is called integration.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau$$

where  $K_p$  is the proportional gain,  $K_i$  is the integral gain,  $e(t)$  is the error at the current time  $t$ , and  $\tau$  is the integration variable.

The Integral integrates from time 0 to the current time  $t$ . we use  $\tau$  for the integration because we need a variable to take on multiple values throughout the integral, but we can't use  $t$  because we already defined that as the current time.

The below figure shows a block diagram for a *system* controlled by a PI controller.

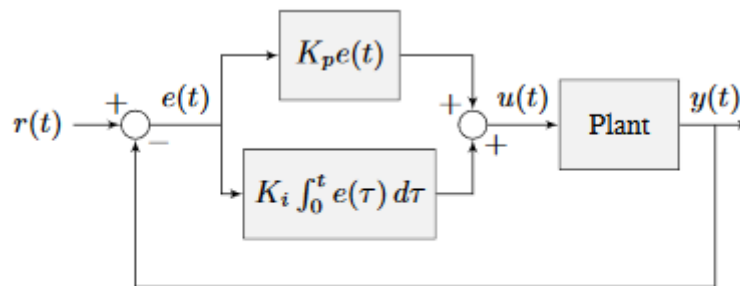


Figure 2.3: PI controller block diagram

When the *system* is close the *setpoint* in steady-state, the proportional term may be too small to pull the *output* all the way to the *setpoint*, and the derivative term is zero. This can result in *steady-state error* as shown in figure 2.4

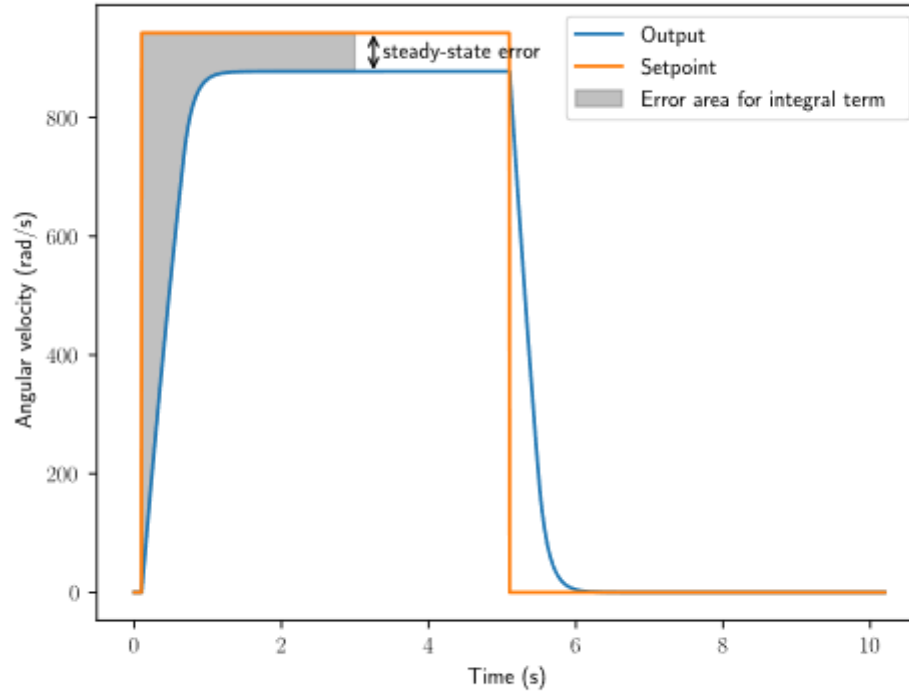


Figure 2.4: P controller with steady-state error

A common way of eliminating *steady-state error* is to integrate the *error* and add it to the *control input*. This increases the *control effort* until the *system* converges. Figure 2.4 shows an example of *steady-state error* for a flywheel, and figure 2.5 shows how an integrator added to the flywheel controller eliminates it. However, too high of an integral gain can lead to overshoot, as shown in figure 2.6.

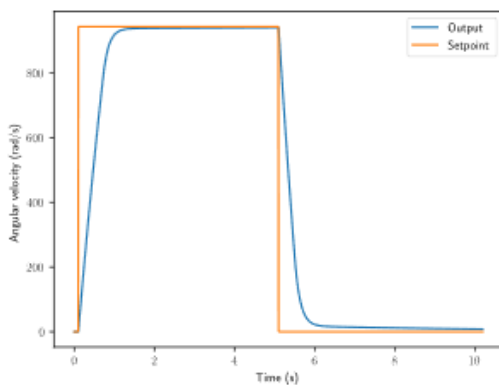
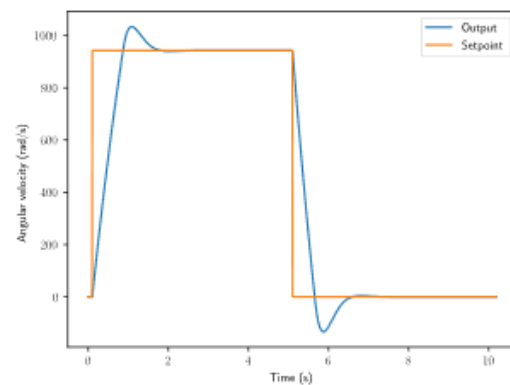


Figure 2.5: PI controller without steady-state error

Figure 2.6: PI controller with overshoot from large  $K_i$  gain

## PID Controller Definition

**Note:** For information on using the WPILib provided PIDController, see the relevant article.

When these terms are combined, one gets the typical definition for a PID controller.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de}{dt}$$

where  $K_p$  is the proportional gain,  $K_i$  is the integral gain,  $K_d$  is the derivative gain,  $e(t)$  is the error at the current time  $t$ , and  $\tau$  is the integration variable.

The below figure shows a block diagram for a PID controller.

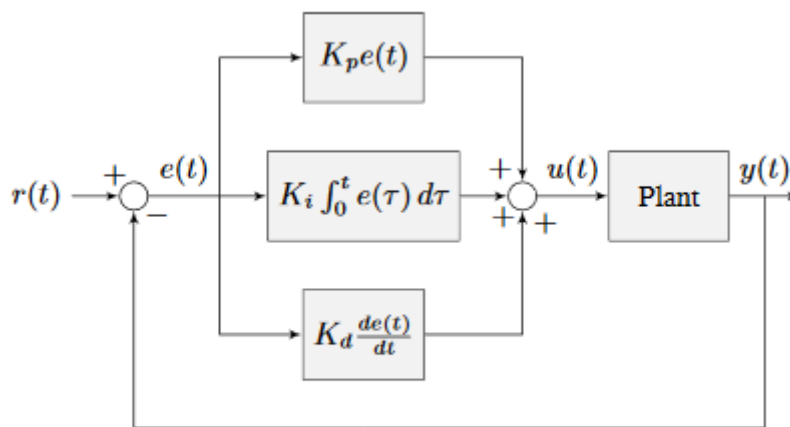


Figure 2.7: PID controller block diagram

## Response Types

A *system* driven by a PID controller generally has three types of responses: underdamped, over-damped, and critically damped. These are shown in figure 2.8.

For the *step responses* in figure 2.7, *rise time* is the time the *system* takes to initially reach the reference after applying the *step input*. *Settling time* is the time the *system* takes to settle at the *reference* after the *step input* is applied.

An *underdamped* response oscillates around the *reference* before settling. An *overdamped* response

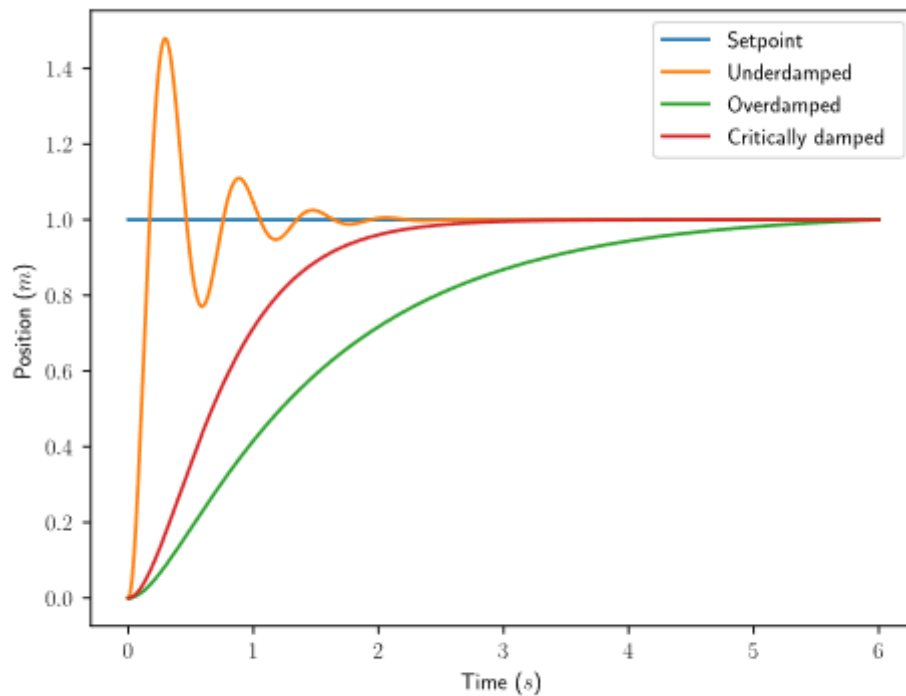


Figure 2.8: PID controller response types

is slow to rise and does not overshoot the *reference*. A *critically damped* response has the fastest *rise time* without overshooting the *reference*.

### 23.1.3 Tuning a PID Controller

These steps apply to position PID controllers. Velocity PID controllers typically don't need  $K_d$ .

1. Set  $K_p$ ,  $K_i$ , and  $K_d$  to zero.
2. Increase  $K_p$  until the *output* starts to oscillate around the *setpoint*.
3. Increase  $K_d$  as much as possible without introducing jittering in the *system response*.

Plot the position *setpoint*, velocity *setpoint*, measured position, and measured velocity. The velocity *setpoint* can be obtained via numerical differentiation of the position *setpoint* (i.e.,  $v_{desired,k} = \frac{r_k - r_{k-1}}{\Delta t}$ ). Increase  $K_p$  until the position tracks well, then increase  $K_d$  until the velocity tracks well.

If the *controller* settles at an *output* above or below the *setpoint*, one can increase  $K_i$  such that the *controller* reaches the *setpoint* in a reasonable amount of time. However, a steady-state feedforward is strongly preferred over integral control (especially for PID control).

**Important:** Adding an integral gain to the *controller* is an incorrect way to eliminate *steady-state error*. A better approach would be to tune it with an integrator added to the *plant*, but

this requires a *model*. Since we are doing output-based rather than model-based control, our only option is to add an integrator to the *controller*.

---

Beware that if  $K_i$  is too large, integral windup can occur. Following a large change in *setpoint*, the integral term can accumulate an error larger than the maximal *control input*. As a result, the system overshoots and continues to increase until this accumulated error is unwound.

---

**Note:** The *frc-characterization toolsuite* can be used to model your system and give accurate Proportional and Derivative values. This is preferred over tuning the controller yourself.

---

### Actuator Saturation

A controller calculates its output based on the error between the *reference* and the current *state*. *Plant* in the real world don't have unlimited control authority available for the controller to apply. When the actuator limits are reached, the controller acts as if the gain has been temporarily reduced.

We'll try to explain this through a bit of math. Let's say we have a controller  $u = k(r - x)$  where  $u$  is the *control effort*,  $k$  is the gain,  $r$  is the *reference*, and  $x$  is the current state. Let  $u_{max}$  be the limit of the actuator's output which is less than the uncapped value of  $u$  and  $k_{max}$  be the associated maximum gain. We will now compare the capped and uncapped controllers for the same *reference* and current *state*.

$$\begin{aligned}u_{max} &< u \\k_{max}(r - x) &< k(r - x) \\k_{max} &< k\end{aligned}$$

For the inequality to hold,  $k_{max}$  must be less than the original value for  $k$ . This reduced gain is evident in a *system response* when there is a linear change in state instead of an exponential one as it approaches the *reference*. This is due to the *control effort* no longer following a decaying exponential plot. Once the *system* is closer to the *reference*, the controller will stop saturating and produce realistic controller values again.

### 23.1.4 Controls Glossary

**reference** The desired state. This value is used as the reference point for a controller's error calculation.

**input** An input to the *plant* (hence the name) that can be used to change the *plant's state*.

**output** Measurements from sensors.

**process variable** The term used to describe the output of a *plant* in the context of PID control.

**setpoint** The term used to describe the *reference* of a PID controller.

**error** *Reference* minus an *output* or *state*.

**state** A characteristic of a *system* (e.g., velocity) that can be used to determine the *system's* future behavior.

**system** A term encompassing a *plant* and its interaction with a *controller* and *observer*, which is treated as a single entity. Mathematically speaking, a *system* maps *inputs* to *outputs* through a linear combination of *states*.

**plant** The *system* or collection of actuators being controlled.

**controller** Used in position or negative feedback with a *plant* to bring about a desired *system state* by driving the difference between a *reference* signal and the *output* to zero.

**observer** In control theory, a system that provides an estimate of the internal *state* of a given real *system* from measurements of the *input* and *output* of the real *system*.

**control input** The input of a *plant* used for the purpose of controlling it

**control effort** A term describing how much force, pressure, etc. an actuator is exerting.

**steady-state error** *Error* after *system* reaches equilibrium.

**step response** The response of a *system* to a *step input*.

**step input** A *system input* that is 0 for  $t < 0$  and a constant greater than 0 for  $t \geq 0$ . A step input that is 1 for  $t \geq 0$  is called a unit step input.

**rise time** The time a *system* takes to initially reach the *reference* after applying a *step input*.

**settling time** The time a *system* takes to settle at the *reference* after a *step input* is applied.

**system response** The behavior of a *system* over time for a given *input*.

**model** A set of mathematical equations that reflects some aspect of a physical *system's* behavior.

## 23.2 Filters

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**Note:** The data used to generate the various demonstration plots in this section can be found [here](#).

---

This section describes a number of filters included with WPILib that are useful for noise reduction and/or input smoothing.

### 23.2.1 Introduction to Filters

Filters are some of the most common tools used in modern technology, and find numerous applications in robotics in both signal processing and controls. Understanding the notion of a filter is crucial to understanding the utility of the various types of filters provided by WPILib.

#### What Is a Filter?

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**Note:** For the sake of this article, we will assume all data are single-dimensional time-series data. Obviously, the concepts involved are more general than this - but a full/rigorous discussion of signals and filtering is out of the scope of this documentation.

---



So, what exactly is a filter, then? Simply put, a filter is a mapping from a stream of inputs to a stream of outputs. That is to say, the value output by a filter (in principle) can depend not only on the *current* value of the input, but on *the entire set of past and future values* (of course, in practice, the filters provided by WPILib are implementable in real-time on streaming data; accordingly, they can only depend on the *past* values of the input, and not on future values). This is an important concept, because generally we use filters to remove/mitigate unwanted *dynamics* from a signal. When we filter a signal, we're interested in modifying *how the signal changes over time*.

### Effects of Using a Filter

#### Noise Reduction

One of the most typical uses of a filter is for noise reduction. A filter that reduces noise is called a *low-pass* filter (because it allows low frequencies to “pass through,” while blocking high-frequencies). Most of the filters currently included in WPILib are effectively low-pass filters.

#### Rate Limiting

Filters are also commonly used to reduce the rate at which a signal can change. This is closely related to noise reduction, and filters that reduce noise also tend to limit the rate of change of their output.

#### Edge Detection

The counterpart to the low-pass filter is the high-pass filter, which only permits high frequencies to pass through to the output. High-pass filters can be somewhat tricky to build intuition for, but a common usage for a high-pass filter is edge-detection - since high-pass filters will reflect sudden changes in the input while ignoring slower changes, they are useful for determining the location of sharp discontinuities in the signal.

#### Phase Lag

An unavoidable negative effect of a real-time low-pass filter is the introduction of “phase lag.” Since, as mentioned earlier, a real-time filter can only depend on past values of the signal (we cannot time-travel to obtain the future values), the filtered value takes some time to “catch up” when the input starts changing. The greater the noise-reduction, the greater the introduced delay. This is, in many ways, *the* fundamental trade-off of real-time filtering, and should be the primary driving factor of your filter design.

Interestingly, high-pass filters introduce a phase *lead*, as opposed to a phase lag, as they exacerbate local changes to the value of the input.

### 23.2.2 Linear Filters

The first (and most commonly-employed) sort of filter that WPILib supports is a *linear filter* - or, more specifically, a linear time-invariant (LTI) filter.

An LTI filter is, put simply, a weighted moving average - the value of the output stream at any given time is a localized, weighted average of the inputs near that time. The difference between different types of LTI filters is thus reduceable to the difference in the choice of the weighting function (also known as a “window function” or an “impulse response”) used. Mathematically, this kind of moving average is known as a [convolution](#).

There are two broad “sorts” of impulse responses: infinite impulse responses (IIR), and finite impulse responses (FIR).

Infinite impulse responses have infinite “support” - that is, they are nonzero over an infinitely-large region. This means, broadly, that they also have infinite “memory” - once a value appears in the input stream, it will influence *all subsequent outputs, forever*. This is typically undesirable from a strict signal-processing perspective, however filters with infinite impulse responses tend to be very easy to compute as they can be expressed by simple recursion relations.

Finite impulse responses have finite “support” - that is, they are nonzero on a bounded region. The “archetypical” FIR filter is a flat moving average - that is, simply setting the output equal to the average of the past  $n$  inputs. FIR filters tend to have more-desirable properties than IIR filters, but are more costly to compute.

Linear filters are supported in WPILib through the `LinearFilter` class ([Java](#), [C++](#)).

### Creating a LinearFilter

---

**Note:** The C++ `LinearFilter` class is templated on the data type used for the input.

---

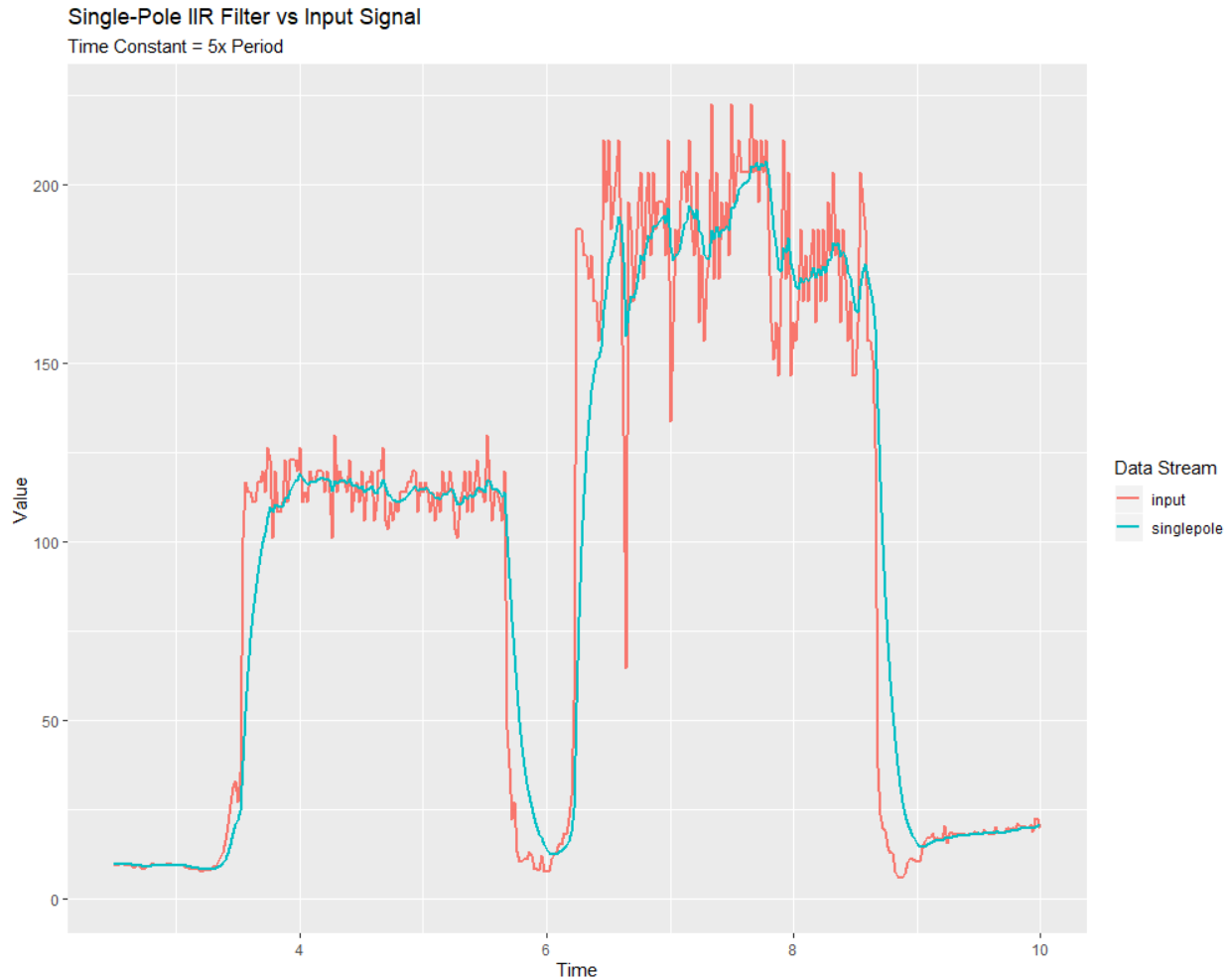
---

**Note:** Because filters have “memory”, each input stream requires its own filter object. Do *not* attempt to use the same filter object for multiple input streams.

---

While it is possible to directly instantiate `LinearFilter` class to build a custom filter, it is far more convenient (and common) to use one of the supplied factory methods, instead:

## singlePoleIIR



The `singlePoleIIR()` factory method creates a single-pole infinite impulse response filter (also known as [exponential smoothing](#), on account of having an exponential impulse response). This is the “go-to,” “first-try” low-pass filter in most applications; it is computationally trivial and works in most cases.

Java

```
// Creates a new Single-Pole IIR filter
// Time constant is 0.1 seconds
// Period is 0.02 seconds - this is the standard FRC main loop period
LinearFilter filter = LinearFilter.singlePoleIIR(0.1, 0.02);
```

C++

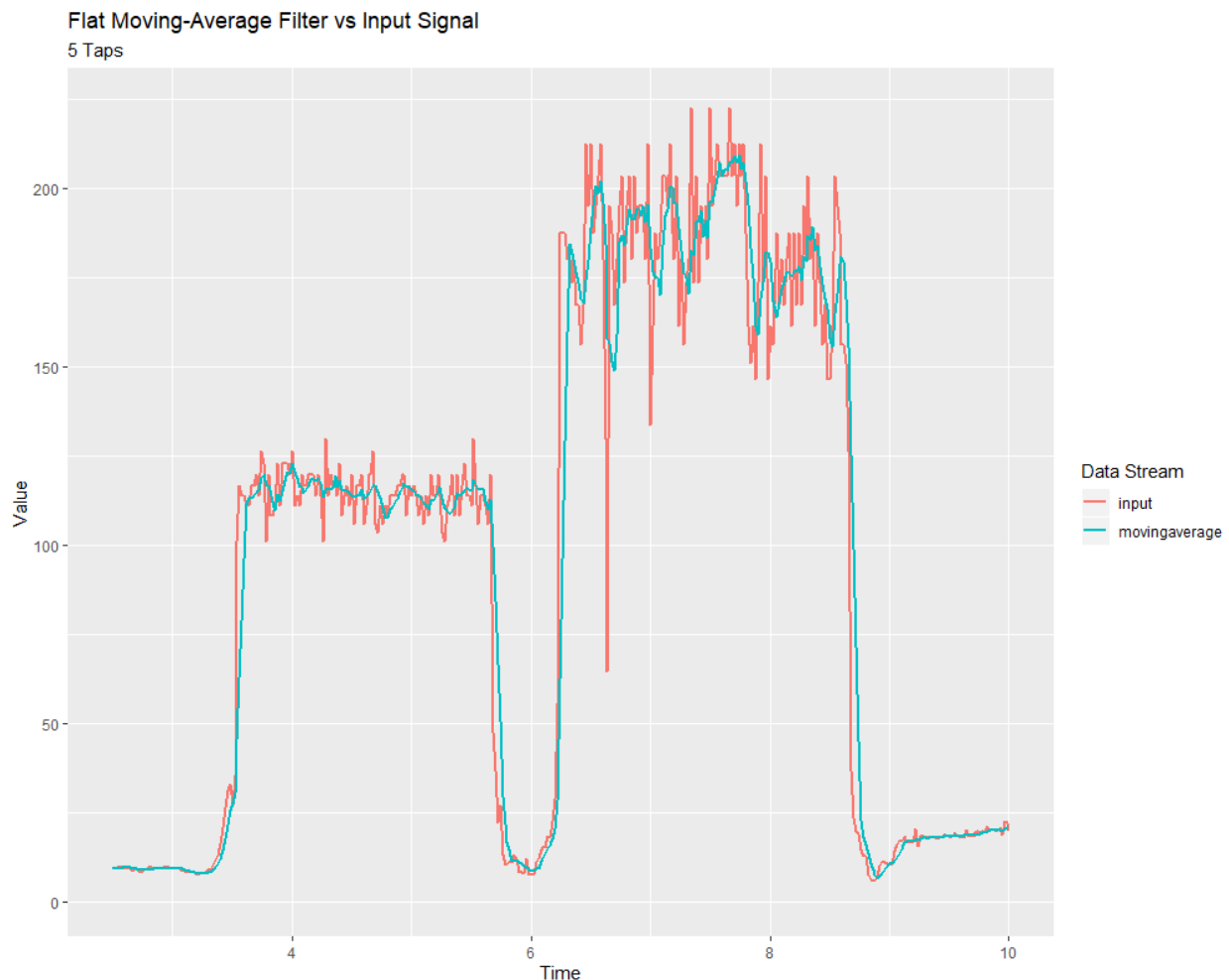
```
// Creates a new Single-Pole IIR filter
// Time constant is 0.1 seconds
// Period is 0.02 seconds - this is the standard FRC main loop period
frc::LinearFilter<double> filter = frc::LinearFilter<double>::SinglePoleIIR(0.1_s, 0.
    02_s);
```

The “time constant” parameter determines the “characteristic timescale” of the filter’s im-

pulse response; the filter will cancel out any signal dynamics that occur on timescales significantly shorter than this. Relatedly, it is also the approximate timescale of the introduced *phase lag*. The reciprocal of this timescale, multiplied by 2 pi, is the “cutoff frequency” of the filter.

The “period” parameter is the period at which the filter’s `calculate()` method will be called. For the vast majority of implementations, this will be the standard main robot loop period of 0.02 seconds.

## movingAverage



The `movingAverage` factory method creates a simple flat moving average filter. This is the simplest possible low-pass FIR filter, and is useful in many of the same contexts as the single-pole IIR filter. It is somewhat more costly to compute, but generally behaves in a somewhat nicer manner.

Java

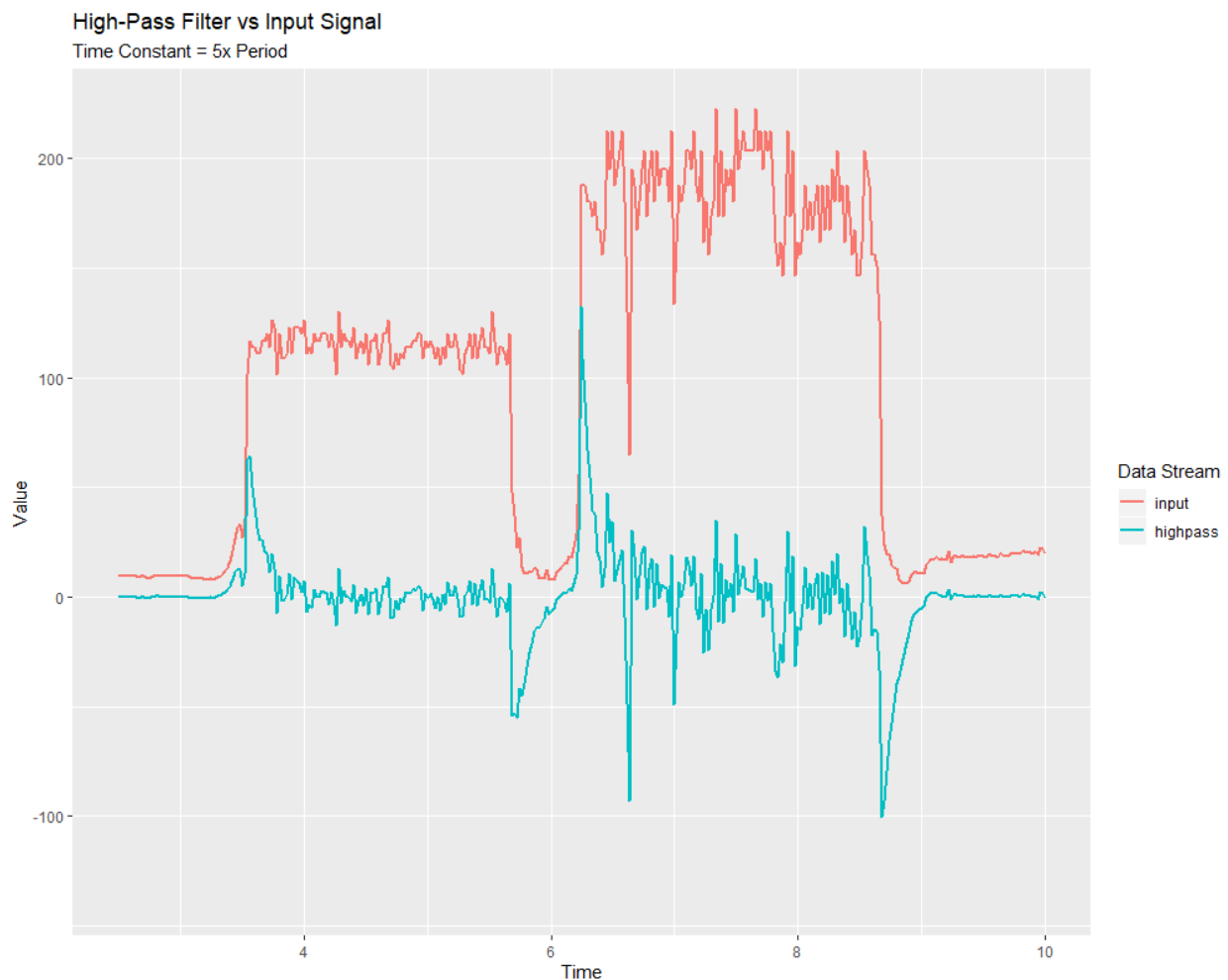
```
// Creates a new flat moving average filter
// Average will be taken over the last 5 samples
LinearFilter filter = LinearFilter.movingAverage(5);
```

C++

```
// Creates a new flat moving average filter
// Average will be taken over the last 5 samples
frc::LinearFilter<double> filter = frc::LinearFilter<double>::MovingAverage(5);
```

The “taps” parameter is the number of samples that will be included in the flat moving average. This behaves similarly to the “time constant” above - the effective time constant is the number of taps times the period at which `calculate()` is called.

## highPass



The `highPass` factory method creates a simple first-order infinite impulse response high-pass filter. This is the “counterpart” to the [singlePoleIIR](#).

Java

```
// Creates a new high-pass IIR filter
// Time constant is 0.1 seconds
// Period is 0.02 seconds - this is the standard FRC main loop period
LinearFilter filter = LinearFilter.highPass(0.1, 0.02);
```

C++

```
// Creates a new high-pass IIR filter
// Time constant is 0.1 seconds
// Period is 0.02 seconds - this is the standard FRC main loop period
frc::LinearFilter<double> filter = frc::LinearFilter<double>::HighPass(0.1_s, 0.02_s);
```

The “time constant” parameter determines the “characteristic timescale” of the filter’s impulse response; the filter will cancel out any signal dynamics that occur on timescales significantly longer than this. Relatedly, it is also the approximate timescale of the introduced *phase lead*. The reciprocal of this timescale, multiplied by 2 pi, is the “cutoff frequency” of the filter.

The “period” parameter is the period at which the filter’s `calculate()` method will be called. For the vast majority of implementations, this will be the standard main robot loop period of 0.02 seconds.

### Using a LinearFilter

**Note:** In order for the created filter to obey the specified timescale parameter, its `calculate()` function *must* be called regularly at the specified period. If, for some reason, a significant lapse in `calculate()` calls must occur, the filter’s `reset()` method should be called before further use.

Once your filter has been created, using it is easy - simply call the `calculate()` method with the most recent input to obtain the filtered output:

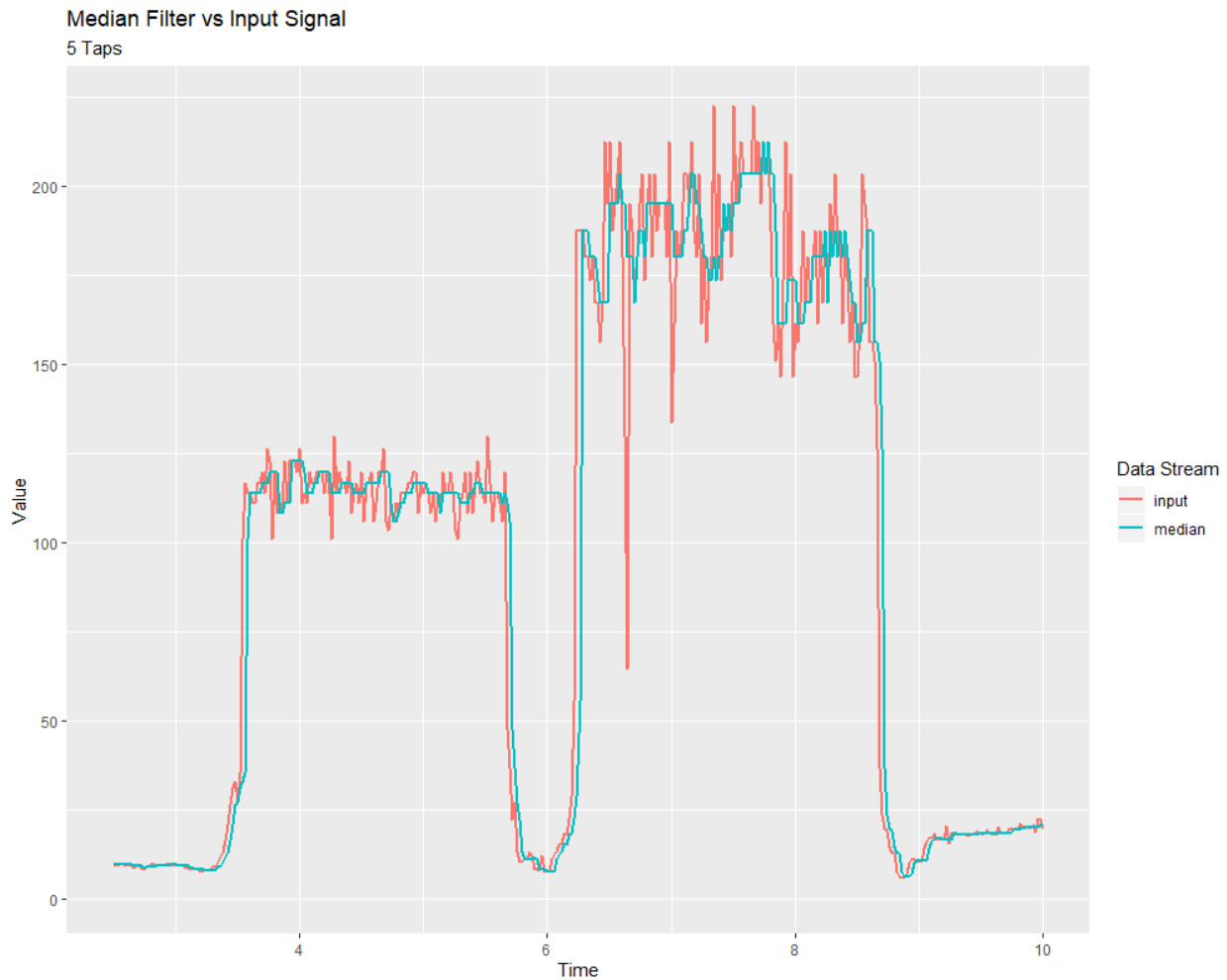
Java

```
// Calculates the next value of the output
filter.calculate(input);
```

C++

```
// Calculates the next value of the output
filter.Calculate(input);
```

### 23.2.3 Median Filter



A **robust** alternative to the *moving-average filter* is the *median filter*. Where a moving average filter takes the arithmetic *mean* of the input over a moving sample window, a median filter (per the name) takes a median instead.

The median filter is most-useful for removing occasional outliers from an input stream. This makes it particularly well-suited to filtering inputs from distance sensors, which are prone to occasional interference. Unlike a moving average, the median filter will remain completely unaffected by small numbers of outliers, no matter how extreme.

The median filter is supported in WPILib through the `MedianFilter` class (Java, C++).

#### Creating a MedianFilter

---

**Note:** The C++ `MedianFilter` class is templated on the data type used for the input.

---

---

**Note:** Because filters have “memory”, each input stream requires its own filter object. Do

---

not attempt to use the same filter object for multiple input streams.

Creating a MedianFilter is simple:

Java

```
// Creates a MedianFilter with a window size of 5 samples
MedianFilter filter = new MedianFilter(5);
```

C++

```
// Creates a MedianFilter with a window size of 5 samples
frc::MedianFilter<double> filter(5);
```

### Using a MedianFilter

Once your filter has been created, using it is easy - simply call the `calculate()` method with the most recent input to obtain the filtered output:

Java

```
// Calculates the next value of the output
filter.calculate(input);
```

C++

```
// Calculates the next value of the output
filter.Calculate(input);
```

## 23.2.4 Slew Rate Limiter

A common use for filters in FRC is to soften the behavior of control inputs (for example, the joystick inputs from your driver controls). Unfortunately, a simple low-pass filter is poorly-suited for this job; while a low-pass filter will soften the response of an input stream to sudden changes, it will also wash out fine control detail and introduce phase lag. A better solution is to limit the rate-of-change of the control input directly. This is performed with a *slew rate limiter* - a filter that caps the maximum rate-of-change of the signal.

A slew rate limiter can be thought of as a sort of primitive motion profile. In fact, the slew rate limiter is the first-order equivalent of the [Trapezoidal Motion Profile](#) supported by WPILib - it is precisely the limiting case of trapezoidal motion when the acceleration constraint is allowed to tend to infinity. Accordingly, the slew rate limiter is a good choice for applying a de-facto motion profile to a stream of velocity setpoints (or voltages, which are usually approximately proportional to velocity). For input streams that control positions, it is usually better to use a proper trapezoidal profile.

Slew rate limiting is supported in WPILib through the `SlewRateLimiter` class ([Java](#), [C++](#)).



### Creating a SlewRateLimiter

---

**Note:** The C++ SlewRateLimiter class is templated on the unit type of the input. For more information on C++ units, see *The C++ Units Library*.

---

---

**Note:** Because filters have “memory”, each input stream requires its own filter object. Do *not* attempt to use the same filter object for multiple input streams.

---

Creating a SlewRateLimiter is simple:

Java

```
// Creates a SlewRateLimiter that limits the rate of change of the signal to 0.5_
↪units per second
SlewRateLimiter filter = new SlewRateLimiter(0.5);
```

C++

```
// Creates a SlewRateLimiter that limits the rate of change of the signal to 0.5_
↪volts per second
frc::SlewRateLimiter<units::volts> filter{0.5_v / 1_s};
```

### Using a SlewRateLimiter

Once your filter has been created, using it is easy - simply call the `calculate()` method with the most recent input to obtain the filtered output:

Java

```
// Calculates the next value of the output
filter.calculate(input);
```

C++

```
// Calculates the next value of the output
filter.Calculate(input);
```

## 23.3 Controllers

This section describes various WPILib feedback and feedforward controller classes that are useful for controlling the motion of FRC mechanisms, as well as motion-profiling classes that can automatically generate setpoints for use with these controllers.

### 23.3.1 PID Control in WPILib

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**Note:** This article covers the in-code implementation of PID Control with WPILib’s provided library classes. Documentation describing the involved concepts in more detail is forthcoming.

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**Note:** For a guide on implementing PID control through the *command-based framework*, see *PID Control through PIDSUBSYSTEMS and PIDCommands*.

---

WPILib supports PID control of mechanisms through the `PIDController` class (Java, C++). This class handles the feedback loop calculation for the user, as well as offering methods for returning the error, setting tolerances, and checking if the control loop has reached its setpoint within the specified tolerances.

### Using the `PIDController` Class

---

**Note:** The `PIDController` class in the `frc` namespace is deprecated - C++ teams should use the one in the `frc2` namespace, instead. Likewise, Java teams should use the class in the `wpilibj.controller` package.

---

### Constructing a `PIDController`

---

**Note:** While `PIDController` may be used asynchronously, it does *not* provide any thread safety features - ensuring threadsafe operation is left entirely to the user, and thus asynchronous usage is recommended only for advanced teams.

---

In order to use WPILib's PID control functionality, users must first construct a `PIDController` object with the desired gains:

Java

```
// Creates a PIDController with gains kP, kI, and kD
PIDController pid = new PIDController(kP, kI, kD);
```

C++

```
// Creates a PIDController with gains kP, kI, and kD
frc2::PIDController pid(kP, kI, kD);
```

An optional fourth parameter can be provided to the constructor, specifying the period at which the controller will be run. The `PIDController` object is intended primarily for synchronous use from the main robot loop, and so this value is defaulted to 20ms.

### Using the Feedback Loop Output

---

**Note:** The `PIDController` assumes that the `calculate()` method is being called regularly at an interval consistent with the configured period. Failure to do this will result in unintended loop behavior.

---

**Warning:** Unlike the old PIDController, the new PIDController does not automatically control an output from its own thread - users are required to call `calculate()` and use the resulting output in their own code.

Using the constructed PIDController is simple: simply call the `calculate()` method from the robot's main loop (e.g. the robot's `autonomousPeriodic()` method):

Java

```
// Calculates the output of the PID algorithm based on the sensor reading  
// and sends it to a motor  
motor.set(pid.calculate(encoder.getDistance(), setpoint));
```

C++

```
// Calculates the output of the PID algorithm based on the sensor reading  
// and sends it to a motor  
motor.Set(pid.Calculate(encoder.GetDistance(), setpoint));
```

### Checking Errors

**Note:** `getPositionError()` and `getVelocityError()` are named assuming that the loop is controlling a position - for a loop that is controlling a velocity, these return the velocity error and the acceleration error, respectively.

The current error of the measured process variable is returned by the `getPositionError()` function, while its derivative is returned by the `getVelocityError()` function:

### Specifying and Checking Tolerances

**Note:** If only a position tolerance is specified, the velocity tolerance defaults to infinity.

**Note:** As above, “position” refers to the process variable measurement, and “velocity” to its derivative - thus, for a velocity loop, these are actually velocity and acceleration, respectively.

Occasionally, it is useful to know if a controller has tracked the setpoint to within a given tolerance - for example, to determine if a command should be ended, or (while following a motion profile) if motion is being impeded and needs to be re-planned.

To do this, we first must specify the tolerances with the `setTolerance()` method; then, we can check it with the `atSetpoint()` method.

Java

```
// Sets the error tolerance to 5, and the error derivative tolerance to 10 per second  
pid.setTolerance(5, 10);
```

(continues on next page)

(continued from previous page)

```
// Returns true if the error is less than 5 units, and the
// error derivative is less than 10 units
pid.atSetpoint();
```

C++

```
// Sets the error tolerance to 5, and the error derivative tolerance to 10 per second
pid.SetTolerance(5, 10);

// Returns true if the error is less than 5 units, and the
// error derivative is less than 10 units
pid.AtSetpoint();
```

## Resetting the Controller

It is sometimes desirable to clear the internal state (most importantly, the integral accumulator) of a `PIDController`, as it may be no longer valid (e.g. when the `PIDController` has been disabled and then re-enabled). This can be accomplished by calling the `reset()` method.

## Setting a Max Integrator Value

**Note:** Integrators introduce instability and hysteresis into feedback loop systems. It is strongly recommended that teams avoid using integral gain unless absolutely no other solution will do - very often, problems that can be solved with an integrator can be better solved through use of a more-accurate *feedforward*.

A typical problem encountered when using integral feedback is excessive “wind-up” causing the system to wildly overshoot the setpoint. This can be alleviated in a number of ways - the WPILib `PIDController` offers an integrator range limiter to help teams overcome this issue.

Enabling this setting with the `setIntegratorRange()` method will prevent the total output contribution from the integral gain from exceeding the user-specified bounds.

Java

```
// The integral gain term will never add or subtract more than 0.5 from
// the total loop output
pid.setIntegratorRange(-0.5, 0.5);
```

C++

```
// The integral gain term will never add or subtract more than 0.5 from
// the total loop output
pid.SetIntegratorRange(-0.5, 0.5);
```

### Setting Continuous Input

**Warning:** If your mechanism is not capable of fully continuous rotational motion (e.g. a turret without a slip ring, whose wires twist as it rotates), *do not* enable continuous input unless you have implemented an additional safety feature to prevent the mechanism from moving past its limit!

**Warning:** The continuous input function does *not* automatically wrap your input values - be sure that your input values, when using this feature, are never outside of the specified range!

Some process variables (such as the angle of a turret) are measured on a circular scale, rather than a linear one - that is, each “end” of the process variable range corresponds to the same point in reality (e.g. 360 degrees and 0 degrees). In such a configuration, there are two possible values for any given error, corresponding to which way around the circle the error is measured. It is usually best to use the smaller of these errors.

To configure a `PIDController` to automatically do this, use the `enableContinuousInput()` method:

Java

```
// Enables continuous input on a range from -180 to 180
pid.enableContinuousInput(-180, 180);
```

C++

```
// Enables continuous input on a range from -180 to 180
pid.EnableContinuousInput(-180, 180);
```

### Clamping Controller Output

Unlike the old `PIDController`, the new controller does not offer any output clamping features, as the user is expected to use the loop output themselves. Output clamping can be easily achieved by composing the controller with WPI’s `clamp()` function (or `std::clamp` in c++):

Java

```
// Clamps the controller output to between -0.5 and 0.5
MathUtil.clamp(pid.calculate(encoder.getDistance(), setpoint), -0.5, 0.5);
```

C++

```
// Clamps the controller output to between -0.5 and 0.5
std::clamp(pid.Calculate(encoder.GetDistance(), setpoint), -0.5, 0.5);
```

### 23.3.2 Feedforward Control in WPILib

So far, we’ve used feedback control for reference tracking (making a system’s output follow a desired reference signal). While this is effective, it’s a reactionary measure; the system won’t

start applying control effort until the system is already behind. If we could tell the controller about the desired movement and required input beforehand, the system could react quicker and the feedback controller could do less work. A controller that feeds information forward into the plant like this is called a feedforward controller.

A feedforward controller injects information about the system's dynamics (like a mathematical model does) or the intended movement. Feedforward handles parts of the control actions we already know must be applied to make a system track a reference, then feedback compensates for what we do not or cannot know about the system's behavior at runtime.

There are two types of feedforwards: model-based feedforward and feedforward for unmodeled dynamics. The first solves a mathematical model of the system for the inputs required to meet desired velocities and accelerations. The second compensates for unmodeled forces or behaviors directly so the feedback controller doesn't have to. Both types can facilitate simpler feedback controllers. We'll cover several examples below.

---

**Note:** The WPILib feedforward classes closely match the available mechanism characterization tools available in the [frc-characterization toolsuite](#) - the characterization toolsuite can be used to quickly and effectively determine the correct gains for each type of feedforward. The toolsuite will indicate the appropriate units for each of the gains.

---

WPILib provides a number of classes to help users implement accurate feedforward control for their mechanisms. In many ways, an accurate feedforward is more important than feedback to effective control of a mechanism. Since most FRC mechanisms closely obey well-understood system equations, starting with an accurate feedforward is both easy and hugely beneficial to accurate and robust mechanism control.

WPILib currently provides the following three helper classes for feedforward control:

- [SimpleMotorFeedforward](#) (Java, C++)
- [ArmFeedforward](#) (Java, C++)
- [ElevatorFeedforward](#) (Java, C++)

## SimpleMotorFeedforward

---

**Note:** In C++, the `SimpleMotorFeedforward` class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in gains *must* have units consistent with the distance units, or a compile-time error will be thrown.  $k_S$  should have units of volts,  $k_V$  should have units of volts \* seconds / distance, and  $k_A$  should have units of volts \* seconds<sup>2</sup> / distance. For more information on C++ units, see [The C++ Units Library](#).

---



---

**Note:** The Java feedforward components will calculate outputs in units determined by the units of the user-provided feedforward gains. Users *must* take care to keep units consistent, as WPILibJ does not have a type-safe unit system.

---

The `SimpleMotorFeedforward` class calculates feedforwards for mechanisms that consist of permanent-magnet DC motors with no external loading other than friction and inertia, such as flywheels and robot drives.

To create a SimpleMotorFeedforward, simply construct it with the required gains:

**Note:** The kA gain can be omitted, and if it is, will default to a value of zero. For many mechanisms, especially those with little inertia, it is not necessary.

---

Java

```
// Create a new SimpleMotorFeedforward with gains kS, kV, and kA
SimpleMotorFeedforward feedforward = new SimpleMotorFeedforward(kS, kV, kA);
```

C++

```
// Create a new SimpleMotorFeedforward with gains kS, kV, and kA
// Distance is measured in meters
frc::SimpleMotorFeedforward<units::meters> feedforward(kS, kV, kA);
```

To calculate the feedforward, simply call the calculate() method with the desired motor velocity and acceleration:

**Note:** The acceleration argument may be omitted from the calculate() call, and if it is, will default to a value of zero. This should be done whenever there is not a clearly-defined acceleration setpoint.

---

Java

```
// Calculates the feedforward for a velocity of 10 units/second and an acceleration_
↳ of 20 units/second^2
// Units are determined by the units of the gains passed in at construction.
feedforward.calculate(10, 20);
```

C++

```
// Calculates the feedforward for a velocity of 10 meters/second and an acceleration_
↳ of 20 meters/second^2
// Output is in volts
feedforward.Calculate(10_mps, 20_mps_sq);
```

## ArmFeedforward

**Note:** In C++, the ArmFeedforward class assumes distances are angular, not linear. The passed-in gains *must* have units consistent with the angular unit, or a compile-time error will be thrown. kS and kCos should have units of volts, kV should have units of volts \* seconds / radians, and kA should have units of volts \* seconds^2 / radians. For more information on C++ units, see [The C++ Units Library](#).

---

**Note:** The Java feedforward components will calculate outputs in units determined by the units of the user-provided feedforward gains. Users *must* take care to keep units consistent, as WPILibJ does not have a type-safe unit system.

---

The ArmFeedforward class calculates feedforwards for arms that are controlled directly by a permanent-magnet DC motor, with external loading of friction, inertia, and mass of the arm. This is an accurate model of most arms in FRC.

To create an ArmFeedforward, simply construct it with the required gains:

**Note:** The kA gain can be omitted, and if it is, will default to a value of zero. For many mechanisms, especially those with little inertia, it is not necessary.

Java

```
// Create a new ArmFeedforward with gains kS, kCos, kV, and kA
ArmFeedforward feedforward = new ArmFeedforward(kS, kCos, kV, kA);
```

C++

```
// Create a new ArmFeedforward with gains kS, kCos, kV, and kA
frc::ArmFeedforward feedforward(kS, kCos, kV, kA);
```

To calculate the feedforward, simply call the calculate() method with the desired arm position, velocity, and acceleration:

**Note:** The acceleration argument may be omitted from the calculate() call, and if it is, will default to a value of zero. This should be done whenever there is not a clearly-defined acceleration setpoint.

Java

```
// Calculates the feedforward for a position of 1 units, a velocity of 2 units/second,
↪ and
// an acceleration of 3 units/second^2
// Units are determined by the units of the gains passed in at construction.
feedforward.calculate(1, 2, 3);
```

C++

```
// Calculates the feedforward for a position of 1 radians, a velocity of 2 radians/
↪ second, and
// an acceleration of 3 radians/second^2
// Output is in volts
feedforward.Calculate(1_rad, 2_rad_per_s, 3_rad/(1_s * 1_s));
```

## ElevatorFeedforward

**Note:** In C++, the ElevatorFeedforward class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in gains *must* have units consistent with the distance units, or a compile-time error will be thrown. kS and kG should have units of volts, kV should have units of volts \* seconds / distance, and kA should have units of volts \* seconds^2 / distance. For more information on C++ units, see [The C++ Units Library](#).



**Note:** The Java feedforward components will calculate outputs in units determined by the units of the user-provided feedforward gains. Users *must* take care to keep units consistent, as WPILibJ does not have a type-safe unit system.

---

The `ElevatorFeedforward` class calculates feedforwards for elevators that consist of permanent-magnet DC motors loaded by friction, inertia, and the mass of the elevator. This is an accurate model of most elevators in FRC.

To create a `ElevatorFeedforward`, simply construct it with the required gains:

**Note:** The `kA` gain can be omitted, and if it is, will default to a value of zero. For many mechanisms, especially those with little inertia, it is not necessary.

---

Java

```
// Create a new ElevatorFeedforward with gains kS, kG, kV, and kA
ElevatorFeedforward feedforward = new ElevatorFeedforward(kS, kG, kV, kA);
```

C++

```
// Create a new ElevatorFeedforward with gains kS, kV, and kA
// Distance is measured in meters
frc::ElevatorFeedforward<units::meters> feedforward(kS, kG, kV, kA);
```

To calculate the feedforward, simply call the `calculate()` method with the desired motor velocity and acceleration:

**Note:** The acceleration argument may be omitted from the `calculate()` call, and if it is, will default to a value of zero. This should be done whenever there is not a clearly-defined acceleration setpoint.

---

Java

```
// Calculates the feedforward for a position of 10 units, velocity of 20 units/second,
// and an acceleration of 30 units/second^2
// Units are determined by the units of the gains passed in at construction.
feedforward.calculate(10, 20, 30);
```

C++

```
// Calculates the feedforward for a position of 10 meters, velocity of 20 meters/
// second,
// and an acceleration of 30 meters/second^2
// Output is in volts
feedforward.Calculate(10_m, 20_mps, 30_mps_sq);
```

## Using Feedforward to Control Mechanisms

**Note:** Since feedforward voltages are physically meaningful, it is best to use the `setVoltage()` (Java, C++) method when applying them to motors to compensate for “voltage

sag” from the battery.

Feedforward control can be used entirely on its own, without a feedback controller. This is known as “open-loop” control, and for many mechanisms (especially robot drives) can be perfectly satisfactory. A SimpleMotorFeedforward might be employed to control a robot drive as follows:

Java

```
public void tankDriveWithFeedforward(double leftVelocity, double rightVelocity) {
    leftMotor.setVoltage(feedforward.calculate(leftVelocity));
    rightMotor.setVoltage(feedforward.calculate(rightVelocity));
}
```

C++

```
void TankDriveWithFeedforward(units::meters_per_second_t leftVelocity,
                               units::meters_per_second_t rightVelocity) {
    leftMotor.SetVoltage(feedforward.Calculate(leftVelocity));
    rightMotor.SetVoltage(feedforward.Calculate(rightVelocity));
}
```

### 23.3.3 Combining Feedforward and PID Control

**Note:** This article covers the in-code implementation of combined feedforward/PID control with WPILib’s provided library classes. Documentation describing the involved concepts in more detail is forthcoming.

Feedforward and feedback controllers can each be used in isolation, but are most effective when combined together. Thankfully, combining these two control methods is *exceedingly* straightforward - one simply adds their outputs together.

#### Using Feedforward with a PIDController

Users familiar with the old PIDController class may notice the lack of any feedforward gain in the new controller. As users are expected to use the controller output themselves, there is no longer any need for the PIDController to implement feedforward - users may simply add any feedforward they like to the output of the controller before sending it to their motors:

Java

```
// Adds a feedforward to the loop output before sending it to the motor
motor.setVoltage(pid.calculate(encoder.getDistance(), setpoint) + feedforward);
```

C++

```
// Adds a feedforward to the loop output before sending it to the motor
motor.SetVoltage(pid.Calculate(encoder.GetDistance(), setpoint) + feedforward);
```

Moreover, feedforward is a separate feature entirely from feedback, and thus has no reason to be handled in the same controller object, as this violates separation of concerns. WPILib

comes with several helper classes to compute accurate feedforward voltages for common FRC mechanisms - for more information, see [Feedforward Control in WPILib](#).

### Using Feedforward Components with PID

---

**Note:** Since feedforward voltages are physically meaningful, it is best to use the `setVoltage()` (Java, C++) method when applying them to motors to compensate for “voltage sag” from the battery.

---

What might a more complete example of combined feedforward/PID control look like? Consider the [drive example](#) from the feedforward page. We can easily modify this to include feedback control (with a `SimpleMotorFeedforward` component):

Java

```
public void tankDriveWithFeedforwardPID(double leftVelocitySetpoint, double_
↪rightVelocitySetpoint) {
    leftMotor.setVoltage(feedforward.calculate(leftVelocitySetpoint)
        + leftPID.calculate(leftEncoder.getRate(), leftVelocitySetpoint));
    rightMotor.setVoltage(feedforward.calculate(rightVelocitySetpoint)
        + rightPID.calculate(rightEncoder.getRate(), rightVelocitySetpoint));
}
```

C++

```
void TankDriveWithFeedforwardPID(units::meters_per_second_t leftVelocitySetpoint,
                                units::meters_per_second_t rightVelocitySetpoint) {
    leftMotor.SetVoltage(feedforward.Calculate(leftVelocitySetpoint)
        + leftPID.Calculate(leftEncoder.getRate(), leftVelocitySetpoint.to<double>()));
    rightMotor.SetVoltage(feedforward.Calculate(rightVelocitySetpoint)
        + rightPID.Calculate(rightEncoder.getRate(), rightVelocitySetpoint.to<double>
↪()));
}
```

Other mechanism types can be handled similarly.

### 23.3.4 Trapezoidal Motion Profiles in WPILib

---

**Note:** This article covers the in-code generation of trapezoidal motion profiles. Documentation describing the involved concepts in more detail is forthcoming.

---

---

**Note:** For a guide on implementing the `TrapezoidProfile` class in the [command-based framework](#) framework, see [Motion Profiling through TrapezoidProfileSubsystems and TrapezoidProfileCommands](#).

---

---

**Note:** The `TrapezoidProfile` class, used on its own, is most useful when composed with a custom controller (such as a “smart” motor controller with a built-in PID functionality). To

---

integrate it with a WPILib PIDController, see [Combining Motion Profiling and PID Control with ProfiledPIDController](#).

While feedforward and feedback control offer convenient ways to achieve a given setpoint, we are often still faced with the problem of generating setpoints for our mechanisms. While the naive approach of immediately commanding a mechanism to its desired state may work, it is often suboptimal. To improve the handling of our mechanisms, we often wish to command mechanisms to a *sequence* of setpoints that smoothly interpolate between its current state, and its desired goal state.

To help users do this, WPILib provides a TrapezoidProfile class ([Java](#), [C++](#)).

## Creating a TrapezoidProfile

**Note:** In C++, the TrapezoidProfile class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see [The C++ Units Library](#).

## Constraints

**Note:** The various [feedforward helper classes](#) provide methods for calculating the maximum simultaneously-achievable velocity and acceleration of a mechanism. These can be very useful for calculating appropriate motion constraints for your TrapezoidProfile.

In order to create a trapezoidal motion profile, we must first impose some constraints on the desired motion. Namely, we must specify a maximum velocity and acceleration that the mechanism will be expected to achieve during the motion. To do this, we create an instance of the TrapezoidProfile.Constraints class ([Java](#), [C++](#)):

Java

```
// Creates a new set of trapezoidal motion profile constraints
// Max velocity of 10 meters per second
// Max acceleration of 20 meters per second squared
new TrapezoidProfile.Constraints(10, 20);
```

C++

```
// Creates a new set of trapezoidal motion profile constraints
// Max velocity of 10 meters per second
// Max acceleration of 20 meters per second squared
frc::TrapezoidProfile<units::meters>::Constraints{10_mps, 20_mps_sq};
```

## Start and End States

Next, we must specify the desired starting and ending states for our mechanisms using the TrapezoidProfile.State class ([Java](#), [C++](#)). Each state has a position and a velocity:

Java

```
// Creates a new state with a position of 5 meters
// and a velocity of 0 meters per second
new TrapezoidProfile.State(5, 0);
```

C++

```
// Creates a new state with a position of 5 meters
// and a velocity of 0 meters per second
frc::TrapezoidProfile<units::meters>::State{5_m, 0_mps};
```

### Putting It All Together

---

**Note:** C++ is often able to infer the type of the inner classes, and thus a simple initializer list (without the class name) can be sent as a parameter. The full class names are included in the example below for clarity.

---

Now that we know how to create a set of constraints and the desired start/end states, we are ready to create our motion profile. The `TrapezoidProfile` constructor takes 3 parameters, in order: the constraints, the goal state, and the initial state.

Java

```
// Creates a new TrapezoidProfile
// Profile will have a max vel of 5 meters per second
// Profile will have a max acceleration of 10 meters per second squared
// Profile will end stationary at 5 meters
// Profile will start stationary at zero position
TrapezoidProfile profile = new TrapezoidProfile(new TrapezoidProfile.Constraints(5,
↪ 10),
                                         new TrapezoidProfile.State(5, 0),
                                         new TrapezoidProfile.State(0, 0));
```

C++

```
// Creates a new TrapezoidProfile
// Profile will have a max vel of 5 meters per second
// Profile will have a max acceleration of 10 meters per second squared
// Profile will end stationary at 5 meters
// Profile will start stationary at zero position
frc::TrapezoidProfile<units::meters> profile(
    frc::TrapezoidProfile<units::meters>::Constraints{5_mps, 10_mps_sq},
    frc::TrapezoidProfile<units::meters>::State{5_m, 0_mps},
    frc::TrapezoidProfile<units::meters>::State{0_m, 0_mps});
```

### Using a TrapezoidProfile

#### Sampling the Profile

Once we've created a `TrapezoidProfile`, using it is very simple: to get the profile state at the given time after the profile has started, call the `calculate()` method:

Java

```
// Returns the motion profile state after 5 seconds of motion
profile.calculate(5);
```

C++

```
// Returns the motion profile state after 5 seconds of motion
profile.Calculate(5_s);
```

## Using the State

The `calculate` method returns a `TrapezoidProfile.State` class (the same one that was used to specify the initial/end states when constructing the profile). To use this for actual control, simply pass the contained position and velocity values to whatever controller you wish (for example, a `PIDController`):

Java

```
var setpoint = profile.calculate(elapsedTime);
controller.calculate(encoder.getDistance(), setpoint.position);
```

C++

```
auto setpoint = profile.Calculate(elapsedTime);
controller.Calculate(encoder.GetDistance(), setpoint.position.to<double>());
```

## Complete Usage Example

**Note:** In this example, the profile is re-computed every timestep. This is a somewhat different usage technique than is detailed above, but works according to the same principles - the profile is sampled at a time corresponding to the loop period to get the setpoint for the next loop iteration.

A more complete example of `TrapezoidProfile` usage is provided in the `ElevatorTrapezoidProfile` example project (Java, C++):

Java

```
8 package edu.wpi.first.wpilibj.examples.elevatortrapezoidprofile;
9
10 import edu.wpi.first.wpilibj.Joystick;
11 import edu.wpi.first.wpilibj.TimedRobot;
12 import edu.wpi.first.wpilibj.controller.SimpleMotorFeedforward;
13 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
14
15 public class Robot extends TimedRobot {
16     private static double kDt = 0.02;
17
18     private final Joystick m_joystick = new Joystick(1);
19     private final ExampleSmartMotorController m_motor = new
    ↳ ExampleSmartMotorController(1);
```

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```

20 // Note: These gains are fake, and will have to be tuned for your robot.
21 private final SimpleMotorFeedforward m_feedforward = new SimpleMotorFeedforward(1,
↪ 1.5);
22
23 private final TrapezoidProfile.Constraints m_constraints =
24     new TrapezoidProfile.Constraints(1.75, 0.75);
25 private TrapezoidProfile.State m_goal = new TrapezoidProfile.State();
26 private TrapezoidProfile.State m_setpoint = new TrapezoidProfile.State();
27
28 @Override
29 public void robotInit() {
30     // Note: These gains are fake, and will have to be tuned for your robot.
31     m_motor.setPID(1.3, 0.0, 0.7);
32 }
33
34 @Override
35 public void teleopPeriodic() {
36     if (m_joystick.getRawButtonPressed(2)) {
37         m_goal = new TrapezoidProfile.State(5, 0);
38     } else if (m_joystick.getRawButtonPressed(3)) {
39         m_goal = new TrapezoidProfile.State(0, 0);
40     }
41
42     // Create a motion profile with the given maximum velocity and maximum
43     // acceleration constraints for the next setpoint, the desired goal, and the
44     // current setpoint.
45     var profile = new TrapezoidProfile(m_constraints, m_goal, m_setpoint);
46
47     // Retrieve the profiled setpoint for the next timestep. This setpoint moves
48     // toward the goal while obeying the constraints.
49     m_setpoint = profile.calculate(kDt);
50
51     // Send setpoint to offboard controller PID
52     m_motor.setSetpoint(ExampleSmartMotorController.PIDMode.kPosition, m_setpoint.
↪ position,
53         m_feedforward.calculate(m_setpoint.velocity) / 12.0);
54 }
55 }

```

C++

```

8 #include <frc/Joystick.h>
9 #include <frc/TimedRobot.h>
10 #include <frc/controller/SimpleMotorFeedforward.h>
11 #include <frc/trajectory/TrapezoidProfile.h>
12 #include <units/units.h>
13 #include <wpi/math>
14
15 #include "ExampleSmartMotorController.h"
16
17 class Robot : public frc::TimedRobot {
18 public:
19     static constexpr units::second_t kDt = 20_ms;
20
21     Robot() {
22         // Note: These gains are fake, and will have to be tuned for your robot.

```

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```

23     m_motor.SetPID(1.3, 0.0, 0.7);
24 }
25
26 void TeleopPeriodic() override {
27     if (m_joystick.GetRawButtonPressed(2)) {
28         m_goal = {5_m, 0_mps};
29     } else if (m_joystick.GetRawButtonPressed(3)) {
30         m_goal = {0_m, 0_mps};
31     }
32
33     // Create a motion profile with the given maximum velocity and maximum
34     // acceleration constraints for the next setpoint, the desired goal, and the
35     // current setpoint.
36     frc::TrapezoidProfile<units::meter> profile{m_constraints, m_goal,
37                                                m_setpoint};
38
39     // Retrieve the profiled setpoint for the next timestep. This setpoint moves
40     // toward the goal while obeying the constraints.
41     m_setpoint = profile.Calculate(kDt);
42
43     // Send setpoint to offboard controller PID
44     m_motor.SetSetpoint(ExampleSmartMotorController::PIDMode::kPosition,
45                        m_setpoint.position.to<double>(),
46                        m_feedforward.Calculate(m_setpoint.velocity) / 12_V);
47 }
48
49 private:
50     frc::Joystick m_joystick{1};
51     ExampleSmartMotorController m_motor{1};
52     frc::SimpleMotorFeedforward<units::meters> m_feedforward{
53         // Note: These gains are fake, and will have to be tuned for your robot.
54         1_V, 1.5_V * 1_s / 1_m};
55
56     frc::TrapezoidProfile<units::meters>::Constraints m_constraints{1.75_mps,
57                                                                    0.75_mps_sq};
58     frc::TrapezoidProfile<units::meters>::State m_goal;
59     frc::TrapezoidProfile<units::meters>::State m_setpoint;
60 };
61
62 #ifndef RUNNING_FRC_TESTS
63 int main() { return frc::StartRobot<Robot>(); }
64 #endif

```

### 23.3.5 Combining Motion Profiling and PID Control with ProfiledPID-Controller

**Note:** For a guide on implementing the ProfiledPIDController class in the *command-based framework* framework, see *Combining Motion Profiling and PID in Command-Based*.

In the previous article, we saw how to use the TrapezoidProfile class to create and use a trapezoidal motion profile. The example code from that article demonstrates manually composing the TrapezoidProfile class with the external PID control feature of a “smart” motor controller.



This combination of functionality (a motion profile for generating setpoints combined with a PID controller for following them) is extremely common. To facilitate this, WPILib comes with a `ProfiledPIDController` class ([Java](#), [C++](#)) that does most of the work of combining these two functionalities. The API of the `ProfiledPIDController` is very similar to that of the `PIDController`, allowing users to add motion profiling to a PID-controlled mechanism with very few changes to their code.

### Using the `ProfiledPIDController` class

---

**Note:** In C++, the `ProfiledPIDController` class is templated on the unit type used for distance measurements, which may be angular or linear. The passed-in values *must* have units consistent with the distance units, or a compile-time error will be thrown. For more information on C++ units, see [The C++ Units Library](#).

---

---

**Note:** Much of the functionality of `ProfiledPIDController` is effectively identical to that of `PIDController`. Accordingly, this article will only cover features that are substantially-changed to accomodate the motion profiling functionality. For information on standard `PIDController` features, see [PID Control in WPILib](#).

---

### Constructing a `ProfiledPIDController`

---

**Note:** C++ is often able to infer the type of the inner classes, and thus a simple initializer list (without the class name) can be sent as a parameter. The full class name is included in the example below for clarity.

---

Creating a `ProfiledPIDController` is nearly identical to [creating a `PIDController`](#). The only difference is the need to supply a set of [trapezoidal profile constraints](#), which will be automatically forwarded to the internally-generated `TrapezoidProfile` instances:

Java

```
// Creates a ProfiledPIDController
// Max velocity is 5 meters per second
// Max acceleration is 10 meters per second
ProfiledPIDController controller = new ProfiledPIDController(
    kP, kI, kD,
    new TrapezoidProfile.Constraints(5, 10));
```

C++

```
// Creates a ProfiledPIDController
// Max velocity is 5 meters per second
// Max acceleration is 10 meters per second
frc::ProfiledPIDController<units::meters> controller(
    kP, kI, kD,
    frc::TrapezoidProfile<units::meters>::Constraints{5_mps, 10_mps_sq});
```

## Goal vs Setpoint

A major difference between a standard `PIDController` and a `ProfiledPIDController` is that the actual *setpoint* of the control loop is not directly specified by the user. Rather, the user specifies a *goal* position or state, and the setpoint for the controller is computed automatically from the generated motion profile between the current state and the goal. So, while the user-side call looks mostly identical:

Java

```
// Calculates the output of the PID algorithm based on the sensor reading
// and sends it to a motor
motor.set(controller.calculate(encoder.getDistance(), goal));
```

C++

```
// Calculates the output of the PID algorithm based on the sensor reading
// and sends it to a motor
motor.Set(controller.Calculate(encoder.GetDistance(), goal));
```

The specified goal value (which can be either a position value or a `TrapezoidProfile.State`, if nonzero velocity is desired) is *not* necessarily the *current* setpoint of the loop - rather, it is the *eventual* setpoint once the generated profile terminates.

## Getting/Using the Setpoint

Since the `ProfiledPIDController` goal differs from the setpoint, it is often desirable to poll the current setpoint of the controller (for instance, to get values to use with *feedforward*). This can be done with the `getSetpoint()` method.

The returned setpoint might then be used as in the following example:

Java

```
// Controls a simple motor's position using a SimpleMotorFeedforward
// and a ProfiledPIDController
public void goToPosition(double goalPosition) {
    motor.setVoltage(
        controller.calculate(encoder.getDistance(), goalPosition)
        + feedforward.calculate(controller.getSetpoint().position,
                               controller.getSetpoint().velocity));
}
```

C++

```
// Controls a simple motor's position using a SimpleMotorFeedforward
// and a ProfiledPIDController
void goToPosition(units::meter_t goalPosition) {
    motor.setVoltage(
        controller.Calculate(units::meter_t(encoder.GetDistance()), goalPosition)
        + feedforward.Calculate(controller.GetSetpoint().position,
                               controller.GetSetpoint().velocity));
}
```

## Complete Usage Example

A more complete example of ProfiledPIDController usage is provided in the ElevatorProfilePID example project (Java, C++):

Java

```

8 package edu.wpi.first.wpilibj.examples.elevatorprofiledpid;
9
10 import edu.wpi.first.wpilibj.Encoder;
11 import edu.wpi.first.wpilibj.Joystick;
12 import edu.wpi.first.wpilibj.PWMVictorSPX;
13 import edu.wpi.first.wpilibj.SpeedController;
14 import edu.wpi.first.wpilibj.TimedRobot;
15 import edu.wpi.first.wpilibj.controller.ProfiledPIDController;
16 import edu.wpi.first.wpilibj.trajectory.TrapezoidProfile;
17
18 public class Robot extends TimedRobot {
19     private static double kDt = 0.02;
20
21     private final Joystick m_joystick = new Joystick(1);
22     private final Encoder m_encoder = new Encoder(1, 2);
23     private final SpeedController m_motor = new PWMVictorSPX(1);
24
25     // Create a PID controller whose setpoint's change is subject to maximum
26     // velocity and acceleration constraints.
27     private final TrapezoidProfile.Constraints m_constraints =
28         new TrapezoidProfile.Constraints(1.75, 0.75);
29     private final ProfiledPIDController m_controller =
30         new ProfiledPIDController(1.3, 0.0, 0.7, m_constraints, kDt);
31
32     @Override
33     public void robotInit() {
34         m_encoder.setDistancePerPulse(1.0 / 360.0 * 2.0 * Math.PI * 1.5);
35     }
36
37     @Override
38     public void teleopPeriodic() {
39         if (m_joystick.getRawButtonPressed(2)) {
40             m_controller.setGoal(5);
41         } else if (m_joystick.getRawButtonPressed(3)) {
42             m_controller.setGoal(0);
43         }
44
45         // Run controller and update motor output
46         m_motor.set(m_controller.calculate(m_encoder.getDistance()));
47     }
48 }

```

C++

```

8 #include <frc/Encoder.h>
9 #include <frc/Joystick.h>
10 #include <frc/PWMVictorSPX.h>
11 #include <frc/TimedRobot.h>
12 #include <frc/controller/ProfiledPIDController.h>
13 #include <frc/trajectory/TrapezoidProfile.h>
14 #include <units/units.h>

```

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```

15 #include <wpi/math>
16
17 class Robot : public frc::TimedRobot {
18 public:
19     static constexpr units::second_t kDt = 20_ms;
20
21     Robot() {
22         m_encoder.SetDistancePerPulse(1.0 / 360.0 * 2.0 * wpi::math::pi * 1.5);
23     }
24
25     void TeleopPeriodic() override {
26         if (m_joystick.GetRawButtonPressed(2)) {
27             m_controller.SetGoal(5_m);
28         } else if (m_joystick.GetRawButtonPressed(3)) {
29             m_controller.SetGoal(0_m);
30         }
31
32         // Run controller and update motor output
33         m_motor.Set(
34             m_controller.Calculate(units::meter_t(m_encoder.GetDistance())));
35     }
36
37 private:
38     frc::Joystick m_joystick{1};
39     frc::Encoder m_encoder{1, 2};
40     frc::PWMVictorSPX m_motor{1};
41
42     // Create a PID controller whose setpoint's change is subject to maximum
43     // velocity and acceleration constraints.
44     frc::TrapezoidProfile<units::meters>::Constraints m_constraints{1.75_mps,
45                                                                    0.75_mps_sq};
46     frc::ProfiledPIDController<units::meters> m_controller{1.3, 0.0, 0.7,
47                                                            m_constraints, kDt};
48 };
49
50 #ifndef RUNNING_FRC_TESTS
51 int main() { return frc::StartRobot<Robot>(); }
52 #endif

```

## 23.4 Trajectory Generation and Following with WPILib

This section describes WPILib support for generating parameterized spline trajectories and following those trajectories with typical FRC robot drives.

### 23.4.1 Trajectory Generation

The 2020 release of WPILib contains classes that help generating trajectories. A trajectory is a smooth curve, with velocities and accelerations at each point along the curve, connecting two endpoints on the field. Generation and following of trajectories is incredibly useful for performing autonomous tasks. Instead of a simple autonomous routine – which involves moving forward, stopping, turning 90 degrees to the right, then moving forward – using trajectories allows for motion along a smooth curve. This has the advantage of speeding up autonomous

routes, creating more time for other tasks; and when implemented well, makes autonomous navigation more accurate and precise.

This article goes over how to generate a trajectory. The next few articles in this series will go over how to actually follow the generated trajectory. There are a few things that your robot must have before you dive into the world of trajectories:

- A way to measure the position and velocity of each side of the robot. An encoder is the best way to do this; however, other options may include optical flow sensors, etc.
- A way to measure the angle or angular rate of the robot chassis. A gyroscope is the best way to do this. Although the angular rate can be calculated using encoder velocities, this method is NOT recommended because of wheel scrubbing.

If you are looking for a simpler way to perform autonomous navigation, see [the section on driving to a distance](#).

### Splines

A spline refers to a set of curves that interpolate between points. Think of it as connecting dots, except with curves. WPILib supports two types of splines: hermite clamped cubic and hermite quintic.

- Hermite clamped cubic: This is the recommended option for most users. Generation of trajectories using these splines involves specifying the (x, y) coordinates of all points, and the headings at the start and end waypoints. The headings at the interior waypoints are automatically determined to ensure continuous curvature (rate of change of the heading) throughout.
- Hermite quintic: This is a more advanced option which requires the user to specify (x, y) coordinates and headings for *all* waypoints. This should be used if you are unhappy with the trajectories that are being generated by the clamped cubic splines or if you want finer control of headings at the interior points.

Splines are used as a tool to generate trajectories; however, the spline itself does not have any information about velocities and accelerations. Therefore, it is not recommended that you use the spline classes directly. In order to generate a smooth path with velocities and accelerations, a *trajectory* must be generated.

### Creating the trajectory config

A configuration must be created in order to generate a trajectory. The config contains information about special constraints, the max velocity, the max acceleration in addition to the start velocity and end velocity. The config also contains information about whether the trajectory should be reversed (robot travels backward along the waypoints). The `TrajectoryConfig` class should be used to construct a config. The constructor for this class takes two arguments, the max velocity and max acceleration. The other fields (`startVelocity`, `endVelocity`, `reversed`, `constraints`) are defaulted to reasonable values (0, 0, false, {}) when the object is created. If you wish to modify the values of any of these fields, you can call the following methods:

- `setStartVelocity(double startVelocityMetersPerSecond)` (Java) / `SetStartVelocity(units::meters_per_second_t startVelocity)` (C++)
- `setEndVelocity(double endVelocityMetersPerSecond)` (Java) / `SetEndVelocity(units::meters_per_second_t endVelocity)` (C++)

- `setReversed(boolean reversed)` (Java) / `SetReversed(bool reversed)` (C++)
- `addConstraint(TrajectoryConstraint constraint)` (Java) / `AddConstraint(TrajectoryConstraint constraint)` (C++)

**Note:** The `reversed` property simply represents whether the robot is traveling backward. If you specify four waypoints, a, b, c, and d, the robot will still travel in the same order through the waypoints when the `reversed` flag is set to `true`. This also means that you must account for the direction of the robot when providing the waypoints. For example, if your robot is facing your alliance station wall and travels backwards to some field element, the starting waypoint should have a rotation of 180 degrees.

## Generating the trajectory

The method used to generate a trajectory is `generateTrajectory(...)`. There are four overloads for this method. Two that use clamped cubic splines and the two others that use quintic splines. For each type of spline, there are two ways to construct a trajectory. The easiest methods are the overloads that accept `Pose2d` objects.

For clamped cubic splines, this method accepts two `Pose2d` objects, one for the starting waypoint and one for the ending waypoint. The method takes in a vector of `Translation2d` objects which represent the interior waypoints. The headings at these interior waypoints are determined automatically to ensure continuous curvature. For quintic splines, the method simply takes in a list of `Pose2d` objects, with each `Pose2d` representing a point and heading on the field.

The more complex overload accepts “control vectors” for splines. This method is used when generating trajectories with Pathweaver, where you are able to control the magnitude of the tangent vector at each point. The `ControlVector` class consists of two double arrays. Each array represents one dimension (x or y), and its elements represent the derivatives at that point. For example, the value at element 0 of the x array represents the x coordinate (0th derivative), the value at element 1 represents the 1st derivative in the x dimension and so on.

When using clamped cubic splines, the length of the array must be 2 (0th and 1st derivatives), whereas when using quintic splines, the length of the array should be 3 (0th, 1st, and 2nd derivative). Unless you know exactly what you are doing, the first and simpler method is HIGHLY recommended for manually generating trajectories. (i.e. when not using Pathweaver JSON files).

Here is an example of generating a trajectory using clamped cubic splines for the 2018 game, FIRST Power Up:

Java

```
class ExampleTrajectory {
    public void generateTrajectory() {

        // 2018 cross scale auto waypoints.
        var sideStart = new Pose2d(Units.feetToMeters(1.54), Units.feetToMeters(23.23),
            Rotation2d.fromDegrees(-180));
        var crossScale = new Pose2d(Units.feetToMeters(23.7), Units.feetToMeters(6.8),
            Rotation2d.fromDegrees(-160));

        var interiorWaypoints = new ArrayList<Translation2d>();
        interiorWaypoints.add(new Translation2d(Units.feetToMeters(14.54), Units.
            ↪ feetToMeters(23.23)));
    }
}
```

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```

        interiorWaypoints.add(new Translation2d(Units.feetToMeters(21.04), Units.
↪ feetToMeters(18.23)));

        TrajectoryConfig config = new TrajectoryConfig(Units.feetToMeters(12), Units.
↪ feetToMeters(12));
        config.setReversed(true);

        var trajectory = TrajectoryGenerator.generateTrajectory(
            sideStart,
            interiorWaypoints,
            crossScale,
            config);
    }
}

```

C++

```

void GenerateTrajectory() {
    // 2018 cross scale auto waypoints
    const frc::Pose2d sideStart{1.54_ft, 23.23_ft, frc::Rotation2d(180_deg)};
    const frc::Pose2d crossScale{23.7_ft, 6.8_ft, frc::Rotation2d(-160_deg)};

    std::vector<frc::Translation2d> interiorWaypoints{
        frc::Translation2d{14.54_ft, 23.23_ft},
        frc::Translation2d{21.04_ft, 18.23_ft}};

    frc::TrajectoryConfig config{12_fps, 12_fps_sq};
    config.SetReversed(true);

    auto trajectory = frc::TrajectoryGenerator::GenerateTrajectory(
        sideStart, interiorWaypoints, crossScale, config);
}

```

**Note:** The Java code utilizes the `Units` utility, which was added to WPILib in 2020 for easy unit conversions.

**Note:** Even though this trajectory generation is orders of magnitude faster than Pathfinder, it is highly recommended to generate all trajectories on startup (`robotInit`) as the generation time is still not negligible. Generation time often ranges from 10 ms to 25 ms for each trajectory.

## Trajectory Constraints

You might have noticed that no special constraints were added when generating the trajectories in the examples above. User-defined constraints are another powerful feature of the WPILib trajectory generation suite. The `TrajectoryConstraint` interface allows users to create their own constraints on velocity and acceleration given the position, curvature, and original velocity at that point in the trajectory.

Java

```

@Override
public double getMaxVelocityMetersPerSecond(Pose2d poseMeters, double_
↪curvatureRadPerMeter,
                                double velocityMetersPerSecond) {
    // code here
}

@Override
public MinMax getMinMaxAccelerationMetersPerSecondSq(Pose2d poseMeters,
                                double curvatureRadPerMeter,
                                double velocityMetersPerSecond) {
    // code here
}

```

C++

```

units::meters_per_second_t MaxVelocity(
const Pose2d& pose, curvature_t curvature,
units::meters_per_second_t velocity) override {
    // code here
}

MinMax MinMaxAcceleration(const Pose2d& pose, curvature_t curvature,
                                units::meters_per_second_t speed) override {
    // code here
}

```

These are the two methods that you should override to create your custom constraint. The `MaxVelocity` method should return the attainable max velocity at that point in the trajectory, given the pose, curvature, and original unconstrained velocity. The `MinMaxAcceleration` method should return the min and max accelerations at that point in the trajectory, given the pose, curvature, and velocity.

User defined constraints are not necessary to generate trajectories. As from the example earlier, you can simply pass in an empty vector. However, there are two out-of-the-box constraints:

- `CentripetalAccelerationConstraint`: Limits the centripetal acceleration throughout the trajectory. This has the effect of slowing down around tight curves.
- `DifferentialDriveKinematicsConstraint`: Makes sure that both wheels (sides) of a differential drive robot stay under the specified max velocity around turns.

See the source code ([Java](#), [C++](#)) for these two constraints for examples on how to write your own custom trajectory constraints.

## 23.4.2 Manipulating Trajectories

Once a trajectory has been generated, you can retrieve information from it using certain methods. These methods will be useful when writing code to follow these trajectories.

### Getting the total duration of the trajectory

Because all trajectories have timestamps at each point, the amount of time it should take for a robot to traverse the entire trajectory is pre-determined. The `TotalTime()` (C++) /



`getTotalTimeSeconds()` (Java) method can be used to determine the time it takes to traverse the trajectory.

Java

```
// Get the total time of the trajectory in seconds  
double duration = trajectory.getTotalTimeSeconds();
```

C++

```
// Get the total time of the trajectory  
units::second_t duration = trajectory.TotalTime();
```

### Sampling the trajectory

The trajectory can be sampled at various timesteps to get the pose, velocity, and acceleration at that point. The `Sample(units::second_t time)` (C++) / `sample(double timeSeconds)` (Java) method can be used to sample the trajectory at any timestep. The parameter refers to the amount of time passed since 0 seconds (the starting point of the trajectory). This method returns a `Trajectory::Sample` with information about that sample point.

Java

```
// Sample the trajectory at 1.2 seconds. This represents where the robot  
// should be after 1.2 seconds of traversal.  
Trajectory.Sample point = trajectory.sample(1.2);
```

C++

```
// Sample the trajectory at 1.2 seconds. This represents where the robot  
// should be after 1.2 seconds of traversal.  
Trajectory::State point = trajectory.Sample(1.2_s);
```

The `Trajectory::Sample` struct has several pieces of information about the sample point:

- `t`: The time elapsed from the beginning of the trajectory up to the sample point.
- `velocity`: The velocity at the sample point.
- `acceleration`: The acceleration at the sample point.
- `pose`: The pose (x, y, heading) at the sample point.
- `curvature`: The curvature (rate of change of heading with respect to distance along the trajectory) at the sample point.

Note: The angular velocity at the sample point can be calculated by multiplying the velocity by the curvature.

### Getting all states of the trajectory (advanced)

A more advanced user can get a list of all states of the trajectory by calling the `States()` (C++) / `getStates()` (Java) method. Each state represents a point on the trajectory. *When the trajectory is created* using the `TrajectoryGenerator::GenerateTrajectory(...)` method, a list of trajectory points / states are created. When the user samples the trajectory at a particular timestep, a new sample point is interpolated between two existing points / states in the list.

### 23.4.3 Transforming Trajectories

Trajectories can be transformed from one coordinate system to another and moved within a coordinate system using the `relativeTo` and the `transformBy` methods. These methods are useful for moving trajectories within space, or redefining an already existing trajectory in another frame of reference.

---

**Note:** Neither of these methods changes the shape of the original trajectory.

---

#### The `relativeTo` Method

The `relativeTo` method is used to redefine an already existing trajectory in another frame of reference. This method takes one argument: a pose, (via a `Pose2d` object) that is defined with respect to the current coordinate system, that represents the origin of the new coordinate system.

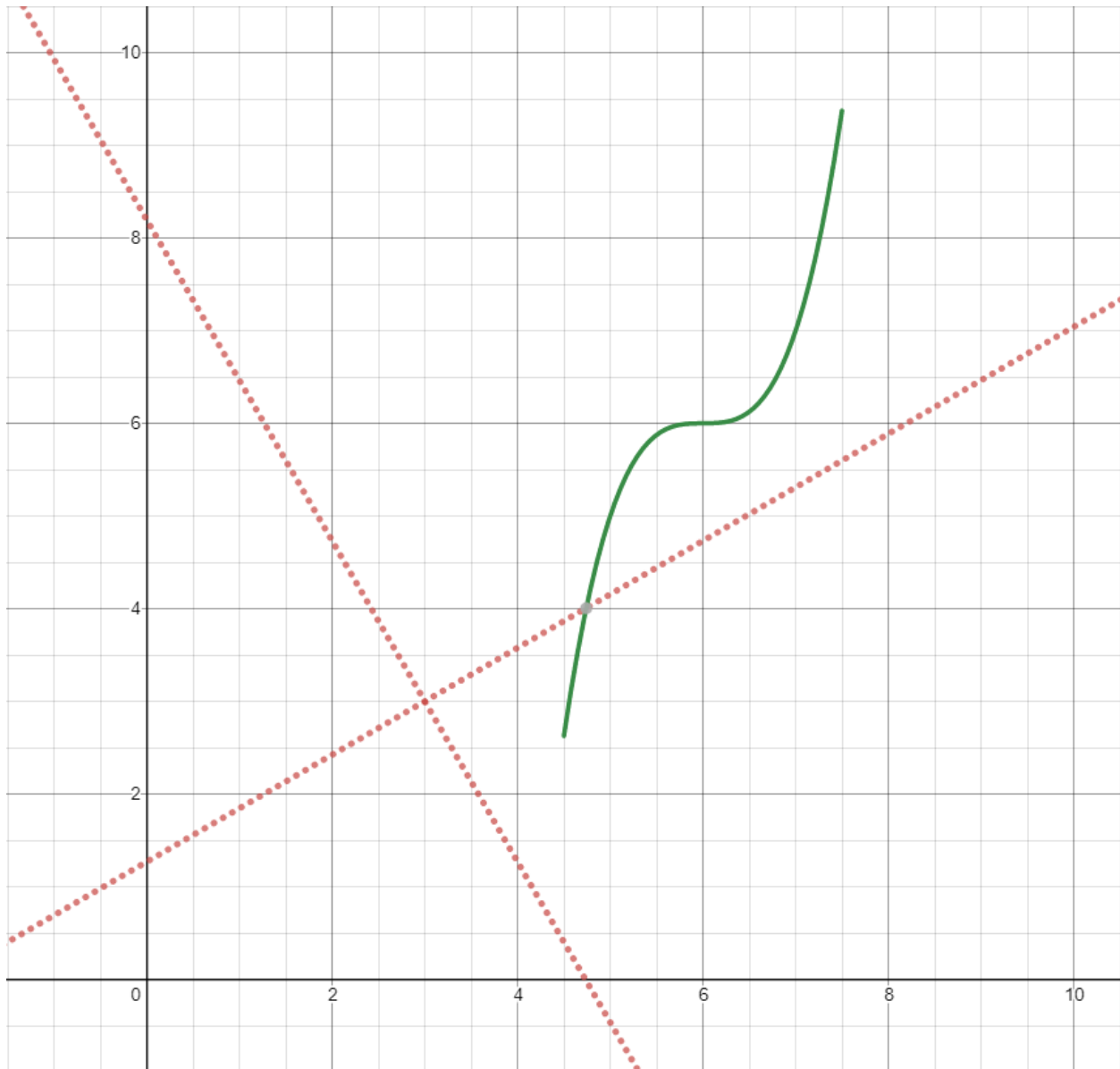
For example, a trajectory defined in coordinate system A can be redefined in coordinate system B, whose origin is at (2, 2, 30 degrees) in coordinate system A, using the `relativeTo` method.

Java

```
Pose2d bOrigin = new Pose2d(2, 2, Rotation2d.fromDegrees(30));
Trajectory bTrajectory = aTrajectory.relativeTo(bOrigin);
```

C++

```
frc::Pose2d bOrigin{2_m, 2_m, frc::Rotation2d(30_deg)};
frc::Trajectory bTrajectory = aTrajectory.RelativeTo(bOrigin);
```



In the diagram above, the original trajectory (`aTrajectory` in the code above) has been defined in coordinate system A, represented by the black axes. The red axes, located at (2, 2) and 30° with respect to the original coordinate system, represent coordinate system B. Calling `relativeTo` on `aTrajectory` will redefine all poses in the trajectory to be relative to coordinate system B (red axes).

### The `transformBy` Method

The `transformBy` method can be used to move (i.e. translate and rotate) a trajectory within a coordinate system. This method takes one argument: a transform (via a `Transform2d` object) that maps the current initial position of the trajectory to a desired initial position of the same trajectory.

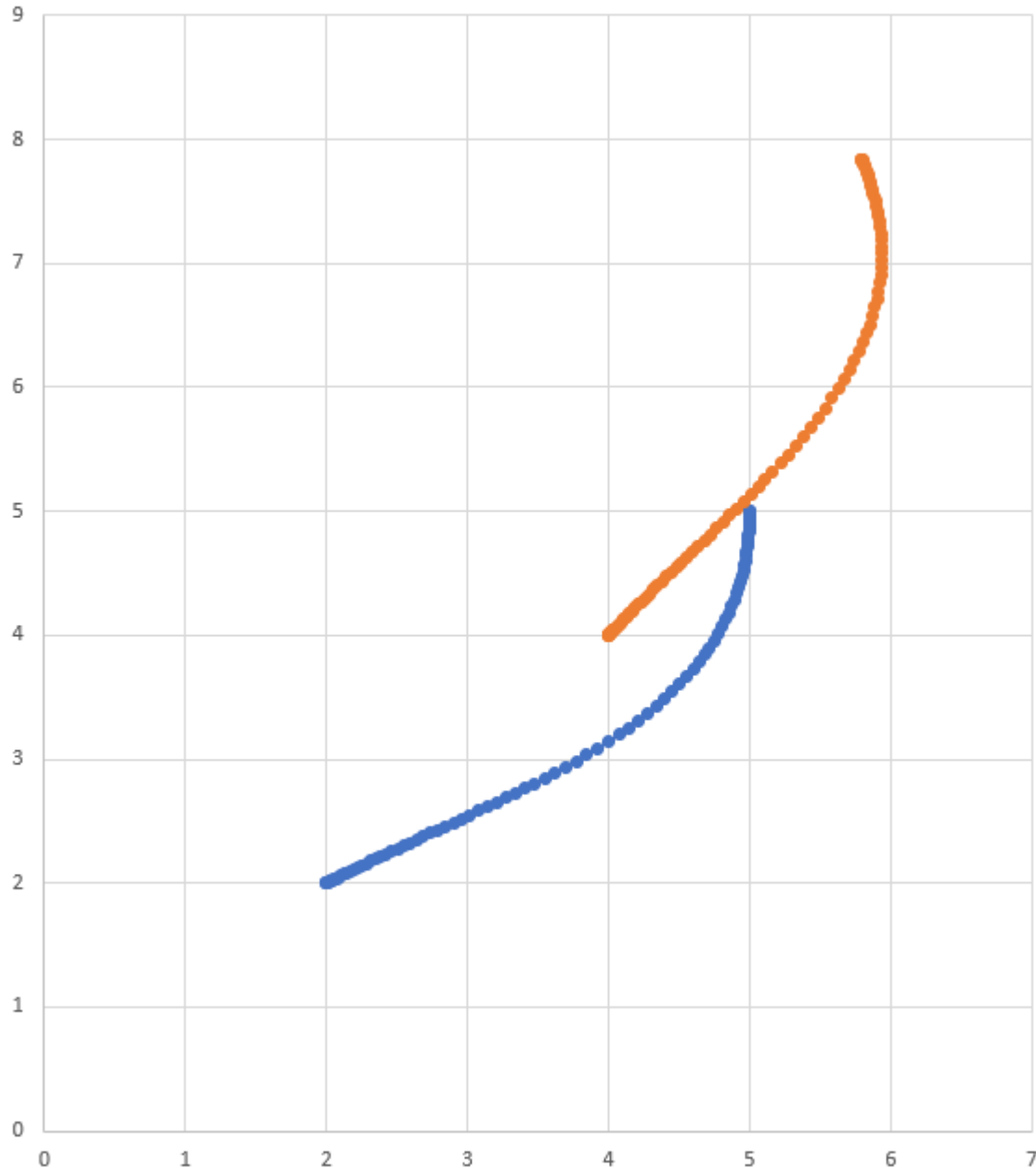
For example, one may want to transform a trajectory that begins at (2, 2, 30 degrees) to make it begin at (4, 4, 50 degrees) using the `transformBy` method.

Java

```
Transform2d transform = new Pose2d(4, 4, Rotation2d.fromDegrees(50)).minus(trajecory.
↳getInitialPose());
Trajectory newTrajectory = trajectory.transformBy(transform);
```

C++

```
frc::Transform2d transform = Pose2d(4_m, 4_m, Rotation2d(50_deg)) - trajectory.
↳InitialPose();
frc::Trajectory newTrajectory = trajectory.TransformBy(transform);
```



In the diagram above, the original trajectory, which starts at (2, 2) and at 30° is visible in blue. After applying the transform above, the resultant trajectory's starting location is changed to

(4, 4) at 50°. The resultant trajectory is visible in orange.

### 23.4.4 Ramsete Controller

The Ramsete Controller is a trajectory tracker that is built in to WPILib. This tracker can be used to accurately track trajectories with correction for minor disturbances.

#### Constructing the Ramsete Controller Object

The Ramsete controller should be initialized with two gains, namely  $b$  and  $zeta$ . Larger values of  $b$  make convergence more aggressive like a proportional term whereas larger values of  $zeta$  provide more damping in the response. These controller gains only dictate how the controller will output adjusted velocities. It does NOT affect the actual velocity tracking of the robot. This means that these controller gains are generally robot-agnostic.

---

**Note:** Gains of 2.0 and 0.7 for  $b$  and  $zeta$  have been tested repeatedly to produce desirable results when all units were in meters. As such, a zero-argument constructor for `RamseteController` exists with gains defaulted to these values.

---

#### Getting Adjusted Velocities

The Ramsete controller returns “adjusted velocities” so that the when the robot tracks these velocities, it accurately reaches the goal point. The controller should be updated periodically with the new goal. The goal comprises of a desired pose, desired linear velocity, and desired angular velocity. Furthermore, the current position of the robot should also be updated periodically. The controller uses these four arguments to return the adjusted linear and angular velocity. Users should command their robot to these linear and angular velocities to achieve optimal trajectory tracking.

---

**Note:** The “goal pose” represents the position that the robot should be at at a particular timestep when tracking the trajectory. It does NOT represent the final endpoint of the trajectory.

---

The controller can be updated using the `Calculate (C++) / calculate (Java)` method. There are two overloads for this method. Both of these overloads accept the current robot position as the first parameter. For the other parameters, one of these overloads takes in the goal as three separate parameters (pose, linear velocity, and angular velocity) whereas the other overload accepts a `Trajectory.State` object, which contains information about the goal pose. For its ease, users should use the latter method when tracking trajectories.

Java

```
Trajectory.State goal = trajectory.sample(3.4); // sample the trajectory at 3.4
↳seconds from the beginning
ChassisSpeeds adjustedSpeeds = controller.calculate(currentRobotPose, goal);
```

C++

```
const Trajectory::State goal = trajectory.Sample(3.4_s); // sample the trajectory at
↳3.4 seconds from the beginning
ChassisSpeeds adjustedSpeeds = controller.Calculate(currentRobotPose, goal);
```

These calculations should be performed at every loop iteration, with an updated robot position and goal.

## Using the Adjusted Velocities

The adjusted velocities are of type `ChassisSpeeds`, which contains a `vx` (linear velocity in the forward direction), a `vy` (linear velocity in the sideways direction), and an `omega` (angular velocity around the center of the robot frame). Because the Ramsete controller is a controller for non-holonomic robots (robots which cannot move sideways), the adjusted speeds object has a `vy` of zero.

The returned adjusted speeds can be converted to usable speeds using the kinematics classes for your drivetrain type. For example, the adjusted velocities can be converted to left and right velocities for a differential drive using a `DifferentialDriveKinematics` object.

Java

```
ChassisSpeeds adjustedSpeeds = controller.calculate(currentRobotPose, goal);
DifferentialDriveWheelSpeeds wheelSpeeds = kinematics.toWheelSpeeds(adjustedSpeeds);
double left = wheelSpeeds.leftMetersPerSecond;
double right = wheelSpeeds.rightMetersPerSecond;
```

C++

```
ChassisSpeeds adjustedSpeeds = controller.Calculate(currentRobotPose, goal);
DifferentialDriveWheelSpeeds wheelSpeeds = kinematics.ToWheelSpeeds(adjustedSpeeds);
units::meter_per_second_t left = wheelSpeeds.left;
units::meter_per_second_t right = wheelSpeeds.right;
```

Because these new left and right velocities are still speeds and not voltages, two PID Controllers, one for each side may be used to track these velocities. Either the WPILib `PIDController` (C++, Java) can be used, or the Velocity PID feature on smart motor controllers such as the TalonSRX and the SparkMAX can be used.

## Ramsete in the Command-Based Framework

For the sake of ease for users, a `RamseteCommand` class is built in to WPILib. For a full tutorial on implementing a path-following autonomous using `RamseteCommand`, see [Trajectory Tutorial](#).

## 23.4.5 Troubleshooting

### Troubleshooting Complete Failures

There are a number of things that can cause your robot to do completely the wrong thing. The below checklist covers some common mistakes.

- My robot doesn't move.

- Are you actually outputting to your motors?
- Is a `MalformedSplineException` getting printed to the driver station? If yes, go to the `MalformedSplineException` section below.
- Is your trajectory very short or in the wrong units?
- My robot swings around to drive the trajectory facing the other direction.
  - Are the start and end headings of your trajectory wrong?
  - Is your robot's gyro getting reset to the wrong heading?
  - *Do you have the reverse flag set incorrectly?*
  - Are your gyro angles clockwise positive? If so, you should negate them.
- My robot just drives in a straight line even though it should turn.
  - Is your gyro set up correctly and returning good data?
  - Are you passing your gyro heading to your odometry object with the correct units?
  - Is your track width correct? Is it in the correct units?
- I get a `MalformedSplineException` printout on the driver station and the robot doesn't move.
  - *Do you have the reverse flag set incorrectly?*
  - Do you have two waypoints very close together with approximately opposite headings?
  - Do you have two waypoints with the same (or nearly the same) coordinates?
- My robot drives way too far.
  - Are your encoder unit conversions set up correctly?
  - Are your encoders connected?
- My robot mostly does the right thing, but it's a little inaccurate.
  - Go to the next section.

### Troubleshooting Poor Performance

---

**Note:** This section is mostly concerned with troubleshooting poor trajectory tracking performance like a meter of error, not catastrophic failures like compilation errors, robots turning around and going in the wrong direction, or `MalformedSplineExceptions`.

---

---

**Note:** This section is designed for differential drive robots, but most of the ideas can be adapted to swerve drive or mecanum.

---

Poor trajectory tracking performance can be difficult to troubleshoot. Although the trajectory generator and follower are intended to be easy-to-use and performant out of the box, there are situations where your robot doesn't quite end up where it should. The trajectory generator and followers have many knobs to tune and many moving parts, so it can be difficult to know where to start, especially because it is difficult to locate the source of trajectory problems from the robot's general behavior.

Because it can be so hard to locate the layer of the trajectory generator and followers that is misbehaving, a systematic, layer-by-layer approach is recommended for general poor tracking performance (e.g. the robot is off by few feet or more than twenty degrees). The below steps are listed in the order that you should do them in; it is important to follow this order so that you can isolate the effects of different steps from each other.

**Note:** The below examples put diagnostic values onto Network Tables. The easiest way to graph these values is to *use Shuffleboard's graphing capabilities*.

## Verify Odometry

If your odometry is bad, then your Ramsete controller may misbehave, because it modifies your robot's target velocities based on where your odometry thinks the robot is.

1. Set up your code to record your robot's position after each odometry update:

Java

```
NetworkTableEntry m_xEntry = NetworkTableInstance.getDefault().getTable(
    ↪ "troubleshooting").getEntry("X");
NetworkTableEntry m_yEntry = NetworkTableInstance.getDefault().getTable(
    ↪ "troubleshooting").getEntry("Y");

@Override
public void periodic() {
    // Update the odometry in the periodic block
    m_odometry.update(Rotation2d.fromDegrees(getHeading()), m_leftEncoder.
    ↪ getDistance(),
        m_rightEncoder.getDistance());

    var translation = m_odometry.getPoseMeters().getTranslation();
    m_xEntry.setNumber(translation.getX());
    m_yEntry.setNumber(translation.getY());
}
```

C++

```
NetworkTableEntry m_xEntry = nt::NetworkTableInstance::GetDefault().GetTable(
    ↪ "troubleshooting")->GetEntry("X");
NetworkTableEntry m_yEntry = nt::NetworkTableInstance::GetDefault().GetTable(
    ↪ "troubleshooting")->GetEntry("Y");

void DriveSubsystem::Periodic() {
    // Implementation of subsystem periodic method goes here.
    m_odometry.Update(frc::Rotation2d(units::degree_t(GetHeading())),
        units::meter_t(m_leftEncoder.GetDistance()),
        units::meter_t(m_rightEncoder.GetDistance()));

    auto translation = m_odometry.GetPose().Translation();
    m_xEntry.SetDouble(translation.X().to<double>());
    m_yEntry.SetDouble(translation.Y().to<double>());
}
```

2. Lay out a tape measure parallel to your robot and push your robot out about one meter along the tape measure. Lay out a tape measure along the Y axis and start over, pushing



your robot one meter along the X axis and one meter along the Y axis in a rough arc.

3. Compare X and Y reported by the robot to actual X and Y. If X is off by more than 5 centimeters in the first test then you should check that you measured your wheel diameter correctly, and that your wheels are not worn down. If the second test is off by more than 5 centimeters in either X or Y then your track width (distance from the center of the left wheel to the center of the right wheel) may be incorrect; if you're sure that you measured the track width correctly with a tape measure then your robot's wheels may be slipping in a way that is not accounted for by track width—if this is the case then you should [run the track width characterization](#) and use that track width instead of the one from your tape measure.

## Verify Feedforward

If your feedforwards are bad then the P controllers for each side of the robot will not track as well, and your `DifferentialDriveVoltageConstraint` will not limit your robot's acceleration accurately. We mostly want to turn off the wheel P controllers so that we can isolate and test the feedforwards.

1. First, we must set disable the P controller for each wheel. Set the P gain to 0 for every controller. In the `RamseteCommand` example, you would set `kPDriveVel` to 0:

Java

```
136     new PIDController(DriveConstants.kPDriveVel, 0, 0),
137     new PIDController(DriveConstants.kPDriveVel, 0, 0),
```

C++

```
80     frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
81     frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
```

2. (Java only) Next, we want to disable the Ramsete controller to make it easier to isolate our problematic behavior. This is a bit more involved, because we can't just set the gains (b and zeta) to 0. Pass the following into your `RamseteCommand`:

Java

```
// Paste this variable in
RamseteController disabledRamsete = new RamseteController() {
    @Override
    public ChassisSpeeds calculate(Pose2d currentPose, Pose2d poseRef, double_
↳ linearVelocityRefMeters,
        double angularVelocityRefRadiansPerSecond) {
        return new ChassisSpeeds(linearVelocityRefMeters, 0.0,
↳ angularVelocityRefRadiansPerSecond);
    }
};

// Be sure to pass your new disabledRamsete variable
RamseteCommand ramseteCommand = new RamseteCommand(
    exampleTrajectory,
    m_robotDrive::getPose,
    disabledRamsete,
    ...
);
```

- Finally, we need to log desired wheel velocity and actual wheel velocity (you should put actual and desired velocities on the same graph if you're using Shuffleboard, or if your graphing software has that capability):

Java

```
var table = NetworkTableInstance.getDefault().getTable("troubleshooting");
var leftReference = table.getEntry("left_reference");
var leftMeasurement = table.getEntry("left_measurement");
var rightReference = table.getEntry("right_reference");
var rightMeasurement = table.getEntry("right_measurement");

var leftController = new PIDController(kPDriveVel, 0, 0);
var rightController = new PIDController(kPDriveVel, 0, 0);
RamseteCommand ramseteCommand = new RamseteCommand(
    exampleTrajectory,
    m_robotDrive::getPose,
    disabledRamsete, // Pass in disabledRamsete here
    new SimpleMotorFeedforward(ksVolts, kvVoltSecondsPerMeter,
↪ kaVoltSecondsSquaredPerMeter),
    kDriveKinematics,
    m_robotDrive::getWheelSpeeds,
    leftController,
    rightController,
    // RamseteCommand passes volts to the callback
    (leftVolts, rightVolts) -> {
        m_robotDrive.tankDriveVolts(leftVolts, rightVolts);

        leftMeasurement.setNumber(m_robotDrive.getWheelSpeeds().leftMetersPerSecond);
        leftReference.setNumber(leftController.getSetpoint());

        rightMeasurement.setNumber(m_robotDrive.getWheelSpeeds().
↪ rightMetersPerSecond);
        rightReference.setNumber(rightController.getSetpoint());
    },
    m_robotDrive
);
```

C++

```
auto table =
    nt::NetworkTableInstance::GetDefault().GetTable("troubleshooting");
auto leftRef = table->GetEntry("left_reference");
auto leftMeas = table->GetEntry("left_measurement");
auto rightRef = table->GetEntry("right_reference");
auto rightMeas = table->GetEntry("right_measurement");

frc2::PIDController leftController(DriveConstants::kPDriveVel, 0, 0);
frc2::PIDController rightController(DriveConstants::kPDriveVel, 0, 0);
frc2::RamseteCommand ramseteCommand(
    exampleTrajectory, [this]() { return m_drive.GetPose(); },
    frc::RamseteController(AutoConstants::kRamseteB,
        AutoConstants::kRamseteZeta),
    frc::SimpleMotorFeedforward<units::meters>(
        DriveConstants::ks, DriveConstants::kv, DriveConstants::ka),
    DriveConstants::kDriveKinematics,
    [this] { return m_drive.GetWheelSpeeds(); }, leftController,
    rightController,
```

(continues on next page)

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```
[=](auto left, auto right) {  
    auto leftReference = leftRef;  
    auto leftMeasurement = leftMeas;  
    auto rightReference = rightRef;  
    auto rightMeasurement = rightMeas;  
  
    m_drive.TankDriveVolts(left, right);  
  
    leftMeasurement.SetDouble(m_drive.GetWheelSpeeds().left.to<double>());  
    leftReference.SetDouble(leftController.GetSetpoint());  
  
    rightMeasurement.SetDouble(m_drive.GetWheelSpeeds().right.to<double>());  
    rightReference.SetDouble(rightController.GetSetpoint());  
},  
{&m_drive});
```

4. Run the robot on a variety of trajectories (curved and straight line), and check to see if the actual velocity tracks the desired velocity by looking at graphs from Network Tables.
5. If the desired and actual are off by *a lot* then you should check if the wheel diameter and encoderEPR you used for characterization were correct. If you've verified that your units and conversions are correct, then you should try recharacterizing on the same floor that you're testing on to see if you can get better data.

## Verify P Gain

If you completed the previous step and the problem went away then your problem can probably be found in one of the next steps. In this step we're going to verify that your wheel P controllers are well-tuned. If you're using Java then we want to turn off Ramsete so that we can just view our PF controllers on their own.

1. You must re-use all the code from the previous step that logs actual vs. desired velocity (and the code that disables Ramsete, if you're using Java), except that **the P gain must be set back to its previous nonzero value.**
2. Run the robot again on a variety of trajectories, and check that your actual vs. desired graphs look good.
3. If the graphs do not look good (i.e. the actual velocity is very different from the desired) then you should try tuning your P gain and rerunning your test trajectories.

## Check Constraints

---

**Note:** Make sure that your P gain is nonzero for this step and that you still have the logging code added in the previous steps. If you're using Java then you should remove the code to disable Ramsete.

---

If your accuracy issue persisted through all of the previous steps then you might have an issue with your constraints. Below are a list of symptoms that the different available constraints will exhibit when poorly tuned.

Test one constraint at a time! Remove the other constraints, tune your one remaining constraint, and repeat that process for each constraint you want to use. The below checklist assumes that you only use one constraint at a time.

- **DifferentialDriveVoltageConstraint:**
  - If your robot accelerates very slowly then it's possible that the max voltage for this constraint is too low.
  - If your robot doesn't reach the end of the path then your characterization data may be problematic.
- **DifferentialDriveKinematicsConstraint:**
  - If your robot ends up at the wrong heading then it's possible that the max drivetrain side speed is too low, or that it's too high. The only way to tell is to tune the max speed and to see what happens.
- **CentripetalAccelerationConstraint:**
  - If your robot ends up at the wrong heading then this could be the culprit. If your robot doesn't seem to turn enough then you should increase the max centripetal acceleration, but if it seems to go around tight turns too quickly then you should decrease the maximum centripetal acceleration.

### **Check Trajectory Waypoints**

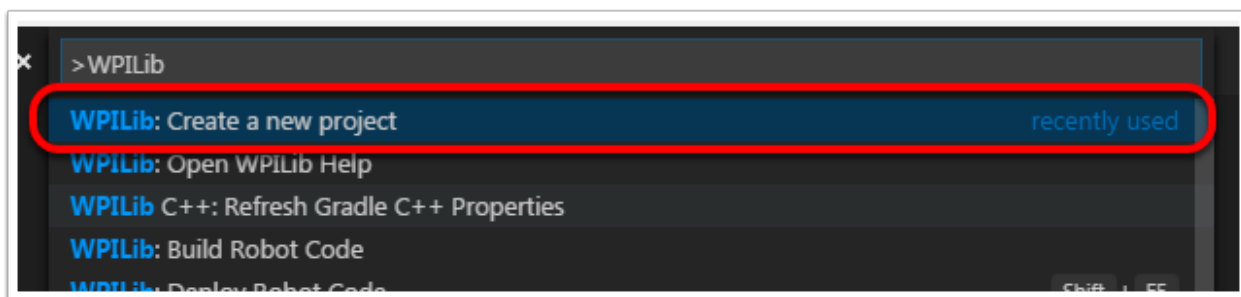
It is possible that your trajectory itself is not very driveable. Try moving waypoints (and headings at the waypoints, if applicable) to reduce sharp turns.



## WPILib Example Projects

**Warning:** While every attempt is made to keep WPILib examples functional, they are *not* intended to be used “as-is.” At the very least, robot-specific constants will need to be changed for the code to work on a user robot. Many empirical constants have their values “faked” for demonstration purposes. Users are strongly encouraged to write their own code (from scratch or from an existing template) rather than copy example code.

WPILib example projects demonstrate a large number of library features and use patterns. Projects range from simple demonstrations of a single functionality to complete, competition-capable robot programs. All of these examples are available in VS Code by entering Control+Shift+P, then selecting *WPILib: Create a new project* and choosing example.



### 24.1 Basic Examples

These examples demonstrate basic/minimal robot functionality. They are useful for beginning teams who are gaining initial familiarity with robot programming, but are highly limited in functionality.

- **ArcadeDrive** (Java, C++): Demonstrates a simple differential drive implementation using “arcade”-style controls through the `DifferentialDrive` class.
- **ArcadeDriveXboxController** (Java, C++): Demonstrates the same functionality seen in the previous example, except using an `XboxController` instead of an ordinary joystick.

- **GettingStarted** (Java, C++): Demonstrates a simple autonomous routine that drives forwards for two seconds at half speed.
- **MecanumDrive** (Java, C++): Demonstrates a simple mecanum drive implementation using the MecanumDrive class.
- **MotorControl** (Java, C++): Demonstrates how to control the output of a motor with a joystick.
- **MotorControlEncoder** (Java, C++): Identical to the above example, except with the addition of an encoder to read the motor position.
- **QuickVision** (Java, C++): Demonstrates how to stream video from a USB camera to the dashboard.
- **Relay** (Java, C++): Demonstrates the use of the Relay class to control a relay output with a set of joystick buttons.
- **Solenoid** (Java, C++): Demonstrates the use of the Solenoid and DoubleSolenoid classes to control solenoid outputs with a set of joystick buttons.
- **TankDrive** (Java): Demonstrates a simple differential drive implementation using “tank”-style controls through the DifferentialDrive class.
- **TankDriveXboxController** (Java, C++): Demonstrates the same functionality seen in the previous example, except using an XboxController instead of an ordinary joystick.

## 24.2 Control Examples

These examples demonstrate WPILib implementations of common robot controls. Sensors may be present, but are not the emphasized concept of these examples.

- **DifferentialDriveBot** (Java, C++): Demonstrates an advanced differential drive implementation, including encoder-and-gyro odometry through the DifferentialDriveOdometry class, and composition with PID velocity control through the DifferentialDriveKinematics and PIDController classes.
- **ElevatorProfiledPID** (Java, C++): Demonstrates the use of the ProfiledPIDController class to control the position of an elevator mechanism.
- **ElevatorTrapezoidProfile** (Java, C++): Demonstrates the use of the TrapezoidProfile class in conjunction with a “smart motor controller” to control the position of an elevator mechanism.
- **GyroMecanum** (Java, C++): Demonstrates field-oriented control of a mecanum robot through the MecanumDrive class in conjunction with a gyro.
- **MecanumBot** (Java, C++): Demonstrates an advanced mecanum drive implementation, including encoder-and-gyro odometry through the MecanumDriveOdometry class, and composition with PID velocity control through the MecanumDriveKinematics and PIDController classes.
- **PotentiometerPID** (Java, C++): Demonstrates the use of the PIDController class and a potentiometer to control the position of an elevator mechanism.
- **SwerveBot** (Java, C++): Demonstrates an advanced swerve drive implementation, including encoder-and-gyro odometry through the SwerveDriveOdometry class, and composition with PID position and velocity control through the SwerveDriveKinematics and PIDController classes.

- **UltrasonicPID** (Java, C++): Demonstrates the use of the `PIDController` class in conjunction with an ultrasonic sensor to drive to a set distance from an object.

## 24.3 Sensor Examples

These examples demonstrate sensor reading and data processing using WPILib. Mechanisms control may be present, but is not the emphasized concept of these examples.

- **AxisCameraSample** (Java, C++): Demonstrates the use of OpenCV and an Axis Netcam to overlay a rectangle on a captured video feed and stream it to the dashboard.
- **CANPDP** (Java, C++): Demonstrates obtaining sensor information from the PDP over CAN using the `PowerDistributionPanel` class.
- **DutyCycleEncoder** (Java, C++): Demonstrates the use of the `DutyCycleEncoder` class to read values from a PWM-type absolute encoder.
- **DutyCycleInput** (Java, C++): Demonstrates the use of the `DutyCycleInput` class to read the frequency and fractional duty cycle of a PWM input.
- **Encoder** (Java, C++): Demonstrates the use of the `Encoder` class to read values from a quadrature encoder.
- **Gyro** (Java, C++): Demonstrates the use of the `AnalogGyro` class to measure robot heading and stabilize driving.
- **IntermediateVision** (Java, C++): Demonstrates the use of OpenCV and a USB camera to overlay a rectangle on a captured video feed and stream it to the dashboard.
- **Ultrasonic** (Java, C++): Demonstrates the use of the `Ultrasonic` class to read data from an ultrasonic sensor in conjunction with the `MedianFilter` class to reduce signal noise.

## 24.4 Command-Based Examples

These examples demonstrate the use of the *Command-Based framework*.

- **ArmBot** (Java, C++): Demonstrates the use of a `ProfiledPIDSubsystem` to control a robot arm.
- **ArmBotOffboard** (Java, C++): Demonstrates the use of a `TrapezoidProfileSubsystem` in conjunction with a “smart motor controller” to control a robot arm.
- **DriveDistanceOffboard** (Java, C++): Demonstrates the use of a `TrapezoidProfileCommand` in conjunction with a “smart motor controller” to drive forward by a set distance with a trapezoidal motion profile.
- **FrisbeeBot** (Java, C++): A complete set of robot code for a simple frisbee-shooting robot typical of the 2013 FRC game *Ultimate Ascent*. Demonstrates simple PID control through the `PIDSubsystem` class.
- **GearsBot** (Java, C++): A complete set of robot code for the WPI demonstration robot, GearsBot.
- **GyroDriveCommands** (Java, C++): Demonstrates the use of `PIDCommand` and `ProfiledPIDCommand` in conjunction with a gyro to turn a robot to face a specified heading and to stabilize heading while driving.



- **HatchbotInlined** (Java, C++): A complete set of robot code for a simple hatch-delivery bot typical of the 2017 FRC game *Steamworks*. Commands are written in an “inline” style, in which explicit subclassing of `Command` is avoided.
- **HatchbotTraditional** (Java, C++): A complete set of robot code for a simple hatch-delivery bot typical of the 2017 FRC game *Steamworks*. Commands are written in a “traditional” style, in which subclasses of `Command` are written for each robot action.
- **MecanumControllerCommand** (Java, C++): Demonstrates trajectory generation and following with a mecanum drive using the `TrajectoryGenerator` and `MecanumControllerCommand` classes.
- **RamseteCommand** (Java, C++): Demonstrates trajectory generation and following with a differential drive using the `TrajectoryGenerator` and `RamseteCommand` classes. A matching step-by-step tutorial can be found [here](#).
- **SchedulerEventLogging** (Java, C++): Demonstrates the use of scheduler event actions to log dashboard event markers whenever a command starts, ends, or is interrupted.
- **SelectCommand** (Java, C++): Demonstrates the use of the `SelectCommand` class to run one of a selection of commands depending on a runtime-evaluated condition.
- **SwerveControllerCommand** (Java, C++): Demonstrates trajectory generation and following with a swerve drive using the `TrajectoryGenerator` and `SwerveControllerCommand` classes.

## 24.5 Miscellaneous Examples

These examples demonstrate miscellaneous WPILib functionality that does not fit into any of the above categories.

- **AddressableLED** (Java, C++): Demonstrates the use of the `AddressableLED` class to control RGB LEDs for robot decoration and/or driver feedback.
- **DMA** (C++): Demonstrates the use of DMA (Direct Memory Access) to read from sensors without using the RoboRIO’s CPU (C++ only).
- **HIDRumble** (Java, C++): Demonstrates the use of the “rumble” functionality for tactile feedback on supported HIDs (such as Xbox Controllers).
- **PacGoat** (Java, C++): A full command-based robot project from FRC Team 190’s 2014 robot. Uses the legacy version of the command framework; categorized as miscellaneous to avoid confusion.
- **Shuffleboard** (Java, C++): Demonstrates configuring tab/widget layouts on the “Shuffleboard” dashboard from robot code through the `Shuffleboard` class’s fluent builder API.

## Trajectory Tutorial

This is full tutorial for implementing trajectory generation and following on a differential-drive robot. The full code used in this tutorial can be found in the RamseteCommand example project ([Java](#), [C++](#)).

### 25.1 Trajectory Tutorial Overview

---

**Note:** Before following this tutorial, it is helpful (but not strictly necessary) to have a baseline familiarity with WPILib's *PID control*, *feedforward*, and *trajectory* features.

---

---

**Note:** The robot code in this tutorial uses the *command-based* framework. The command-based framework is strongly recommended for beginning and intermediate teams.

---

The goal of this tutorial is to provide “end-to-end” instruction on implementing a trajectory-following autonomous routine for a differential-drive robot. By following this tutorial, readers will learn how to:

1. Accurately characterize their robot's drivetrain to obtain accurate feedforward calculations and approximate feedback gains.
2. Configure a drive subsystem track the robot's pose using WPILib's odometry library.
3. Generate a simple trajectory through a set of waypoints using WPILib's TrajectoryGenerator class.
4. Follow the generated trajectory in an autonomous routine using WPILib's RamseteCommand class with the calculated feedforward/feedback gains and pose.

This tutorial is intended to be approachable for teams without a great deal of programming expertise. While the WPILib library offers significant flexibility in the manner in which its trajectory-following features are implemented, closely following the implementation outlined in this tutorial should provide teams with a relatively-simple, clean, and repeatable solution for autonomous movement.

The full robot code for this tutorial can be found in the [RamseteCommand Example Project](#) (Java, C++).

### 25.1.1 Why Trajectory Following?

FRC games often feature autonomous tasks that require a robot to effectively and accurately move from a known starting location to a known scoring location. Historically, the most common solution for this sort of task in FRC has been a “drive-turn-drive” approach - that is, drive forward by a known distance, turn by a known angle, and drive forward by another known distance.

While the “drive-turn-drive” approach is certainly functional, in recent years teams have begun tracking smooth trajectories which require the robot to drive and turn at the same time. While this is a fundamentally more-complicated technical task, it offers significant benefits: in particular, since the robot no longer has to stop to change directions, the paths can be driven much faster, allowing a robot to score more game pieces during the autonomous period.

Beginning in 2020, WPILib now supplies teams with working, advanced code solutions for trajectory generation and tracking, significantly lowering the “barrier-to-entry” for this kind of advanced and effective autonomous motion.

### 25.1.2 Required Equipment

To follow this tutorial, you will need ready access to the following materials:

1. A differential-drive robot (such as the [AndyMark AM14U4](#)), equipped with:
  - Quadrature encoders for measuring the wheel rotation of each side of the drive.
  - A gyroscope for measuring robot heading.
2. A driver-station computer configured with:
  - *FRC Driver Station*.
  - *WPILib*.
  - *The FRC-Characterization Toolsuite*.

## 25.2 Step 1: Characterizing Your Robot Drive

---

**Note:** For detailed instructions on using the FRC-Characterization tool, see its [dedicated documentation](#).

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**Note:** The drive characterization process requires ample space for the robot to drive. Be sure to have *at least* a 10' stretch (ideally closer to 20') in which the robot can drive during the characterization routine.

---

---

**Note:** The characterization data for this tutorial has been generously provided by Team 5190, who generated it as part of a demonstration of this functionality at the 2019 North Carolina State University P2P Workshop.

---

Before accurately following a path with a robot, it is important to have an accurate model for how the robot moves in response to its control inputs. Determining such a model is a process called “system identification.” WPILib’s FRC-Characterization is a tool for drive system identification.

### 25.2.1 Gathering the Data

We begin by gathering our drive characterization data.

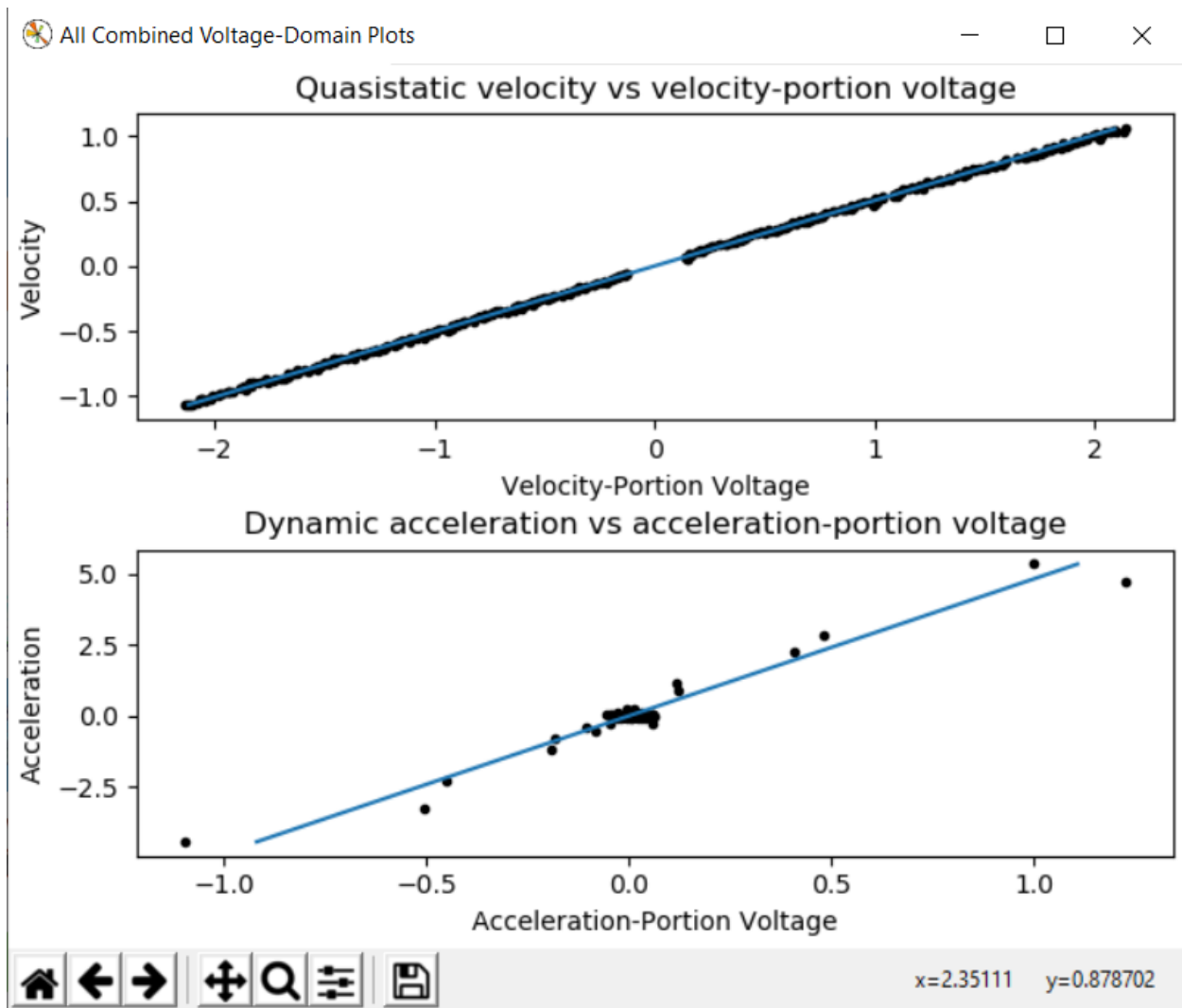
1. *Generate a robot project.*
  - Our example project uses the “simple” project type. Other project types (e.g. Talon and NEO) can be used without much difference; however, be *sure* to specify the required robot parameters correctly, regardless of project type!
  - WPILib’s trajectory library assumes units of meters are used universally for distance - accordingly, be certain that your robot’s wheel diameter is specified in meters!
2. *Deploy the robot project.*
3. *Run the Characterization Routine.*

### 25.2.2 Analyzing the Data

Once the characterization routine has been run and the data file has been saved, it is time to *open it in the analysis pane*.

#### Checking Diagnostics

Per the *FRC-Characterization guide*, we first view the diagnostics to ensure that our data look reasonable:



As our data look reasonably linear and our threshold seems to be set correctly, we may move on to the next step.

### Record Feedforward Gains

**Note:** Feedforward gains do *not*, in general, transfer across robots. Do *not* use the gains from this tutorial for your own robot.

We now record the feedforward gains calculated by the tool:

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Meters Subset: All Combined

Wheel Diameter (units): .15

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: 8	kS: 0.814	Gain Settings Preset: WPILib (2020-)
Time-Domain Diagnostics	Motion Threshold (units/s): 0.05	kV: 3.06	Controller Period (s): 0.02
Voltage-Domain Diagnostics		kA: 0.677	Max Controller Output: 12
3D Diagnostics		r-squared: 0.998	Time-Normalized Controller: <input checked="" type="checkbox"/>
	Track Width: 0.56341078		Loop Type: Position
		Controller Type: Onboard	kV: 3.06
		Post-Encoder Gearing: 1	kA: 0.677
		Encoder EPR: 4096	Calculate Optimal Controller Gains
		Has Slave: <input type="checkbox"/>	kP: 43.6
		Slave Update Period (s): 0.01	kD: 20.2

Since our wheel diameter was specified in meters, our feedforward gains are in the following units:

- kS: Volts
- kV: Volts \* Seconds / Meters
- kA: Volts \* Seconds<sup>2</sup> / Meters

If you have specified your units correctly, your feedforward gains will likely be within an order of magnitude of the ones reported here (a possible exception exists for kA, which may be vanishingly small if your robot is light). If they are not, it is possible you specified one of your drive parameters incorrectly when generating your robot project. A good test for this is to calculate the “theoretical” value of kV, which is 12 volts divided by the theoretical free speed of your drivetrain (which is, in turn, the free speed of the motor times the wheel circumference divided by the gear reduction). This value should agree very closely with the kV measured by the tool - if it does not, you have likely made an error somewhere.

## Calculate Feedback Gains

**Note:** Feedback gains do *not*, in general, transfer across robots. Do *not* use the gains from this tutorial for your own robot.

We now *calculate the feedback gains* for the PID control that we will use to follow the path. Trajectory following with WPILib’s RAMSETE controller uses velocity closed-loop control, so we first select Velocity mode in the characterization tool:

FRC Drive Characterization Tool

Select Data File: C:/development/projects/characterization-ozzy/characterization-data20200113-1802.json Units: Meters Subset: All Combined

Wheel Diameter (units): .15

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: 8	kS: 0.814	Gain Settings Preset: WPILib (2020-)
Time-Domain Diagnostics	Motion Threshold (units/s): 0.05	kV: 3.06	Controller Period (s): 0.02
Voltage-Domain Diagnostics		kA: 0.677	Max Controller Output: 12
3D Diagnostics		r-squared: 0.998	Time-Normalized Controller: <input checked="" type="checkbox"/>
	Track Width: 0.56341078		Loop Type: Velocity
		Controller Type: Onboard	kV: 3.06
		Post-Encoder Gearing: 1	kA: 0.677
		Encoder EPR: 4096	Calculate Optimal Controller Gains
		Has Slave: <input type="checkbox"/>	kP: 19.3
		Slave Update Period (s): 0.01	kD: 0.0

Since we will be using the WPILib PIDController for our velocity loop, we furthermore select the WPILib (2020-) option from the drop-down “presets” menu. This is *very* important, as the feedback gains will not be in the correct units if we do not select the correct preset:

The screenshot shows the FRC Drive Characterization Tool interface. The 'Feedback Analysis' tab is active. The 'Gain Settings Preset' is set to 'WPILib (2020-)' and is highlighted with a red box. The 'Loop Type' is set to 'Velocity'. The 'Calculate Optimal Controller Gains' button is visible. The 'kP' value is 19.3 and the 'kD' value is 0.0.

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: 8	kS: 0.814	Gain Settings Preset: WPILib (2020-)
Time-Domain Diagnostics	Motion Threshold (units/s): 0.05	kV: 3.06	Controller Period (s): 0.02
Voltage-Domain Diagnostics		kA: 0.677	Max Controller Output: 12
3D Diagnostics		r-squared: 0.998	Time-Normalized Controller: <input checked="" type="checkbox"/>
	Track Width: 0.56341078		Controller Type: Onboard
			Post-Encoder Gearing: 1
			Encoder EPR: 4096
			Has Slave: <input type="checkbox"/>
			Slave Update Period (s): 0.01
			kV: 3.06
			kA: 0.677
			kP: 19.3
			kD: 0.0

Finally, we calculate and record the feedback gains for our control loop. Since it is a velocity controller, only a P gain is required:

The screenshot shows the FRC Drive Characterization Tool interface. The 'Feedback Analysis' tab is active. The 'Gain Settings Preset' is set to 'WPILib (2020-)' and is highlighted with a red box. The 'Loop Type' is set to 'Position'. The 'Calculate Optimal Controller Gains' button is visible. The 'kP' value is 43.6 and the 'kD' value is 20.2.

Feedforward Analysis		Feedback Analysis	
Analyze Data	Accel Window Size: 8	kS: 0.814	Gain Settings Preset: WPILib (2020-)
Time-Domain Diagnostics	Motion Threshold (units/s): 0.05	kV: 3.06	Controller Period (s): 0.02
Voltage-Domain Diagnostics		kA: 0.677	Max Controller Output: 12
3D Diagnostics		r-squared: 0.998	Time-Normalized Controller: <input checked="" type="checkbox"/>
	Track Width: 0.56341078		Controller Type: Onboard
			Post-Encoder Gearing: 1
			Encoder EPR: 4096
			Has Slave: <input type="checkbox"/>
			Slave Update Period (s): 0.01
			kV: 3.06
			kA: 0.677
			kP: 43.6
			kD: 20.2

Assuming we have done everything correctly, our proportional gain will be in units of Volts \* Seconds / Meters. Thus, our calculated gain means that, for each meter per second of velocity error, the controller will output an additional 8.5 volts.

## 25.3 Step 2: Entering the Calculated Constants

**Note:** In C++, it is important that the feedforward constants be entered as the correct unit type. For more information on C++ units, see [The C++ Units Library](#).

Now that we have our characterization constants, it is time to place them in our code. The recommended place for this is the Constants file of the [standard command-based project structure](#).

The relevant parts of the constants file from the RamseteCommand Example Project (Java, C++) can be seen below.

### 25.3.1 Feedforward/Feedback Gains

Firstly, we must enter the feedforward and feedback gains which we obtained from the characterization tool.

**Note:** Feedforward and feedback gains do *not*, in general, transfer across robots. Do *not* use the gains from this tutorial for your own robot.

Java

```

44 // These are example values only - DO NOT USE THESE FOR YOUR OWN ROBOT!
45 // These characterization values MUST be determined either experimentally or
↳ theoretically
46 // for *your* robot's drive.
47 // The Robot Characterization Toolsuite provides a convenient tool for obtaining
↳ these
48 // values for your robot.
49 public static final double ksVolts = 0.22;
50 public static final double kvVoltSecondsPerMeter = 1.98;
51 public static final double kaVoltSecondsSquaredPerMeter = 0.2;
52
53 // Example value only - as above, this must be tuned for your drive!
54 public static final double kPDriveVel = 8.5;

```

C++ (Header)

```

46 // These are example values only - DO NOT USE THESE FOR YOUR OWN ROBOT!
47 // These characterization values MUST be determined either experimentally or
48 // theoretically for *your* robot's drive. The Robot Characterization
49 // Toolsuite provides a convenient tool for obtaining these values for your
50 // robot.
51 constexpr auto ks = 0.22_V;
52 constexpr auto kv = 1.98 * 1_V * 1_s / 1_m;
53 constexpr auto ka = 0.2 * 1_V * 1_s * 1_s / 1_m;
54
55 // Example value only - as above, this must be tuned for your drive!
56 constexpr double kPDriveVel = 8.5;

```

### 25.3.2 DifferentialDriveKinematics

Additionally, we must create an instance of the DifferentialDriveKinematics class, which allows us to use the trackwidth (i.e. horizontal distance between the wheels) of the robot to convert from chassis speeds to wheel speeds. As elsewhere, we keep our units in meters.

Java

```

32 public static final double kTrackwidthMeters = 0.69;
33 public static final DifferentialDriveKinematics kDriveKinematics =
34     new DifferentialDriveKinematics(kTrackwidthMeters);

```

C++ (Header)

```

35 constexpr auto kTrackwidth = 0.69_m;
36 extern const frc::DifferentialDriveKinematics kDriveKinematics;

```



### 25.3.3 Max Trajectory Velocity/Acceleration

We must also decide on a nominal max acceleration and max velocity for the robot during path-following. The maximum velocity value should be set somewhat below the nominal free-speed of the robot. Due to the later use of the `DifferentialDriveVoltageConstraint`, the maximum acceleration value is not extremely crucial.

Java

```
62 public static final double kMaxSpeedMetersPerSecond = 3;
63 public static final double kMaxAccelerationMetersPerSecondSquared = 3;
```

C++ (Header)

```
60 constexpr auto kMaxSpeed = 3_mps;
61 constexpr auto kMaxAcceleration = 3_mps_sq;
```

### 25.3.4 Ramsete Parameters

Finally, we must include a pair of parameters for the RAMSETE controller. The values shown below should work well for most robots, provided distances have been correctly measured in meters - for more information on tuning these values (if it is required), see [Constructing the Ramsete Controller Object](#).

Java

```
65 // Reasonable baseline values for a RAMSETE follower in units of meters and
66 ↪seconds
67 public static final double kRamseteB = 2;
67 public static final double kRamseteZeta = 0.7;
```

C++ (Header)

```
63 // Reasonable baseline values for a RAMSETE follower in units of meters and
64 // seconds
65 constexpr double kRamseteB = 2;
66 constexpr double kRamseteZeta = 0.7;
```

## 25.4 Step 3: Creating a Drive Subsystem

Now that our drive is characterized, it is time to start writing our robot code *proper*. As mentioned before, we will use the *command-based* framework for our robot code. Accordingly, our first step is to write a suitable drive *subsystem* class.

The full drive class from the RamseteCommand Example Project (Java, C++) can be seen below. The rest of the article will describe the steps involved in writing this class.

Java

```
8 package edu.wpi.first.wpilibj.examples.ramsetecommand.subsystems;
9
10 import edu.wpi.first.wpilibj.ADXRS450_Gyro;
11 import edu.wpi.first.wpilibj.Encoder;
```

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```

12 import edu.wpi.first.wpilibj.PWMVictorSPX;
13 import edu.wpi.first.wpilibj.SpeedControllerGroup;
14 import edu.wpi.first.wpilibj.drive.DifferentialDrive;
15 import edu.wpi.first.wpilibj.geometry.Pose2d;
16 import edu.wpi.first.wpilibj.geometry.Rotation2d;
17 import edu.wpi.first.wpilibj.interfaces.Gyro;
18 import edu.wpi.first.wpilibj.kinematics.DifferentialDriveOdometry;
19 import edu.wpi.first.wpilibj.kinematics.DifferentialDriveWheelSpeeds;
20 import edu.wpi.first.wpilibj2.command.SubsystemBase;
21
22 import edu.wpi.first.wpilibj.examples.ramsetecommand.Constants.DriveConstants;
23
24 public class DriveSubsystem extends SubsystemBase {
25     // The motors on the left side of the drive.
26     private final SpeedControllerGroup m_leftMotors =
27         new SpeedControllerGroup(new PWMVictorSPX(DriveConstants.kLeftMotor1Port),
28                                 new PWMVictorSPX(DriveConstants.kLeftMotor2Port));
29
30     // The motors on the right side of the drive.
31     private final SpeedControllerGroup m_rightMotors =
32         new SpeedControllerGroup(new PWMVictorSPX(DriveConstants.kRightMotor1Port),
33                                 new PWMVictorSPX(DriveConstants.kRightMotor2Port));
34
35     // The robot's drive
36     private final DifferentialDrive m_drive = new DifferentialDrive(m_leftMotors, m_
↪rightMotors);
37
38     // The left-side drive encoder
39     private final Encoder m_leftEncoder =
40         new Encoder(DriveConstants.kLeftEncoderPorts[0], DriveConstants.
↪kLeftEncoderPorts[1],
41                     DriveConstants.kLeftEncoderReversed);
42
43     // The right-side drive encoder
44     private final Encoder m_rightEncoder =
45         new Encoder(DriveConstants.kRightEncoderPorts[0], DriveConstants.
↪kRightEncoderPorts[1],
46                     DriveConstants.kRightEncoderReversed);
47
48     // The gyro sensor
49     private final Gyro m_gyro = new ADXRS450_Gyro();
50
51     // Odometry class for tracking robot pose
52     private final DifferentialDriveOdometry m_odometry;
53
54     /**
55      * Creates a new DriveSubsystem.
56      */
57     public DriveSubsystem() {
58         // Sets the distance per pulse for the encoders
59         m_leftEncoder.setDistancePerPulse(DriveConstants.kEncoderDistancePerPulse);
60         m_rightEncoder.setDistancePerPulse(DriveConstants.kEncoderDistancePerPulse);
61
62         resetEncoders();
63         m_odometry = new DifferentialDriveOdometry(Rotation2d.fromDegrees(getHeading()));
64     }

```

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```

65
66 @Override
67 public void periodic() {
68     // Update the odometry in the periodic block
69     m_odometry.update(Rotation2d.fromDegrees(getHeading()), m_leftEncoder.
↪ getDistance(),
70                     m_rightEncoder.getDistance());
71 }
72
73 /**
74  * Returns the currently-estimated pose of the robot.
75  *
76  * @return The pose.
77  */
78 public Pose2d getPose() {
79     return m_odometry.getPoseMeters();
80 }
81
82 /**
83  * Returns the current wheel speeds of the robot.
84  *
85  * @return The current wheel speeds.
86  */
87 public DifferentialDriveWheelSpeeds getWheelSpeeds() {
88     return new DifferentialDriveWheelSpeeds(m_leftEncoder.getRate(), m_rightEncoder.
↪ getRate());
89 }
90
91 /**
92  * Resets the odometry to the specified pose.
93  *
94  * @param pose The pose to which to set the odometry.
95  */
96 public void resetOdometry(Pose2d pose) {
97     resetEncoders();
98     m_odometry.resetPosition(pose, Rotation2d.fromDegrees(getHeading()));
99 }
100
101 /**
102  * Drives the robot using arcade controls.
103  *
104  * @param fwd the commanded forward movement
105  * @param rot the commanded rotation
106  */
107 public void arcadeDrive(double fwd, double rot) {
108     m_drive.arcadeDrive(fwd, rot);
109 }
110
111 /**
112  * Controls the left and right sides of the drive directly with voltages.
113  *
114  * @param leftVolts the commanded left output
115  * @param rightVolts the commanded right output
116  */
117 public void tankDriveVolts(double leftVolts, double rightVolts) {
118     m_leftMotors.setVoltage(leftVolts);

```

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```

119     m_rightMotors.setVoltage(-rightVolts);
120     m_drive.feed();
121 }
122
123 /**
124  * Resets the drive encoders to currently read a position of 0.
125  */
126 public void resetEncoders() {
127     m_leftEncoder.reset();
128     m_rightEncoder.reset();
129 }
130
131 /**
132  * Gets the average distance of the two encoders.
133  *
134  * @return the average of the two encoder readings
135  */
136 public double getAverageEncoderDistance() {
137     return (m_leftEncoder.getDistance() + m_rightEncoder.getDistance()) / 2.0;
138 }
139
140 /**
141  * Gets the left drive encoder.
142  *
143  * @return the left drive encoder
144  */
145 public Encoder getLeftEncoder() {
146     return m_leftEncoder;
147 }
148
149 /**
150  * Gets the right drive encoder.
151  *
152  * @return the right drive encoder
153  */
154 public Encoder getRightEncoder() {
155     return m_rightEncoder;
156 }
157
158 /**
159  * Sets the max output of the drive. Useful for scaling the drive to drive more
160  * slowly.
161  *
162  * @param maxOutput the maximum output to which the drive will be constrained
163  */
164 public void setMaxOutput(double maxOutput) {
165     m_drive.setMaxOutput(maxOutput);
166 }
167
168 /**
169  * Zeroes the heading of the robot.
170  */
171 public void zeroHeading() {
172     m_gyro.reset();
173 }

```

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```

174  /**
175   * Returns the heading of the robot.
176   *
177   * @return the robot's heading in degrees, from -180 to 180
178   */
179  public double getHeading() {
180      return Math.IEEEremainder(m_gyro.getAngle(), 360) * (DriveConstants.kGyroReversed
181      ↪ ? -1.0 : 1.0);
182  }
183
184  /**
185   * Returns the turn rate of the robot.
186   *
187   * @return The turn rate of the robot, in degrees per second
188   */
189  public double getTurnRate() {
190      return m_gyro.getRate() * (DriveConstants.kGyroReversed ? -1.0 : 1.0);
191  }

```

## C++ (Header)

```

8  #pragma once
9
10 #include <frc/ADXRS450_Gyro.h>
11 #include <frc/Encoder.h>
12 #include <frc/PWMMotorSPX.h>
13 #include <frc/SpeedControllerGroup.h>
14 #include <frc/drive/DifferentialDrive.h>
15 #include <frc/geometry/Pose2d.h>
16 #include <frc/kinematics/DifferentialDriveOdometry.h>
17 #include <frc2/command/SubsystemBase.h>
18 #include <units/units.h>
19
20 #include "Constants.h"
21
22 class DriveSubsystem : public frc2::SubsystemBase {
23 public:
24     DriveSubsystem();
25
26     /**
27      * Will be called periodically whenever the CommandScheduler runs.
28      */
29     void Periodic() override;
30
31     // Subsystem methods go here.
32
33     /**
34      * Drives the robot using arcade controls.
35      *
36      * @param fwd the commanded forward movement
37      * @param rot the commanded rotation
38      */
39     void ArcadeDrive(double fwd, double rot);
40
41     /**

```

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```

42  * Controls each side of the drive directly with a voltage.
43  *
44  * @param left the commanded left output
45  * @param right the commanded right output
46  */
47  void TankDriveVolts(units::volt_t left, units::volt_t right);
48
49  /**
50   * Resets the drive encoders to currently read a position of 0.
51   */
52  void ResetEncoders();
53
54  /**
55   * Gets the average distance of the TWO encoders.
56   *
57   * @return the average of the TWO encoder readings
58   */
59  double GetAverageEncoderDistance();
60
61  /**
62   * Gets the left drive encoder.
63   *
64   * @return the left drive encoder
65   */
66  frc::Encoder& GetLeftEncoder();
67
68  /**
69   * Gets the right drive encoder.
70   *
71   * @return the right drive encoder
72   */
73  frc::Encoder& GetRightEncoder();
74
75  /**
76   * Sets the max output of the drive. Useful for scaling the drive to drive
77   * more slowly.
78   *
79   * @param maxOutput the maximum output to which the drive will be constrained
80   */
81  void SetMaxOutput(double maxOutput);
82
83  /**
84   * Returns the heading of the robot.
85   *
86   * @return the robot's heading in degrees, from 180 to 180
87   */
88  double GetHeading();
89
90  /**
91   * Returns the turn rate of the robot.
92   *
93   * @return The turn rate of the robot, in degrees per second
94   */
95  double GetTurnRate();
96
97  /**

```

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```

98     * Returns the currently-estimated pose of the robot.
99     *
100    * @return The pose.
101    */
102    frc::Pose2d GetPose();
103
104    /**
105     * Returns the current wheel speeds of the robot.
106     *
107     * @return The current wheel speeds.
108     */
109    frc::DifferentialDriveWheelSpeeds GetWheelSpeeds();
110
111    /**
112     * Resets the odometry to the specified pose.
113     *
114     * @param pose The pose to which to set the odometry.
115     */
116    void ResetOdometry(frc::Pose2d pose);
117
118    private:
119    // Components (e.g. motor controllers and sensors) should generally be
120    // declared private and exposed only through public methods.
121
122    // The motor controllers
123    frc::PWMVictorSPX m_left1;
124    frc::PWMVictorSPX m_left2;
125    frc::PWMVictorSPX m_right1;
126    frc::PWMVictorSPX m_right2;
127
128    // The motors on the left side of the drive
129    frc::SpeedControllerGroup m_leftMotors{m_left1, m_left2};
130
131    // The motors on the right side of the drive
132    frc::SpeedControllerGroup m_rightMotors{m_right1, m_right2};
133
134    // The robot's drive
135    frc::DifferentialDrive m_drive{m_leftMotors, m_rightMotors};
136
137    // The left-side drive encoder
138    frc::Encoder m_leftEncoder;
139
140    // The right-side drive encoder
141    frc::Encoder m_rightEncoder;
142
143    // The gyro sensor
144    frc::ADXRS450_Gyro m_gyro;
145
146    // Odometry class for tracking robot pose
147    frc::DifferentialDriveOdometry m_odometry;
148    };

```

C++ (Source)

```

8  #include "subsystems/DriveSubsystem.h"
9

```

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```

10 #include <frc/geometry/Rotation2d.h>
11 #include <frc/kinematics/DifferentialDriveWheelSpeeds.h>
12
13 using namespace DriveConstants;
14
15 DriveSubsystem::DriveSubsystem()
16     : m_left1{kLeftMotor1Port},
17       m_left2{kLeftMotor2Port},
18       m_right1{kRightMotor1Port},
19       m_right2{kRightMotor2Port},
20       m_leftEncoder{kLeftEncoderPorts[0], kLeftEncoderPorts[1]},
21       m_rightEncoder{kRightEncoderPorts[0], kRightEncoderPorts[1]},
22       m_odometry{frc::Rotation2d(units::degree_t(GetHeading()))} {
23     // Set the distance per pulse for the encoders
24     m_leftEncoder.SetDistancePerPulse(kEncoderDistancePerPulse);
25     m_rightEncoder.SetDistancePerPulse(kEncoderDistancePerPulse);
26
27     ResetEncoders();
28 }
29
30 void DriveSubsystem::Periodic() {
31     // Implementation of subsystem periodic method goes here.
32     m_odometry.Update(frc::Rotation2d(units::degree_t(GetHeading())),
33                      units::meter_t(m_leftEncoder.GetDistance()),
34                      units::meter_t(m_rightEncoder.GetDistance()));
35 }
36
37 void DriveSubsystem::ArcadeDrive(double fwd, double rot) {
38     m_drive.ArcadeDrive(fwd, rot);
39 }
40
41 void DriveSubsystem::TankDriveVolts(units::volt_t left, units::volt_t right) {
42     m_leftMotors.SetVoltage(left);
43     m_rightMotors.SetVoltage(-right);
44     m_drive.Feed();
45 }
46
47 void DriveSubsystem::ResetEncoders() {
48     m_leftEncoder.Reset();
49     m_rightEncoder.Reset();
50 }
51
52 double DriveSubsystem::GetAverageEncoderDistance() {
53     return (m_leftEncoder.GetDistance() + m_rightEncoder.GetDistance()) / 2.0;
54 }
55
56 frc::Encoder& DriveSubsystem::GetLeftEncoder() { return m_leftEncoder; }
57
58 frc::Encoder& DriveSubsystem::GetRightEncoder() { return m_rightEncoder; }
59
60 void DriveSubsystem::SetMaxOutput(double maxOutput) {
61     m_drive.SetMaxOutput(maxOutput);
62 }
63
64 double DriveSubsystem::GetHeading() {
65     return std::remainder(m_gyro.GetAngle(), 360) * (kGyroReversed ? -1.0 : 1.0);

```

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```

66 }
67
68 double DriveSubsystem::GetTurnRate() {
69     return m_gyro.GetRate() * (kGyroReversed ? -1.0 : 1.0);
70 }
71
72 frc::Pose2d DriveSubsystem::GetPose() { return m_odometry.GetPose(); }
73
74 frc::DifferentialDriveWheelSpeeds DriveSubsystem::GetWheelSpeeds() {
75     return {units::meters_per_second_t(m_leftEncoder.GetRate()),
76            units::meters_per_second_t(m_rightEncoder.GetRate())};
77 }
78
79 void DriveSubsystem::ResetOdometry(frc::Pose2d pose) {
80     ResetEncoders();
81     m_odometry.ResetPosition(pose,
82                             frc::Rotation2d(units::degree_t(GetHeading())));
83 }

```

### 25.4.1 Configuring the Drive Encoders

The drive encoders measure the rotation of the wheels on each side of the drive. To properly configure the encoders, we need to specify two things: the ports the encoders are plugged into, and the distance per encoder pulse. Then, we need to write methods allowing access to the encoder values from code that uses the subsystem.

#### Encoder Ports

The encoder ports are specified in the encoder's constructor, like so:

Java

```

38 // The left-side drive encoder
39 private final Encoder m_leftEncoder =
40     new Encoder(DriveConstants.kLeftEncoderPorts[0], DriveConstants.
41 ↪ kLeftEncoderPorts[1],
42                DriveConstants.kLeftEncoderReversed);
43
44 // The right-side drive encoder
45 private final Encoder m_rightEncoder =
46     new Encoder(DriveConstants.kRightEncoderPorts[0], DriveConstants.
47 ↪ kRightEncoderPorts[1],
48                DriveConstants.kRightEncoderReversed);

```

C++ (Source)

```

20     m_leftEncoder{kLeftEncoderPorts[0], kLeftEncoderPorts[1]},
21     m_rightEncoder{kRightEncoderPorts[0], kRightEncoderPorts[1]},

```

## Encoder Distance per Pulse

The distance per pulse is specified by calling the encoder's `setDistancePerPulse` method. Note that for the WPILib Encoder class, "pulse" refers to a full encoder cycle (i.e. four edges), and thus will be 1/4 the value that was specified in the FRC-Characterization config. Remember, as well, that the distance should be measured in meters!

Java

```
58 // Sets the distance per pulse for the encoders
59 m_leftEncoder.setDistancePerPulse(DriveConstants.kEncoderDistancePerPulse);
60 m_rightEncoder.setDistancePerPulse(DriveConstants.kEncoderDistancePerPulse);
```

C++ (Source)

```
23 // Set the distance per pulse for the encoders
24 m_leftEncoder.SetDistancePerPulse(kEncoderDistancePerPulse);
25 m_rightEncoder.SetDistancePerPulse(kEncoderDistancePerPulse);
```

## Encoder Accessor Method

To access the values measured by the encoders, we include the following method:

Java

```
82 /**
83  * Returns the current wheel speeds of the robot.
84  *
85  * @return The current wheel speeds.
86  */
87 public DifferentialDriveWheelSpeeds getWheelSpeeds() {
88     return new DifferentialDriveWheelSpeeds(m_leftEncoder.getRate(), m_rightEncoder.
89     ↪ getRate());
89 }
```

C++ (Source)

```
74 frc::DifferentialDriveWheelSpeeds DriveSubsystem::GetWheelSpeeds() {
75     return {units::meters_per_second_t(m_leftEncoder.GetRate()),
76            units::meters_per_second_t(m_rightEncoder.GetRate())};
77 }
```

We wrap the measured encoder values in a `DifferentialDriveWheelSpeeds` object for easier integration with the `RamseteCommand` class later on.

## 25.4.2 Configuring the Gyroscope

The gyroscope measures the rate of change of the robot's heading (which can then be integrated to provide a measurement of the robot's heading relative to when it first turned on). In our example, we use the [Analog Devices ADXRS450 FRC Gyro Board](#), which has been included in the kit of parts for several years:

Java

```
48 // The gyro sensor
49 private final Gyro m_gyro = new ADXRS450_Gyro();
```

C++ (Header)

```
143 // The gyro sensor
144 frc::ADXRS450_Gyro m_gyro;
```

### Gyroscope Accessor Method

To access the current heading measured by the gyroscope, we include the following method:

Java

```
174 /**
175  * Returns the heading of the robot.
176  *
177  * @return the robot's heading in degrees, from -180 to 180
178  */
179 public double getHeading() {
180     return Math.IEEEremainder(m_gyro.getAngle(), 360) * (DriveConstants.kGyroReversed
181     ↪ ? -1.0 : 1.0);
181 }
```

C++ (Source)

```
64 double DriveSubsystem::GetHeading() {
65     return std::remainder(m_gyro.GetAngle(), 360) * (kGyroReversed ? -1.0 : 1.0);
66 }
```

## 25.4.3 Configuring the Odometry

Now that we have our encoders and gyroscope configured, it is time to set up our drive subsystem to automatically compute its position from the encoder and gyroscope readings.

First, we create a member instance of the `DifferentialDriveOdometry` class:

Java

```
51 // Odometry class for tracking robot pose
52 private final DifferentialDriveOdometry m_odometry;
```

C++ (Header)

```
146 // Odometry class for tracking robot pose
147 frc::DifferentialDriveOdometry m_odometry;
```

### Updating the Odometry

The odometry class must be regularly updated to incorporate new readings from the encoder and gyroscope. We accomplish this inside the subsystem's periodic method, which is automatically called once per main loop iteration:

Java

```

66  @Override
67  public void periodic() {
68      // Update the odometry in the periodic block
69      m_odometry.update(Rotation2d.fromDegrees(getHeading()), m_leftEncoder.
    ↪ getDistance(),
70                      m_rightEncoder.getDistance());
71  }

```

C++ (Source)

```

30  void DriveSubsystem::Periodic() {
31      // Implementation of subsystem periodic method goes here.
32      m_odometry.Update(frc::Rotation2d(units::degree_t(GetHeading())),
33                      units::meter_t(m_leftEncoder.GetDistance()),
34                      units::meter_t(m_rightEncoder.GetDistance()));
35  }

```

### Odometry Accessor Method

To access the robot's current computed pose, we include the following method:

Java

```

72  /**
73   * Returns the currently-estimated pose of the robot.
74   *
75   * @return The pose.
76   */
77  public Pose2d getPose() {
78      return m_odometry.getPoseMeters();
79  }

```

C++ (Source)

```

72  frc::Pose2d DriveSubsystem::GetPose() { return m_odometry.GetPose(); }

```

### 25.4.4 Voltage-Based Drive Method

Finally, we must include one additional method - a method that allows us to set the voltage to each side of the drive using the `setVoltage()` method of the `SpeedController` interface. The default WPILib drive class does not include this functionality, so we must write it ourselves:

Java

```

111 /**
112  * Controls the left and right sides of the drive directly with voltages.
113  *
114  * @param leftVolts the commanded left output
115  * @param rightVolts the commanded right output
116  */
117  public void tankDriveVolts(double leftVolts, double rightVolts) {
118      m_leftMotors.setVoltage(leftVolts);
119      m_rightMotors.setVoltage(-rightVolts);

```

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```

120     m_drive.feed();
121 }

```

C++ (Source)

```

41 void DriveSubsystem::TankDriveVolts(units::volt_t left, units::volt_t right) {
42     m_leftMotors.SetVoltage(left);
43     m_rightMotors.SetVoltage(-right);
44     m_drive.Feed();

```

It is very important to use the `setVoltage()` method rather than the ordinary `set()` method, as this will automatically compensate for battery “voltage sag” during operation. Since our feedforward voltages are physically-meaningful (as they are based on measured characterization data), this is essential to ensuring their accuracy.

## 25.5 Step 4: Creating and Following a Trajectory

With our drive subsystem written, it is now time to generate a trajectory and write an autonomous command to follow it.

As per the *standard command-based project structure*, we will do this in the `getAutonomousCommand` method of the `RobotContainer` class. The full method from the RamseteCommand Example Project (Java, C++) can be seen below. The rest of the article will break down the different parts of the method in more detail.

Java

```

82  /**
83   * Use this to pass the autonomous command to the main {@link Robot} class.
84   *
85   * @return the command to run in autonomous
86   */
87  public Command getAutonomousCommand() {
88
89      // Create a voltage constraint to ensure we don't accelerate too fast
90      var autoVoltageConstraint =
91          new DifferentialDriveVoltageConstraint(
92              new SimpleMotorFeedforward(DriveConstants.kSVolts,
93                                          DriveConstants.kVVoltsSecondsPerMeter,
94                                          DriveConstants.kAVoltsSecondsSquaredPerMeter),
95              DriveConstants.kDriveKinematics,
96              10);
97
98      // Create config for trajectory
99      TrajectoryConfig config =
100          new TrajectoryConfig(AutoConstants.kMaxSpeedMetersPerSecond,
101                               AutoConstants.kMaxAccelerationMetersPerSecondSquared)
102          // Add kinematics to ensure max speed is actually obeyed
103          .setKinematics(DriveConstants.kDriveKinematics)
104          // Apply the voltage constraint
105          .addConstraint(autoVoltageConstraint);
106
107      // An example trajectory to follow. All units in meters.
108      Trajectory exampleTrajectory = TrajectoryGenerator.generateTrajectory(

```

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```

109 // Start at the origin facing the +X direction
110 new Pose2d(0, 0, new Rotation2d(0)),
111 // Pass through these two interior waypoints, making an 's' curve path
112 List.of(
113     new Translation2d(1, 1),
114     new Translation2d(2, -1)
115 ),
116 // End 3 meters straight ahead of where we started, facing forward
117 new Pose2d(3, 0, new Rotation2d(0)),
118 // Pass config
119 config
120 );
121
122 RamseteCommand ramseteCommand = new RamseteCommand(
123     exampleTrajectory,
124     m_robotDrive::getPose,
125     new RamseteController(AutoConstants.kRamseteB, AutoConstants.kRamseteZeta),
126     new SimpleMotorFeedforward(DriveConstants.ksVolts,
127                               DriveConstants.kvVoltSecondsPerMeter,
128                               DriveConstants.kaVoltSecondsSquaredPerMeter),
129     DriveConstants.kDriveKinematics,
130     m_robotDrive::getWheelSpeeds,
131     new PIDController(DriveConstants.kPDriveVel, 0, 0),
132     new PIDController(DriveConstants.kPDriveVel, 0, 0),
133     // RamseteCommand passes volts to the callback
134     m_robotDrive::tankDriveVolts,
135     m_robotDrive
136 );
137
138 // Run path following command, then stop at the end.
139 return ramseteCommand.andThen(() -> m_robotDrive.tankDriveVolts(0, 0));
140 }

```

## C++ (Source)

```

48 frc2::Command* RobotContainer::GetAutonomousCommand() {
49     // Create a voltage constraint to ensure we don't accelerate too fast
50     frc::DifferentialDriveVoltageConstraint autoVoltageConstraint(
51         frc::SimpleMotorFeedforward<units::meters>(
52             DriveConstants::ks, DriveConstants::kv, DriveConstants::ka),
53         DriveConstants::kDriveKinematics, 10_V);
54
55     // Set up config for trajectory
56     frc::TrajectoryConfig config(AutoConstants::kMaxSpeed,
57                                AutoConstants::kMaxAcceleration);
58     // Add kinematics to ensure max speed is actually obeyed
59     config.SetKinematics(DriveConstants::kDriveKinematics);
60     // Apply the voltage constraint
61     config.AddConstraint(autoVoltageConstraint);
62
63     // An example trajectory to follow. All units in meters.
64     auto exampleTrajectory = frc::TrajectoryGenerator::GenerateTrajectory(
65         // Start at the origin facing the +X direction
66         frc::Pose2d(0_m, 0_m, frc::Rotation2d(0_deg)),
67         // Pass through these two interior waypoints, making an 's' curve path
68         {frc::Translation2d(1_m, 1_m), frc::Translation2d(2_m, -1_m)},

```

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```

69 // End 3 meters straight ahead of where we started, facing forward
70 frc::Pose2d(3_m, 0_m, frc::Rotation2d(0_deg)),
71 // Pass the config
72 config);
73
74 frc2::RamseteCommand ramseteCommand(
75     exampleTrajectory, [this]() { return m_drive.GetPose(); },
76     frc::RamseteController(AutoConstants::kRamseteB,
77                           AutoConstants::kRamseteZeta),
78     frc::SimpleMotorFeedforward<units::meters>(
79         DriveConstants::ks, DriveConstants::kv, DriveConstants::ka),
80     DriveConstants::kDriveKinematics,
81     [this] { return m_drive.GetWheelSpeeds(); },
82     frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
83     frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
84     [this](auto left, auto right) { m_drive.TankDriveVolts(left, right); },
85     {&m_drive});
86
87 // no auto
88 return new frc2::SequentialCommandGroup(
89     std::move(ramseteCommand),
90     frc2::InstantCommand([this] { m_drive.TankDriveVolts(0_V, 0_V); }, {}));

```

### 25.5.1 Configuring the Trajectory Constraints

First, we must set some configuration parameters for the trajectory which will ensure that the generated trajectory is followable.

#### Creating a Voltage Constraint

The first piece of configuration we will need is a voltage constraint. This will ensure that the generated trajectory never commands the robot to go faster than it is capable of achieving with the given voltage supply:

Java

```

89 // Create a voltage constraint to ensure we don't accelerate too fast
90 var autoVoltageConstraint =
91     new DifferentialDriveVoltageConstraint(
92         new SimpleMotorFeedforward(DriveConstants.kSVolts,
93                                     DriveConstants.kVVoltsSecondsPerMeter,
94                                     DriveConstants.kAVoltsSecondsSquaredPerMeter),
95         DriveConstants.kDriveKinematics,
96         10);

```

C++ (Source)

```

49 // Create a voltage constraint to ensure we don't accelerate too fast
50 frc::DifferentialDriveVoltageConstraint autoVoltageConstraint(
51     frc::SimpleMotorFeedforward<units::meters>(
52         DriveConstants::ks, DriveConstants::kv, DriveConstants::ka),
53     DriveConstants::kDriveKinematics, 10_V);

```

Notice that we set the maximum voltage to 10V, rather than the nominal battery voltage of 12V. This gives us some “headroom” to deal with “voltage sag” during operation.

## Creating the Configuration

Now that we have our voltage constraint, we can create our `TrajectoryConfig` instance, which wraps together all of our path constraints:

Java

```

98 // Create config for trajectory
99 TrajectoryConfig config =
100     new TrajectoryConfig(AutoConstants.kMaxSpeedMetersPerSecond,
101                          AutoConstants.kMaxAccelerationMetersPerSecondSquared)
102     // Add kinematics to ensure max speed is actually obeyed
103     .setKinematics(DriveConstants.kDriveKinematics)
104     // Apply the voltage constraint
105     .addConstraint(autoVoltageConstraint);

```

C++ (Source)

```

55 // Set up config for trajectory
56 frc::TrajectoryConfig config(AutoConstants::kMaxSpeed,
57                             AutoConstants::kMaxAcceleration);
58 // Add kinematics to ensure max speed is actually obeyed
59 config.SetKinematics(DriveConstants::kDriveKinematics);
60 // Apply the voltage constraint
61 config.AddConstraint(autoVoltageConstraint);

```

## 25.5.2 Generating the Trajectory

With our trajectory configuration in hand, we are now ready to generate our trajectory. For this example, we will be generating a “clamped cubic” trajectory - this means we will specify full robot poses at the endpoints, and positions only for interior waypoints (also known as “knot points”). As elsewhere, all distances are in meters.

Java

```

108 Trajectory exampleTrajectory = TrajectoryGenerator.generateTrajectory(
109     // Start at the origin facing the +X direction
110     new Pose2d(0, 0, new Rotation2d(0)),
111     // Pass through these two interior waypoints, making an 's' curve path
112     List.of(
113         new Translation2d(1, 1),
114         new Translation2d(2, -1)
115     ),
116     // End 3 meters straight ahead of where we started, facing forward
117     new Pose2d(3, 0, new Rotation2d(0)),
118     // Pass config
119     config
120 );

```

C++ (Source)



```

63 // An example trajectory to follow. All units in meters.
64 auto exampleTrajectory = frc::TrajectoryGenerator::GenerateTrajectory(
65     // Start at the origin facing the +X direction
66     frc::Pose2d(0_m, 0_m, frc::Rotation2d(0_deg)),
67     // Pass through these two interior waypoints, making an 's' curve path
68     {frc::Translation2d(1_m, 1_m), frc::Translation2d(2_m, -1_m)},
69     // End 3 meters straight ahead of where we started, facing forward
70     frc::Pose2d(3_m, 0_m, frc::Rotation2d(0_deg)),
71     // Pass the config
72     config);

```

**Note:** Instead of generating the trajectory on the roboRIO as outlined above, one can also *import a PathWeaver JSON*.

### 25.5.3 Creating the RamseteCommand

**Note:** It is very important that the initial robot pose match the first pose in the trajectory. For the purposes of our example, the robot will be reliably starting at a position of (0,0) with a heading of 0. In actual use, however, it is probably not desirable to base your coordinate system on the robot position, and so the starting position for both the robot and the trajectory should be set to some other value. If you wish to use a trajectory that has been defined in robot-centric coordinates in such a situation, you can transform it to be relative to the robot's current pose using the `transformBy` method. For more information about transforming trajectories, see *Transforming Trajectories*.

Now that we have a trajectory, we can create a command that, when executed, will follow that trajectory. To do this, we use the `RamseteCommand` class (Java, C++)

Java

```

122 RamseteCommand ramseteCommand = new RamseteCommand(
123     exampleTrajectory,
124     m_robotDrive::getPose,
125     new RamseteController(AutoConstants.kRamseteB, AutoConstants.kRamseteZeta),
126     new SimpleMotorFeedforward(DriveConstants.kSVolts,
127                                 DriveConstants.kVVoltSecondsPerMeter,
128                                 DriveConstants.kAVoltSecondsSquaredPerMeter),
129     DriveConstants.kDriveKinematics,
130     m_robotDrive::getWheelSpeeds,
131     new PIDController(DriveConstants.kPDriveVel, 0, 0),
132     new PIDController(DriveConstants.kPDriveVel, 0, 0),
133     // RamseteCommand passes volts to the callback
134     m_robotDrive::tankDriveVolts,
135     m_robotDrive
136 );

```

C++ (Source)

```

74 frc2::RamseteCommand ramseteCommand(
75     exampleTrajectory, [this]() { return m_drive.GetPose(); },
76     frc::RamseteController(AutoConstants::kRamseteB,

```

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```

77         AutoConstants::kRamseteZeta),
78         frc::SimpleMotorFeedforward<units::meters>(
79             DriveConstants::ks, DriveConstants::kv, DriveConstants::ka),
80         DriveConstants::kDriveKinematics,
81         [this] { return m_drive.GetWheelSpeeds(); },
82         frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
83         frc2::PIDController(DriveConstants::kPDriveVel, 0, 0),
84         [this](auto left, auto right) { m_drive.TankDriveVolts(left, right); },
85         {&m_drive});
86
87 // no auto
88 return new frc2::SequentialCommandGroup(
89     std::move(ramseteCommand),
90     frc2::InstantCommand([this] { m_drive.TankDriveVolts(0_V, 0_V); }, {}));

```

This declaration is fairly substantial, so we'll go through it argument-by-argument:

1. The trajectory: This is the trajectory to be followed; accordingly, we pass the command the trajectory we just constructed in our earlier steps.
2. The pose supplier: This is a method reference (or lambda) to the *drive subsystem method that returns the pose*. The RAMSETE controller needs the current pose measurement to determine the required wheel outputs.
3. The RAMSETE controller: This is the RamseteController object (Java, C++) that will perform the path-following computation that translates the current measured pose and trajectory state into a chassis speed setpoint.
4. The drive feedforward: This is a SimpleMotorFeedforward object (Java, C++) that will automatically perform the correct feedforward calculation with the feedforward gains (kS, kV, and kA) that we obtained from the drive characterization tool.
5. The drive kinematics: This is the DifferentialDriveKinematics object (Java, C++) that we constructed earlier in our constants file, and will be used to convert chassis speeds to wheel speeds.
6. The wheel speed supplier: This is a method reference (or lambda) to the *drive subsystem method that returns the wheel speeds*.
7. The left-side PIDController: This is the PIDController object (Java, C++) that will track the left-side wheel speed setpoint, using the P gain that we obtained from the drive characterization tool.
8. The right-side PIDController: This is the PIDController object (Java, C++) that will track the right-side wheel speed setpoint, using the P gain that we obtained from the drive characterization tool.
9. The output consumer: This is a method reference (or lambda) to the *drive subsystem method that passes the voltage outputs to the drive motors*.
10. The robot drive: This is the drive subsystem itself, included to ensure the command does not operate on the drive at the same time as any other command that uses the drive.

Finally, note that we append a final “stop” command in sequence after the path-following command, to ensure that the robot stops moving at the end of the trajectory.

### **25.5.4 Video**

If all has gone well, your robot's autonomous routine should look something like this:

## 26.1 Wiring Best Practices

---

**Hint:** The article Wiring the FRC Control System walks through the details of what connects where to wire up the FRC Control System, this article provides some additional “Best Practices” that may increase reliability and make maintenance easier.

---

### 26.1.1 Vibration/Shock

An FRC Robot is an incredibly rough environment when it comes to vibrations and shock loads. While many of the FRC specific electronics are extensively tested for mechanical robustness in these conditions, a few components, such as the radio, are not specifically designed for use on a mobile platform. Taking steps to reduce the shock and vibration these components are exposed to may help reduce failures. Some suggestions that may reduce mechanical failures:

- **Vibration Isolation** - Make sure to isolate any components which create excessive vibration, such as compressors, using “vibration isolators”. This will help reduce vibration on the robot which can loosen fasteners and cause premature fatigue failure on some electronic components.
- **Bumpers** - Use Bumpers to cover as much of the robot as possible for your design. While the rules require specific bumper coverage around the corners of your robot, maximizing the use of bumpers increases the likelihood that all collisions will be damped by your bumpers. Bumpers significantly reduce the g-forces experienced in a collision compared to hitting directly on a hard robot surface, reducing the shock experienced by the electronics and decreasing the chance of a shock related failure.
- **Shock Mounting** - You may choose to shock mount some or all of your electronic components to further reduce the forces they see in robot collisions. This is especially helpful for the robot radio and other electronics such as co-processors, which may not be designed for use on mobile platforms. Vibration isolators, springs, foams, or mounting to flexible materials all may reduce the shock forces seen by these components.

### **26.1.2 Redundancy**

Unfortunately there are few places in the FRC Control System where redundancy is feasible. Taking advantage of opportunities for redundancy can increase reliability. The primary example of this is wiring the barrel connector to the radio in addition to the provided PoE connection. This ensures that if one of the cables becomes damaged or dislodged, the other will maintain power to the radio. Keep an eye out for other potential areas to provide redundancy when wiring and programming your robot.

### **26.1.3 Port Savers**

For any connections on the Robot or Driver station that may be frequently plugged and unplugged (such as DS joysticks, DS Ethernet, roboRIO USB tether, and Ethernet tether) using a “Port Saver” or “pigtail” can substantially reduce the potential for damaging the port. This type of device can serve double duty, both reducing the number of cycles that the port on the electronic device sees, as well as relocating the connection to a more convenient location. Make sure to secure the port saver (see the next item) to avoid port damage.

### **26.1.4 Wire Management and Strain Relief**

One of the most critical components to robot reliability and maintenance is good wire management and strain relief. Good wire management is comprised of a few components:

- Make sure cables are the correct length. Any excess wire length is just more to manage. If you must have extra wire due to additional length on COTS cabling, secure the extra into a small bundle using separate cable ties before securing the rest of the wire.
- Ensure that cables are secured close to connection points, with enough slack to avoid putting strain on connectors. This is called strain relief, and is critical to minimizing the likelihood that a cable comes unplugged or a wire breaks off at a connection point (these are generally stress concentrators).
- Secure cables near any moving components. Make sure that all wire runs are secure and protected from moving components, even if the moving components were to bend or over-travel.
- Secure cables at additional points as necessary to keep wiring neat and clean. Take care to not over secure wires; if wires are secured in too many locations, it may actually make troubleshooting and maintenance more difficult.

### **26.1.5 Documentation**

A great way to make maintenance easier is to create documentation describing what is connected where on the robot. There are a number of ways of creating this type of documentation which range from complete wiring diagrams to excel charts to a quick list of what functions are attached to which channels. Many teams also integrate these lists with labeling (see the next bullet).

When a wire is accidentally cut, or a mechanism is malfunctioning, or a component burns out, it will be much easier to repair if you have some documentation to tell you what is connected where without having to trace the wiring all the way through (even if your wiring is neat!)

### 26.1.6 Labeling

Labeling is a great way to supplement the wiring documentation described above. There are many different strategies to labeling wiring and electronics, all with their own pros and cons. Labels for electronics and flags for wires can be made by hand, or using a label maker (some can also do heat-shrink labels), or you can use different colors of electrical tape or labeling flags to indicate different things. Whatever system you choose, make sure you understand how it complements your documentation and make sure everyone on your team is familiar with it.

### 26.1.7 Check all wiring and connections

After all wiring on the robot is complete, make sure to check each connection, pulling on each, to ensure that everything is secure. Additionally, ensure that no stray wire “whiskers” are sticking out of any connection point and that no uninsulated connections are exposed. If any connections come loose while testing, or any “whiskers” are discovered, re-make the connection and make sure to have a second person check it when complete.

A common source of poor connections is screw-type or nut-and-bolt fasteners. For any connections of this type on the robot (e.g. battery connections, main breaker, PDP, roboRIO), make sure the fasteners are tight. For nut-and-bolt style connections, ensure that the wire/terminal cannot be rotated by hand; if you can rotate your battery wire or main breaker connection by grasping the terminal and twisting, the connection is not tight enough.

Another common source of failures is the fuses at the end of the PDP. Ensure these fuses are completely seated; you may need to apply more force than you expect to seat them completely. If the fuses are seated properly they will likely be difficult or impossible to remove by hand.

Snap-in connections such as the SB-50 connector should be secured using clips or cable ties to ensure they do not pop loose during impacts.

### 26.1.8 Re-Check Early and Often

Re-check the entire electrical system as thoroughly as possible after playing the first match or two (or doing very vigorous testing). The first few impacts the robot sees may loosen fasteners or expose issues.

Create a checklist for re-checking electrical connections on a regular basis. As a very rough starting point, rotational fasteners such as battery and PDP connections should be checked every 1-3 matches. Spring type connections such as the WAGO and Weidmuller connectors likely only need to be checked once per event. Ensure that the team knows who is responsible for completing the checklist and how they will document that it has been done.

### 26.1.9 Battery Maintenance

Take good care of your batteries! A bad battery can easily cause a robot to function poorly, or not at all, during a match. Label all of your batteries to help keep track of usage during the event. Many teams also include information such as the age of the battery on this label.

- **Never lift or carry batteries by the wires! Carrying batteries by the wires** has the potential to damage the internal connection between the terminals and the plates, dramatically increasing internal resistance and degrading performance.

- **Mark any dropped battery bad until a complete test can be conducted.** In addition to the mentioned terminal connections, dropping a battery also has the potential to damage individual cells. This damage may not register on a simple voltage test, instead hiding until the battery is placed under load.
- **Rotate batteries evenly. This helps ensure that batteries have the most time to charge and rest and that they wear evenly** (equal number of charge/discharge cycles)
- **Load test batteries if possible to monitor health. There are a number of** commercially available products teams use to load test batteries, including at least one designed specifically for FRC. A load test can provide an indicator of battery health by measuring internal resistance. This measurement is much more meaningful when it comes to match performance than a simple no-load voltage number provided by a multimeter.

### 26.1.10 Check DS Logs

After each match, review the DS logs to see what the battery voltage and current usage looks like. Once you have established what the normal range of these items is for your robot, you may be able to spot potential issues (bad batteries, failing motors, mechanical binding) before they become critical failures.

## 26.2 Wiring Pneumatics

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**Hint:** For pneumatics safety & mechanical requirements, consult this year's Robot Construction rules. For mechanical design guidelines, the FIRST Pneumatics Manual is located [here](#) (last updated 2017)

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### 26.2.1 Wiring Overview

A single PCM will support most pneumatics applications, providing an output for the compressor, input for the pressure switch, and outputs for up to 8 solenoid channels (12V or 24V selectable). The module is connected to the roboRIO over the CAN bus and powered via 12V from the PDP.

For complicated robot designs requiring more channels or multiple solenoid voltages, additional PCMs can be added to the control system.

### 26.2.2 PCM Power and Control Wiring

The first PCM on your robot can be wired from the PDP VRM/PCM connectors on the end of the PDP. The PCM is connected to the roboRIO via CAN and can be placed anywhere in the middle of the CAN chain (or on the end with a custom terminator). For more details on wiring a single PCM, see [Pneumatics Control Module Power \(Optional\)](#)

Additional PCMs can be wired to a standard WAGO connector on the side of the PDP and protected with a 20A or smaller circuit breaker. Additional PCMs should also be placed anywhere in the middle of the CAN chain.

### **26.2.3 The Compressor**

The compressor can be wired directly to the Compressor Out connectors on the PCM. If additional length is required, make sure to use 18 AWG wire or larger for the extension.

### **26.2.4 The Pressure Switch**

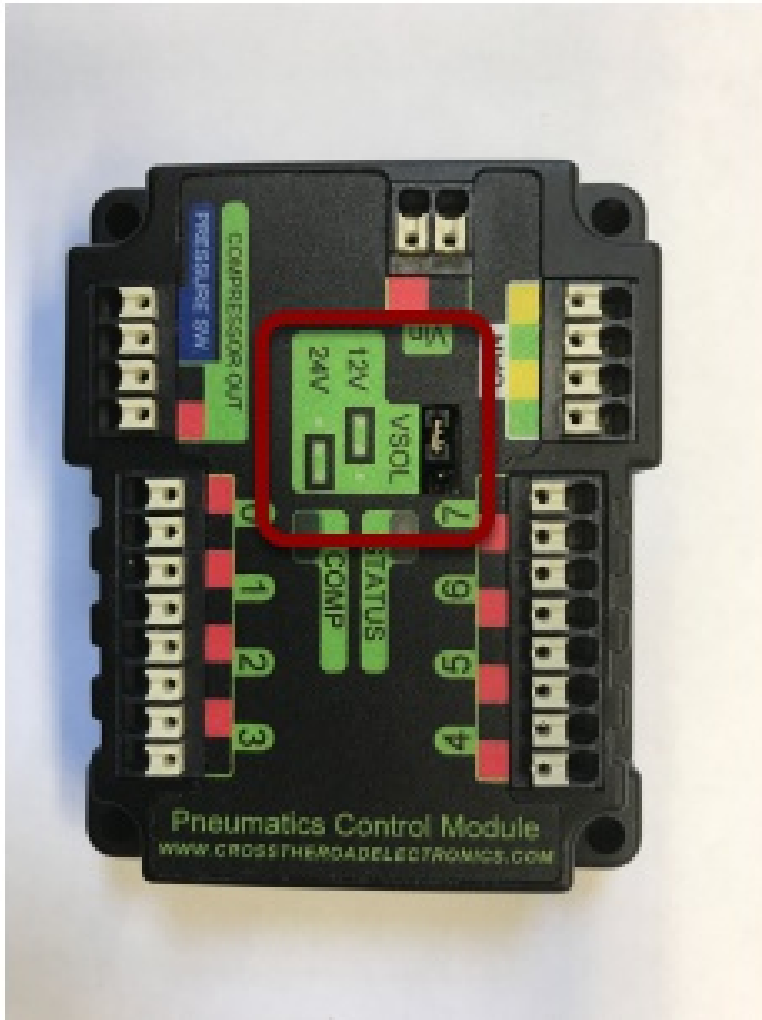
The pressure switch should be connected directly to the pressure switch input terminals on the PCM. There is no polarity on the input terminals or on the pressure switch itself, either terminal on the PCM can be connected to either terminal on the switch. Ring or spade terminals are recommended for the connection to the switch screws (note that the screws are slightly larger than #6, but can be threaded through a ring terminal with a hole for a #6 screw such as the terminals shown in the image).

### **26.2.5 Solenoids**

Each solenoid channel should be wired directly to a numbered pair of terminals on the PCM. A single acting solenoid will use one numbered terminal pair. A double acting solenoid will use two pairs. If your solenoid does not come with color coded wiring, check the datasheet to make sure to wire with the proper polarity.



### 26.2.6 Solenoid Voltage Jumper



The PCM is capable of powering either 12V or 24V solenoids, but all solenoids connected to a single PCM must be the same voltage. The PCM ships with the jumper in the 12V position as shown in the image. To use 24V solenoids move the jumper from the left two pins (as shown in the image) to the right two pins. The overlay on the PCM also indicates which position corresponds to which voltage. You may need to use a tool such as a small screwdriver, small pair of pliers, or a pair of tweezers to remove the jumper.

## 26.3 Status Light Quick Reference

Many of the components of the FRC Control System have indicator lights that can be used to quickly diagnose problems with your robot. This guide shows each of the hardware components and describes the meaning of the indicators. Photos and information from Innovation FIRST and Cross the Road Electronics.

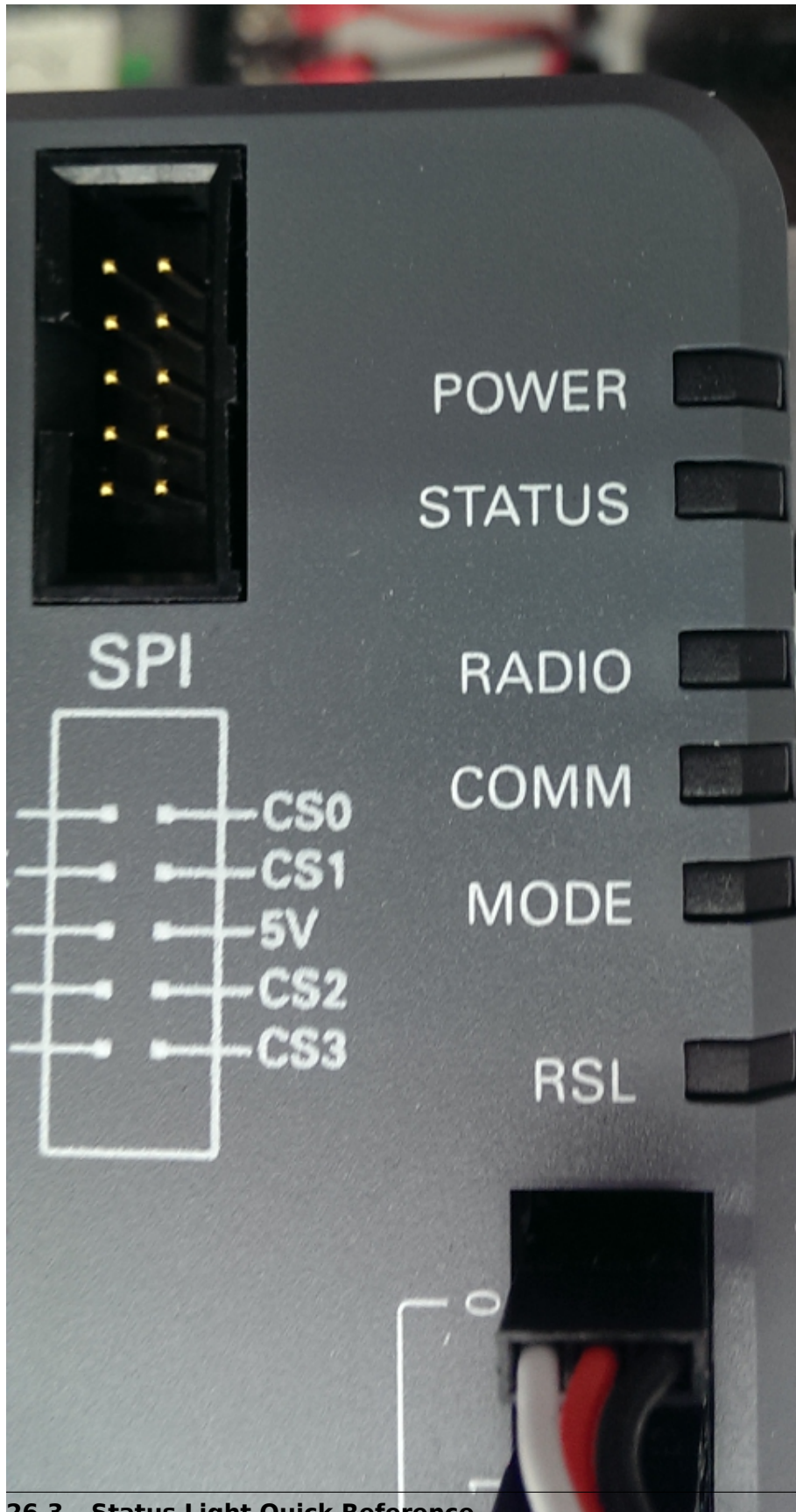
### 26.3.1 Robot Signal Light (RSL)



- Solid ON - Robot On and Disabled
- Blinking - Robot On and Enabled
- Off - Robot Off, roboRIO not powered or RSL not wired properly.



### 26.3.2 roboRIO



### roboRIO Power

- Green - Power is good
- Amber - Brownout protection tripped, outputs disabled
- Red - Power fault, check user rails for short circuit

### roboRIO Status

- On while the controller is booting, then should turn off
- 2 blinks - Software error, reimage roboRIO
- 3 blinks - Safe Mode, restart roboRIO, reimage if not resolved
- 4 blinks - Software crashed twice without rebooting, reboot roboRIO, reimage if not resolved
- Constant flash or stays solid on - Unrecoverable error

### roboRIO Radio

- Not currently implemented

### roboRIO Comm

- Off - No Communication
- Red Solid - Communication with DS, but no user code
- Red Blinking - E-stop
- Green Solid - Good communication with DS

### roboRIO Mode

- Off - Outputs disabled (robot in Disabled, brown-out, etc.)
- Amber/Orange - Autonomous Enabled
- Green - Teleop Enabled
- Red - Test Enabled

### roboRIO RSL

- See above

### 26.3.3 OpenMesh Radio

Power	
Blue	On or Powering Up
Blue Blinking	Powering Up
Eth Link	
Blue	Link Up
Blue Blinking	Traffic Present
WiFi	
	Bridge Mode, Unlinked or non-FRC firmware
Off	
Red	AP, Unlinked
Yellow\Orange	AP, Linked
Green	Bridge Mode, Linked

**WiFi light only works after radio has been power cycled.**



#### Radio Power

- Blue - On or Powering Up
- Blue Blinking - Powering Up

#### Radio Eth Link

- Blue - Link Up
- Blue Blinking - Link Up + Traffic Present

#### Radio WiFi

- Off - Bridge Mode Unlinked or Non-FRC Firmware
- Red - AP Mode Unlinked
- Yellow/Orange - AP Mode Linked
- Green - Bridge Mode Linked

## 26.3.4 Power Distribution Panel



LED Fault Table

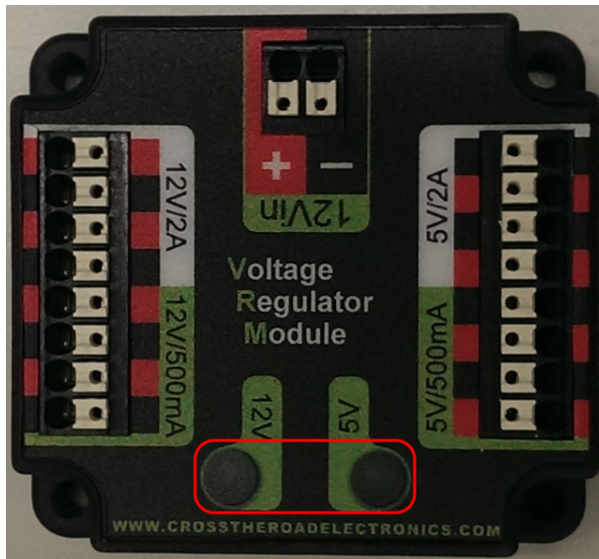
LED	Strobe	Slow	Long
Green	No Fault - Robot Enabled	No Fault - Robot Disabled	NA
Orange	NA	Sticky Fault	NA
Red	NA	No CAN Comm	NA

\*If PCM LED contains more than one color, see LED Special States Table

LED Special States Table

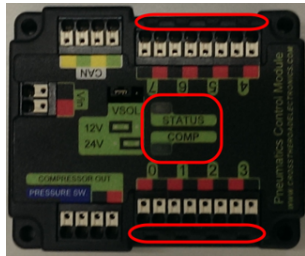
LED Colors	Problem
Red/ Orange	Damaged Hardware
Green/ Orange	In Bootloader
No LED	No Power / Incorrect Polarity

## 26.3.5 Voltage Regulator Module



The status LEDs on the VRM indicate the state of the two power supplies. If the supply is functioning properly the LED should be lit bright green. If the LED is not lit or is dim, the output may be shorted or drawing too much current.

### 26.3.6 Pneumatics Control Module (PCM)



**LED Fault Table**

LED	Strobe	Slow	Long
Green	No Fault - Robot Enabled	No Fault - Robot Disabled	NA
Orange	NA	Sticky Fault	NA
Red	NA	No CAN Comm OR Solenoid Fault (Blinks Solenoid Index)	Compressor Fault

\*If PCM LED contains more than one color, see LED Special States Table

**LED Special States Table**

LED Colors	Problem
Red/ Orange	Damaged Hardware
Green/ Orange	In Bootloader
No LED	No Power / Incorrect Polarity

**Solenoid Channel LEDs** - These LEDs are lit red if the Solenoid channel is enabled and not lit if it is disabled.

#### PCM Comp

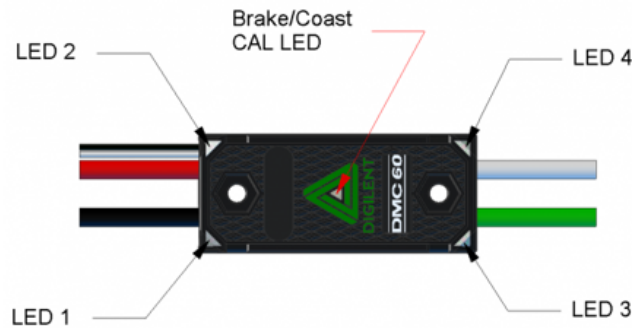
This is the Compressor LED. This LED is green when the compressor output is active (compressor is currently on) and off when the compressor output is not active.

#### PCM Status

The status LED indicates device status as indicated by the two tables above. For more information on resolving PCM faults see the PCM User Manual. Note that the No CAN Comm fault will not occur only if the device cannot see communicate with any other device, if the PCM and PDP can communicate with each other, but not the roboRIO you will NOT see a No Can Comm fault.



## 26.3.7 Digilent DMC-60



At power-on the RGB LEDs will display a progressive blue color, which continually gets brighter. This lasts for approximately five seconds. During this time the motor controller will not respond to an input signal, nor will the output drivers be enabled. After the initial power-on has completed the device will begin normal operation and what gets displayed on the RGB LEDs will be a function of the input signal being applied, as well as the current fault state. Assuming that no faults have occurred the RGB LEDs will function as follows:

Servo Input Signal Applied	LED State
No input signal or invalid input pulse width	Alternate between top (LED1 and LED2) and bottom (LED3 and LED4) LEDs being on and off. When on, the LEDs display color is orange.
Neutral input pulse width	All 4 LEDs on solid orange
Positive input pulse width	LEDs blink green in a clockwise circular pattern (LED1→LED2→LED3→LED4→LED1). The rate at which the LEDs update is proportional to the duty cycle of the output and increases with increased duty cycle. At 100% duty cycle, all four LEDs turn on solid green.
Negative input pulse width	LEDs blink red in a counter-clockwise circular pattern (LED1→LED4→LED3→LED2→LED1). The rate at which the LEDs update is proportional to the duty cycle of the output and increases with increased duty cycle. At 100% duty cycle, all four LEDs turn on solid red.

### 9 Fault Indicators

When a fault condition is detected the output duty cycle is reduced to 0% and a fault is signaled. The output will remain disabled for 3 seconds. During this time the onboard LEDs (LED1, LED2, LED3, and LED4) are used to indicate the fault condition. The fault condition is indicated by toggling between the top (LED1 and LED2) and bottom (LED3 and LED4) LEDs being on and off. The top LEDs will be Red during them on state. The color of the bottom LEDs depends on which faults are presently active. The table below describes how the color of the bottom LEDs maps to the presently active faults.

Color	Over Temperature	Under Voltage
Green	✓	X
Blue	X	✓
Cyan/Aqua	✓	✓

When the center LED is off the device is operating in coast mode. When the center LED is illuminated the device is operating in brake mode. The Brake/Coast mode can be toggled by pressing down on the center of the triangle and then releasing the button.

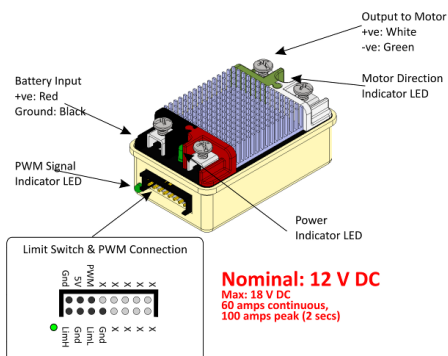
## 26.3.8 Jaguar speed controllers



LED State	Module Status
<b>Normal Operating Conditions</b>	
Solid Yellow	Neutral (speed set to 0)
Fast Flashing Green	Forward
Fast Flashing Red	Reverse
Solid Green	Full-speed forward
Solid Red	Full-speed reverse
<b>Fault Conditions</b>	
Slow Flashing Yellow	Loss of servo or Network link
Fast Flashing Yellow	Invalid CAN ID
Slow Flashing Red	Voltage, Temperature, or Limit Switch fault condition
Slow Flashing Red and Yellow	Current fault condition

LED State	Module Status
<b>Calibration Conditions</b>	
Fast Flashing Red and Green	Calibration mode active
Fast Flashing Red and Yellow	Calibration mode failure
Slow Flashing Green and Yellow	Calibration mode success
Slow Flashing Red and Green	Calibration mode reset to factory default settings success
<b>Other Conditions</b>	
Slow Flashing Green	Waiting in CAN Assignment mode

## 26.3.9 Mindsensors SD 540



### Power LED

This LED will turn Red when Power is supplied.

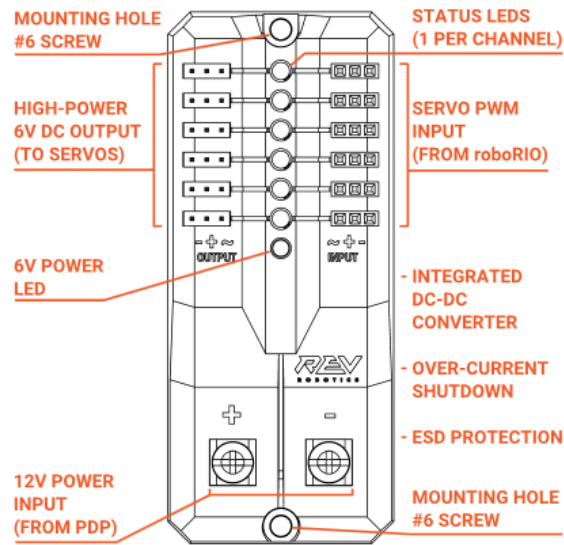
### Motor LED

This LED turns Red in Forward direction and Green in Reverse direction.

### PWM Signal LED

This LED turns Red when no valid PWM signal is detected, and turns Green when valid PWM signal is detected.

## 26.3.10 REV Robotics Servo Power Module



### STATUS LEDs

Each channel has a corresponding status LED that will indicate the sensed state of the connected PWM signal. The table below describes each state's corresponding LED pattern.

State	Pattern
No Signal	Blinking Amber
Left/Reverse Signal	Solid Red
Center/Neutral Signal	Solid Amber
Right/Forward Signal	Solid Green

- 6V Power LED off, dim or flickering with power applied = Over-current shutdown

## 26.3.11 REV Robotics SPARK

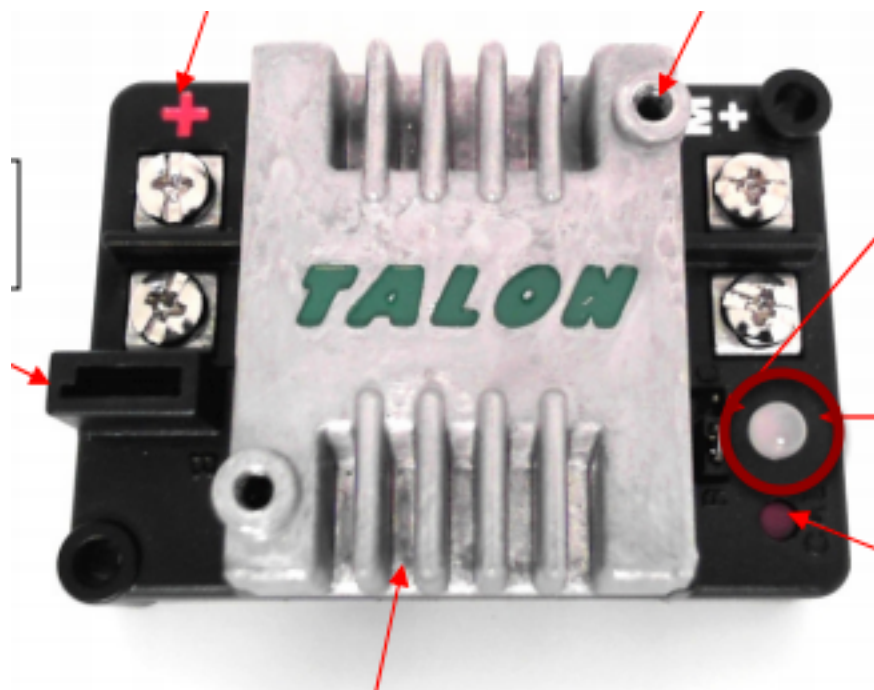
### 2.6 STATUS LED

The SPARK can display information about its current mode of operation via its tri-colored STATUS LED. The STATUS LED is located next to the motor output terminals and is labeled as STATUS with raised lettering on the SPARK housing.

Figure 2-6 shows the status codes associated with each operating state of the SPARK.

Time Scale		LED Status Code	
		1 second	1 second
State		Normal Operation	
No Signal	Brake		
	Coast		
Full Forward			
Proportional Forward			
Neutral	Brake		
	Coast		
Proportional Reverse			
Full Reverse			
Forward Limit Tripped			
Reverse Limit Tripped			
		Calibration	
Calibration Mode			
Successful Calibration			
Failed Calibration			
		Factory Reset	
Reset to Factory Defaults		Mode button held during power up	Mode button released
			

## 26.3.12 Talon speed controllers



The LED is used to indicate the direction and percentage of throttle and state of calibration. The LED may be one of three colors; red, orange or green. A solid green LED indicates positive output voltage equal to the input voltage of the Talon. A solid Red LED indicates an output voltage that is equal to the input voltage multiplied by -1(input voltage = 12 volts, output equals -12 volts). The LED will blink it's corresponding color for any throttle less than 100% (red indicates negative polarity, green indicates positive). The rate at which the led blinks is proportional to the percent throttle. The faster the LED blinks the closer the output

is to 100% in either polarity.

The LED will blink orange any time the Talon is in the disabled state. This will happen if the PWM input signal is lost, or in FRC, when the robot is disabled. If the Talon is in the enabled state and the throttle is within the 4% dead band, the LED will remain solid orange.

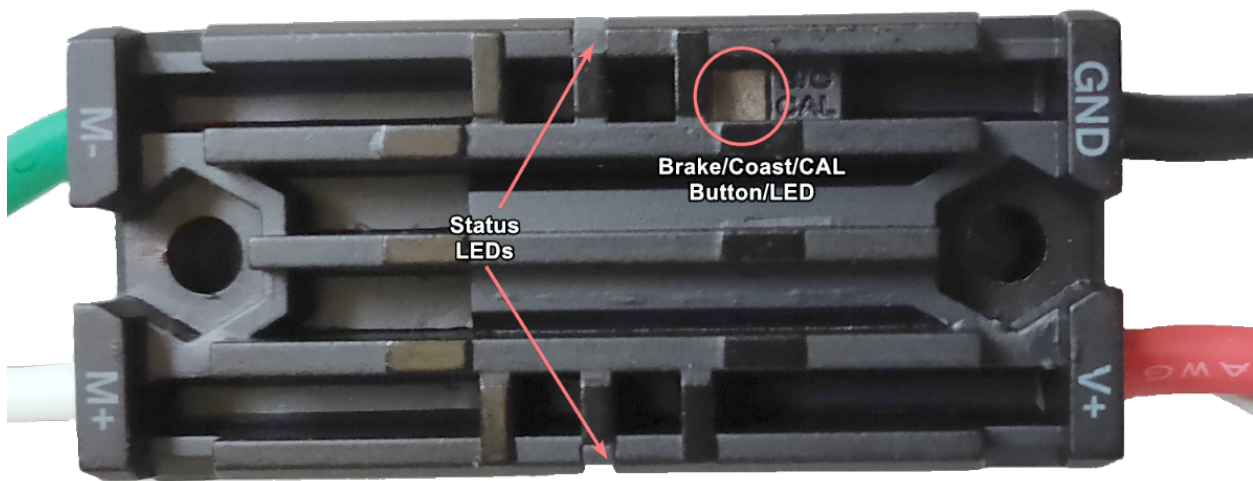
Flashing Red/Green indicate ready for calibration. Several green flashes indicates successful calibration, and red several times indicates unsuccessful calibration.

### 26.3.13 Victor speed controllers

#### LED Indicator Status:

- Green - full forward
- Orange - neutral / brake
- Red - full reverse
- Flashing orange - no PWM signal
- Flashing red/green - calibration mode
- Flashing green - successful calibration
- Flashing red - unsuccessful calibration

### 26.3.14 Victor-SP speed controllers



Brake/Coast/Cal Button/LED - Red if the controller is in brake mode, off if the controller is in coast mode

#### Status

The Status LEDs are used to indicate the direction and percentage of throttle and state of calibration. The LEDs may be one of three colors; red, orange or green. Solid green LEDs

indicate positive output voltage equal to the input voltage of the Victor-SP. Solid Red LEDs indicate an output voltage that is equal to the input voltage multiplied by -1(input voltage = 12 volts, output equals -12 volts). The LEDs will blink in the corresponding color for any throttle less than 100% (red indicates negative polarity, green indicates positive). The rate at which the LEDs blink is proportional to the percent throttle. The faster the LEDs blink the closer the output is to 100% in either polarity.

The LEDs will blink orange any time the Victor-SP is in the disabled state. This will happen if the PWM input signal is lost, or in FRC, when the robot is disabled. If the Victor-SP is in the enabled state and the throttle is within the 4% dead band, the LED will remain solid orange.

Flashing Red/Green indicate ready for calibration. Several green flashes indicates successful calibration, and red several times indicates unsuccessful calibration.

### 26.3.15 Talon-SRX speed controllers

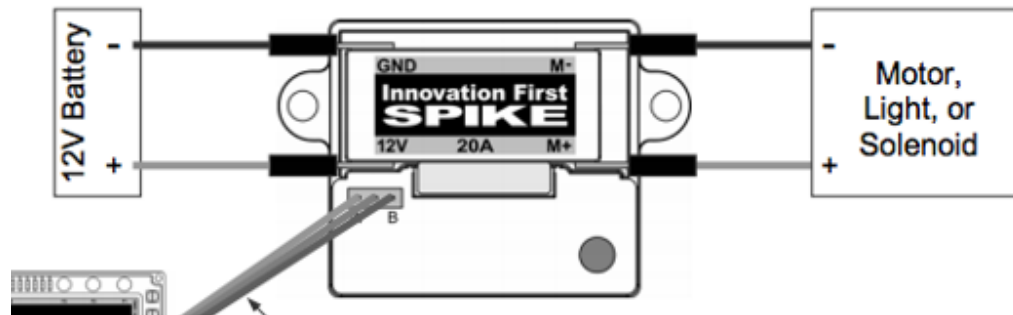
Blink Codes During Calibration	
Status LEDs Blink Code	Talon SRX State
Flashing Red/Green	Calibration Mode
Blinking Green	Successful Calibration
Blinking Red	Failed Calibration

Blink Codes During Normal Operation		
LEDs	Colors	Talon SRX State
Both	Blinking Green	Forward throttle is applied. Blink rate is proportional to Duty Cycle
Both	Blinking Red	Reverse throttle is applied. Blink rate is proportional to Duty Cycle
None	None	No Power is being applied to Talon SRX
LEDs Alternate <sup>1</sup>	Off/Orange	CAN bus detected, robot disabled
LEDs Alternate <sup>1</sup>	Off/Slow Red	CAN bus/PWM is not detected
LEDs Alternate <sup>1</sup>	Off/Fast Red	Fault Detected
LEDs Alternate <sup>1</sup>	Red/Orange	Damaged Hardware
LEDs Strobe "towards" (M+) <sup>2</sup>	Off/Red	Forward Limit Switch or Forward Soft Limit
LEDs Strobe "towards" (M-) <sup>2</sup>	Off/Red	Reverse Limit Switch or Reverse Soft Limit
LED1 Only "closest" to M+/V+	Green/Orange	In Boot-loader

B/C CAL Blink Codes	
B/C CAL Button Color	Talon SRX State
Solid Red	Brake Mode
Off	Coast Mode



### 26.3.16 Spike relay configured as a motor, light, or solenoid switch

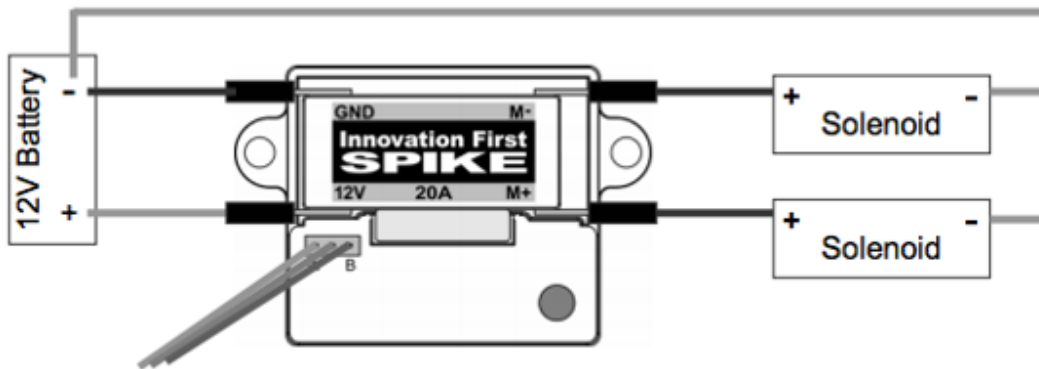


INPUTS		OUTPUTS		Indicator	Motor Function
Fwd(Wht)	Rev(Red)	M+	M-		
0	0	GND	GND	Orange	OFF / Brake Condition (default)
1	0	+12v	GND	Green	Motor rotates in one direction
0	1	GND	+12v	Red	Motor rotates in opposite direction
1	1	+12v	+12v	Off	OFF / Brake Condition

Notes:

1. 'Brake' refers to the dynamic stopping of the motor due to the shorting of the motor inputs. This condition is not optional when going to an off state.
2. The INPUT Fwd and Rev are defined as follows: 0 (Off) and 1 (On).

### 26.3.17 Spike relay configured as for one or two solenoids



INPUT		OUTPUTS		Indicator	Solenoid Function
Fwd(Wht)	Rev(Red)	M+	M-		
0	0	GND	GND	Orange	Both Solenoids OFF (default)
1	0	+12v	GND	Green	Solenoid connected to M+ is ON
0	1	GND	+12v	Red	Solenoid connected to M- is ON
1	1	+12v	+12v	Off	Both Solenoids ON

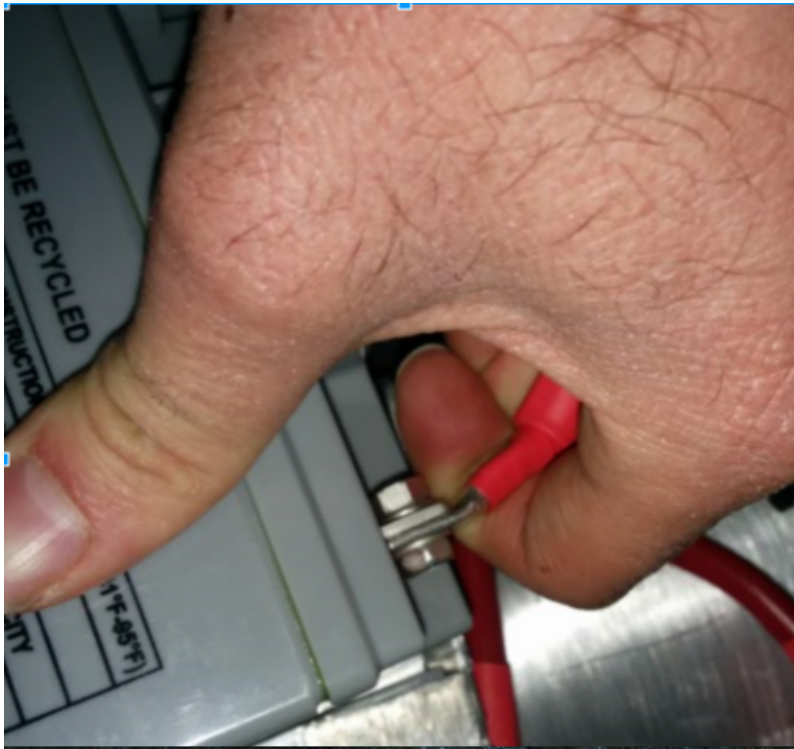
Note:

1. The INPUT Fwd and Rev are defined as follows: 0 (Off) and 1 (On).

## 26.4 Robot Preemptive Troubleshooting

**Note:** In *FIRST*® Robotics Competition, robots take a lot of stress while driving around the field. It is important to make sure that connections are tight, parts are bolted securely in place and that everything is mounted so that a robot bouncing around the field does not break.

### 26.4.1 Check battery connections



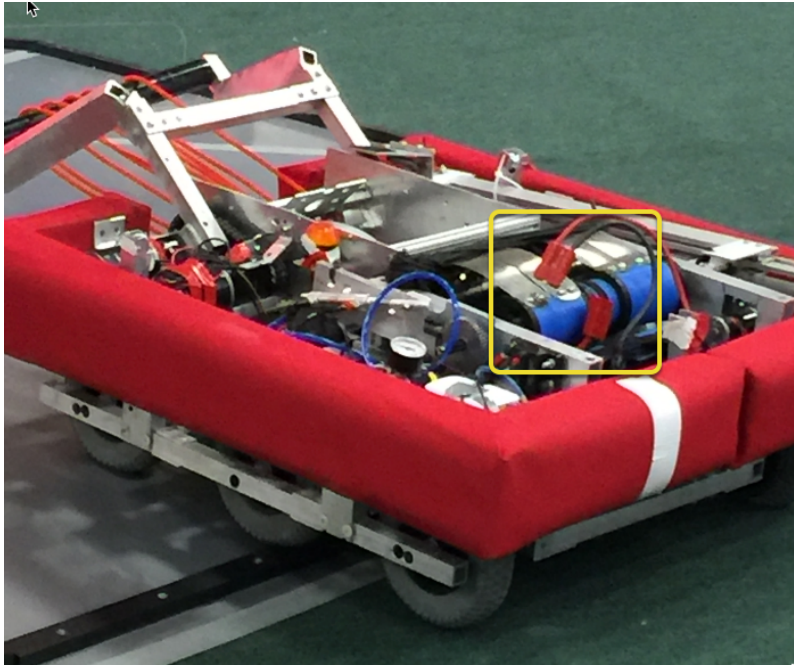
The tape that should be covering the battery connection in these examples has been removed to illustrate what is going on. On your robots, the connections should be covered.

Wiggle battery harness connector. Often these are loose because the screws loosen, or sometimes the crimp is not completely closed. You will only catch the really bad ones though because often the electrical tape stiffens the connection to a point where it feels stiff. Using a voltmeter or Battery Beak will help with this.

Apply considerable force onto the battery cable at 90 degrees to try to move the direction of the cable leaving the battery, if successful the connection was not tight enough to begin with and it should be redone.



### 26.4.2 Secure the battery to robot connection



In almost every event we see at least one robot where a not properly secured battery connector (the large Anderson) comes apart and disconnects power from the robot. This has happened in championship matches on the Einstein and everywhere else. Its an easy to ensure that this doesn't happen to you by securing the two connectors by wrapping a tie wrap around the connection. 10 or 12 tie wraps for the piece of mind during an event is not a high price to pay to guarantee that you will not have the problem of this robot from an actual event after a bumpy ride over a defense.

### 26.4.3 120 Amp circuit breaker



Apply a twisting force onto the cable to rotate the harness. If you are successful then the screw is not tight enough. Split washers might help here, but in the mean time, these require checking every few matches.

Because the metal is just molded into the case, every once in awhile you will break off the bolt, ask any veteran team and they'll tell you they go through a number of these every few seasons. After tightening the nut, retest by once again trying to twist the cable.

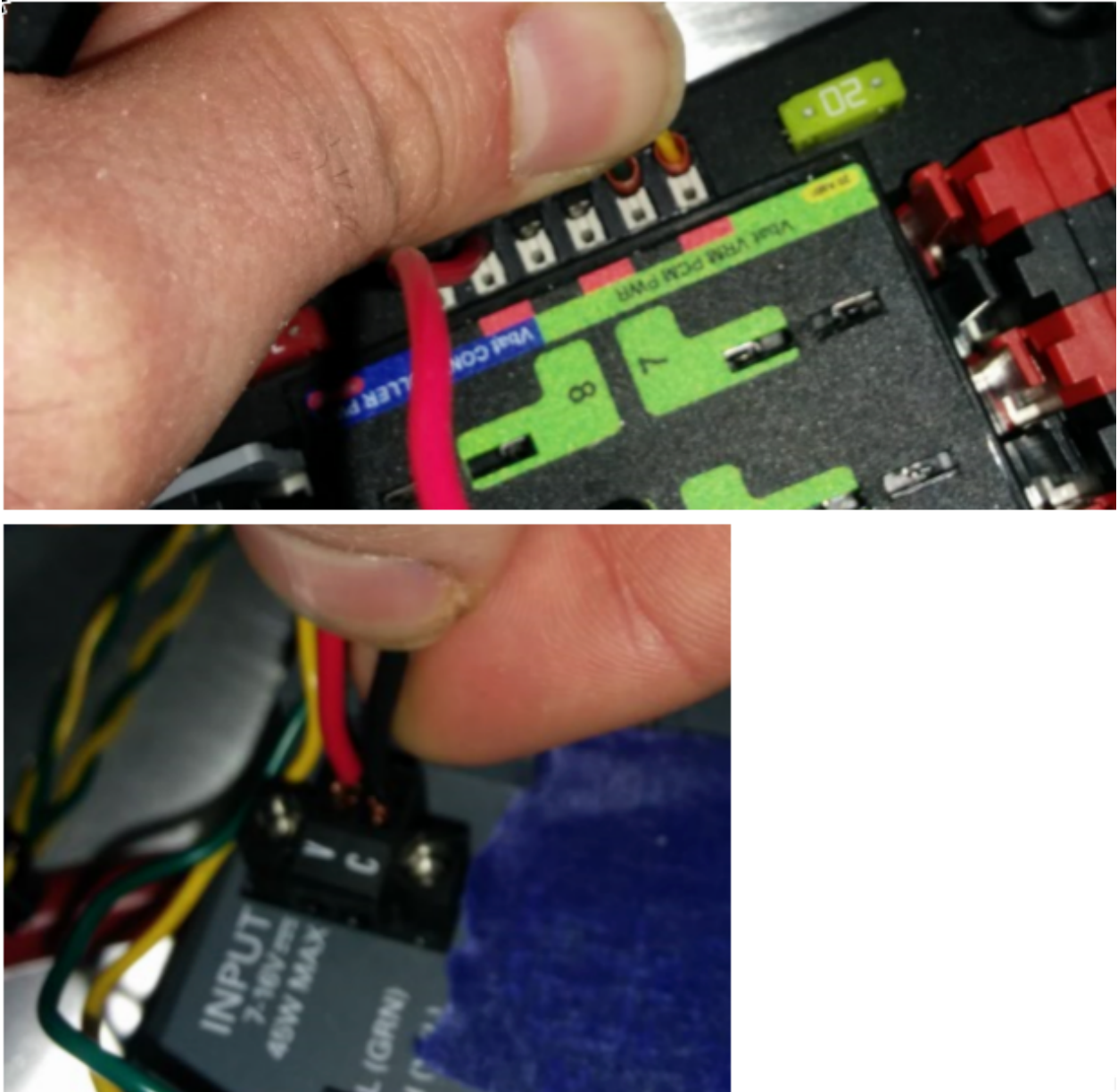
#### 26.4.4 Power Distribution Panel (PDP)



Just by removing the battery cover, often you can confirm the washer.

Make sure that split washers were placed under the PDP screws, but it is not easy to visually confirm, and sometimes you can't. You can check by removing the case. Also if you squeeze the red and black wires together, sometimes you can catch the really loose connections.

### 26.4.5 Tug test everything



The Weidmuller contacts for power, compressor output, roboRIO power connector, and radio power are important to verify by tugging on the connections as shown. Make sure that none of the connections pull out.

Look for possible or impending shorts with Weidmuller connections that are close to each other, and have too-long wire-lead lengths (wires that are stripped extra long).

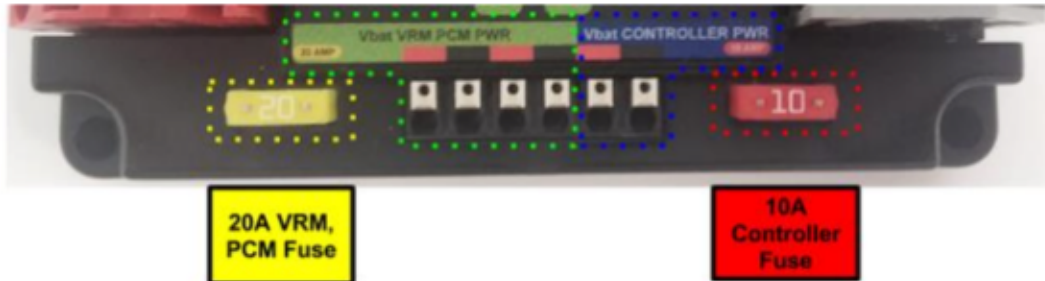
Spade connectors can also fail due to improper crimps, so tug-test those as well.



## 26.4.6 Blade fuses

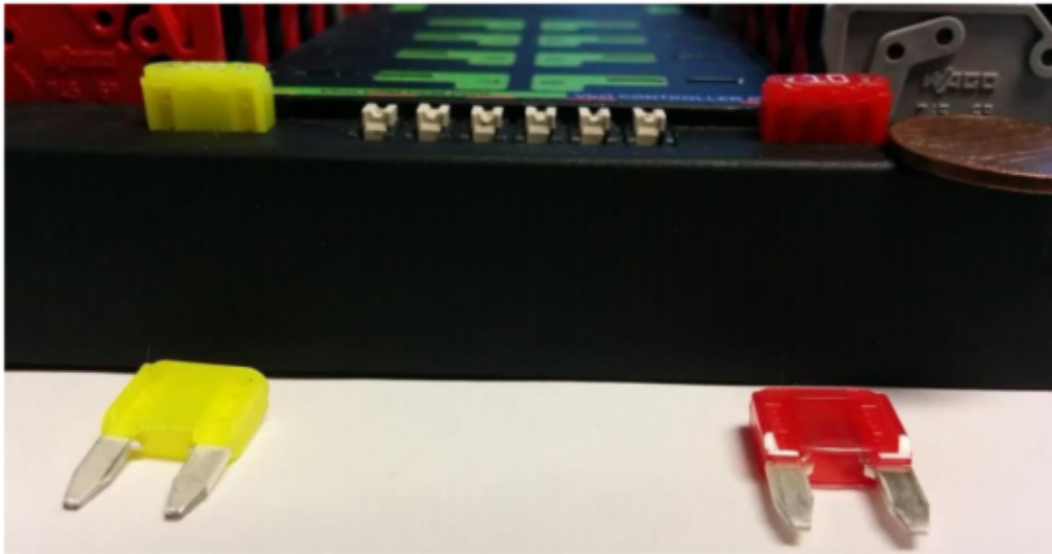


### 2.4. Blade Fuse



Be sure to place the 20A fuse (yellow) on the left and the 10A fuse (red) on the right.

**Warning:** Also take care to ensure **fuses are fully seated** into the fuse holders. The fuses should descend **at least** as far as the figure below (different brand fuses have different lead lengths). It should be **nearly impossible to remove the fuse** with bare hands (without the use of pliers). If this is not properly done, the robot/radio may exhibit **intermittent connectivity issues**.



If you can remove the blade fuses by hand then they are not in completely. Make sure that they are completely seated in the PDP so that they don't pop out during robot operation.

## 26.4.7 roboRIO swarf

Swarf is: fine chips or filings of stone, metal, or other material produced by a machining operation. Often modifications must be made to a robot while the control system parts are in place. The circuit board for the roboRIO is conformally coated, but that doesn't absolutely guarantee that metal chips won't short out traces or components inside the case. In this case, you must exercise care in making sure that none of the chips end up in the roboRIO or any of the other components. In particular, the exposed 3 pin headers are a place where chips

can enter the case. A quick sweep through each of the four sides with a flashlight is usually sufficient to find the really bad areas of infiltration.

### **26.4.8 Radio barrel jack**

Make sure the correct barrel jack is used, not one that is too small and falls out for no reason. This isn't common, but ask an FTA and every once in awhile a team will use some random barrel jack that is not sized correctly, and it falls out in a match on first contact.

### **26.4.9 Ethernet cable**

If the RIO to radio ethernet cable is missing the clip that locks the connector in, get another cable. This is a common problem that will happen several times in every competition. Make sure that your cables are secure. The clip often breaks off, especially when pulling it through a tight path, it snags on something then breaks.

### **26.4.10 Cable slack**

Cables must be tightened down, particularly the radio power and ethernet cable. The radio power cables don't have a lot of friction force and will fall out (even if it is the correct barrel) if the weight of the cable-slack is allowed to swing freely.

Ethernet cable is also pretty heavy, if it's allowed to swing freely, the plastic clip may not be enough to hold the ethernet pin connectors in circuit.

### **26.4.11 Reproducing problems in the pit**

Beyond the normal shaking and rattling of all cables while the robot is power and tethered, you might try picking up one side of the robot off the ground and drop it, and see if you lose connection. The driving on the field, especially when trying to breach defenses will often be very violent. It's better to see it fail in the pit rather than in a critical match.

When doing this test it's important to be ethernet tethered and not USB tethered, otherwise you are not testing all of the critical paths. Check firmware and versions

Robot inspectors do this, but you should do it as well, it helps robot inspectors out and they appreciate it. And it guarantees that you are running with the most recent, bug fixed code. You wouldn't want to lose a match because of an out of date piece of control system software on your robot.

### **26.4.12 Driver station checks**

We often see problems with the Drivers Station. You should:

- ALWAYS bring the laptop power cable to the field, it doesn't matter how good the battery is, you are allowed to plug in at the field.
- Check the power and sleep settings, turn off sleep and hibernate, screen savers, etc.
- Turn off power management for USB devices (dev manager)

- Turn off power management for ethernet ports (dev manager)
- Turn off windows defender
- Turn off firewall
- Close all apps except for DS/Dashboard when out on the field.
- Verify that there is nothing unnecessary running in the application tray in the start menu (bottom right side)

### 26.4.13 Handy tools



There never seems to be enough light inside robots, at least not enough to scrutinize the critical connection points, so consider using a handheld LED flashlight to inspect the connections on your robot. They're available from home depot or any hardware/automotive store.

A WAGO tool is nice tool for redoing Weidmuller connections with stranded wires. Often I'll do one to show the team, and then have them do the rest using the WAGO tool to press down the white-plunger while they insert the stranded wire. The angle of the WAGO tool makes this particularly helpful.

## 27.1 Sensor Overview - Hardware

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**Note:** This section covers sensor hardware, not the use of sensors in code. For a software sensor guide, see [Sensor Overview - Software](#).

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In order to be effective, it is often vital for robots to be able to gather information about their surroundings. Devices that provide feedback to the robot on the state of its environment are called “sensors.” There are a large variety of sensors available to FRC teams, for measuring everything from on-field positioning to robot orientation to motor/mechanism positioning. Making use of sensors is an absolutely crucial skill for on-field success; while most FRC games do have tasks that can be accomplished by a “blind” robot, the best robots rely heavily on sensors to accomplish game tasks as quickly and reliably as possible.

Additionally, sensors can be extremely important for robot safety - many robot mechanisms are capable of breaking themselves if used incorrectly. Sensors provide a safeguard against this, allowing robots to, for example, disable a motor if a mechanism is against a hard-stop.

### 27.1.1 Types of sensors

Sensors used in FRC can be generally categorized in two different ways: by function, and by communication protocol. The former categorization is relevant for robot design; the latter for wiring and programming.

#### Sensors by function

Sensors can provide feedback on a variety of different aspects of the robot’s state. Sensor functions common to FRC include:

- [Proximity switches](#)
  - Mechanical proximity switches (“limit switches”)
  - Magnetic proximity switches
  - Inductive proximity switches



- Photoelectric proximity switches
- Distance sensors
  - *Ultrasonic sensors*
  - *Triangulating rangefinders*
  - *LIDAR*
- Shaft rotation sensors
  - *Encoders*
  - *Potentiometers*
- *Accelerometers*
- *Gyroscopes*

### Sensors by communication protocol

In order for a sensor to be useful, it must be able to “talk” to the roboRIO. There are three main methods by which sensors can communicate their readings to the roboRIO:

- *Analog input*
- *Digital input*
- *Serial bus*
  - SPI
  - I2C
  - RS232
  - USB

In general, support for sensors that communicate via analog and digital inputs is straightforward, while communication over serial bus is more complicated.

## 27.2 Analog Inputs - Hardware

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**Note:** This section covers analog input hardware. For a software guide to analog inputs, see *Analog Inputs - Software*.

---

An **analog signal** is a signal whose value can lie anywhere in a continuous interval. This lies in stark contrast to a **digital signal**, which can take only one of several discrete values. The roboRIO’s analog input ports allow the measurement of analog signals with values from 0V to 5V.

In practice, there is no way to measure a “true” analog signal with a digital device such as a computer (like the roboRIO). Accordingly, the analog inputs are actually measured as a 12-bit digital signal - however, this is quite a high resolution<sup>1</sup>.

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<sup>1</sup> A 12-bit resolution yields  $2^{12}$ , or 4096 different values. For a 5V range, that’s an effective resolution of approximately 1.2 mV, or .0012V. The actual accuracy specification is plus-or-minus 50mV, so the discretization is not the limiting factor in the measurement accuracy.

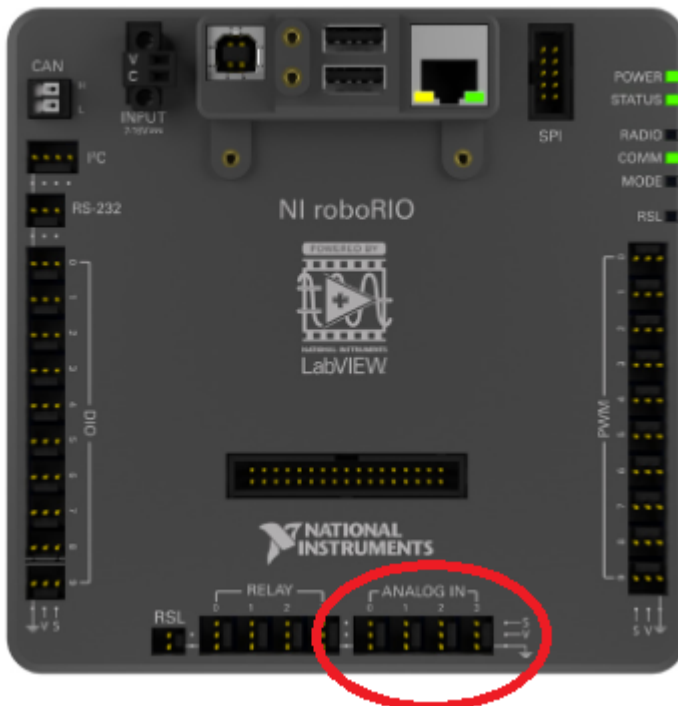
Analog inputs are typically (but not always!) used for sensors whose measurements vary continuously over a range, such as *ultrasonic rangefinders* and *potentiometers*, as they can communicate by outputting a voltage proportional to their measurements.

### 27.2.1 Connecting to roboRIO analog input ports

**Note:** An additional four analog inputs are available via the “MXP” expansion port. To use these, a breakout board of some sort that connects to the MXP is needed.

**Warning:** Always consult the technical specifications of the sensor you are using *before* wiring the sensor, to ensure that the correct wire is being connected to each pin. Failure to do so can result in damage to the sensor or the RIO.

**Warning:** **Never** directly connect the power pin to the ground pin on any port on the roboRIO! This will trigger protection features on the roboRIO and may result in unexpected behavior.



The roboRIO has 4 built-in analog input ports (numbered 0-3), as seen in the image above. Each port has three pins - signal (“S”), power (“V”), and ground (“G”). The “power” and “ground” pins are used to power the peripheral sensors that connect to the analog input ports - there is a constant 5V potential difference between the “power” and the “ground”

pins<sup>2</sup>. The signal pin is the pin on which the signal is actually measured.

### Connecting a sensor to a single analog input port

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**Note:** Some simple sensors (such as *potentiometers*) may have interchangeable power and ground connections.

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Most sensors that connect to analog input ports will have three wires - signal, power, and ground - corresponding precisely to the three pins of the analog input ports. They should be connected accordingly.

### Connecting a sensor to multiple analog input ports

Some sensors may need to connect to multiple analog input ports in order to function. In general, these sensors will only ever require a single power and a single ground pin - only the signal pin of the additional port(s) will be needed.

## 27.2.2 Footnotes

## 27.3 Analog Potentiometers - Hardware

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**Note:** This section covers analog potentiometer hardware. For a software guide to analog potentiometers, see *Analog Potentiometers - Software*.

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**Warning:** Potentiometers generally have a mechanically-limited travel range. Users should be careful that their mechanisms do not turn their potentiometers past their maximum travel, as this will damage or destroy the potentiometer.

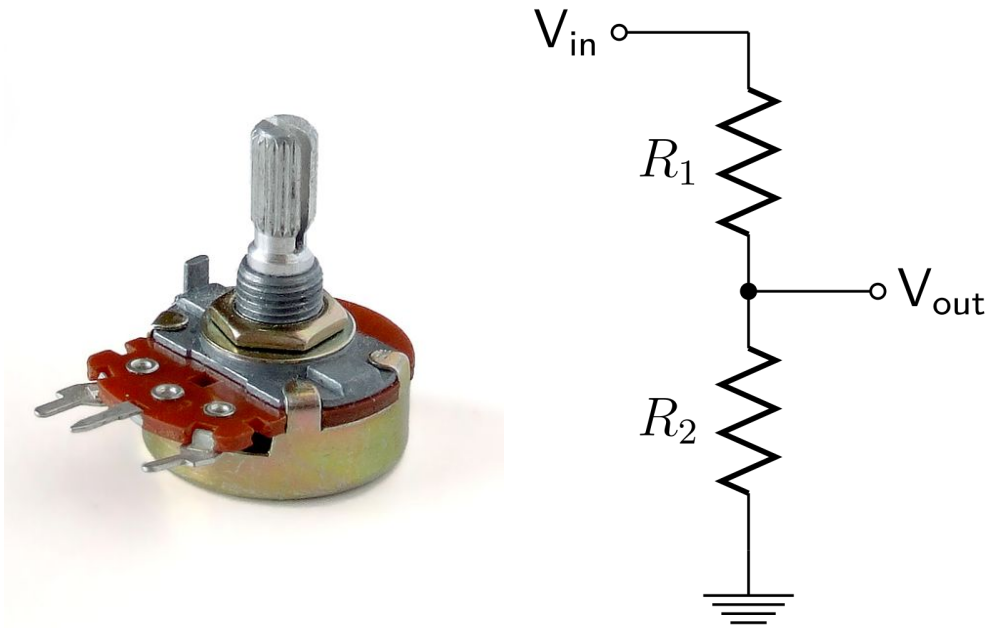
Apart from *quadrature encoders*, another common way of measuring rotation on FRC robots is with analog potentiometers. A potentiometer is simply a variable resistor - as the shaft of the potentiometer turns, the resistance changes (usually linearly). Placing this resistor in a *voltage divider* allows the user to easily measure the resistance by measuring the voltage across the potentiometer, which can then be used to calculate the rotational position of the shaft.

### 27.3.1 Wiring an analog potentiometer

As suggested by the names, analog potentiometers connect to the roboRIO's *analog input* ports. To understand how exactly to wire potentiometers, however, it is important to understand their internal circuitry.

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<sup>2</sup> All power pins are actually connected to a single rail, as are all ground pins - there is no need to use the power/ground pins corresponding to a given signal pin.



The picture above on the left shows a typical potentiometer. There are three pins, just as there are on the RIO's analog inputs. The middle pin is the signal pin, while the outer pins can both be *either* power or ground.

As mentioned before, a potentiometer is a voltage divider, as shown in the circuit diagram on the right. As the potentiometer shaft turns, the resistances  $R_1$  and  $R_2$  change; however, their sum remains constant<sup>1</sup>. Thus, the voltage across the entire potentiometer remains constant (for the roboRIO, this would be 5 volts), but the voltage between the signal pin and either the voltage or ground pin varies linearly as the shaft turns.

Since the circuit is symmetric, it is reversible - this allows the user to choose at which end of the travel the measured voltage is zero, and at which end it is 5 volts. To reverse the directionality of the sensor, it can simply be wired backwards! Be sure to check the directionality of your potentiometer with a multimeter to be sure it is in the desired orientation before soldering your wires to the contacts.

### 27.3.2 Absolute encoders

An “absolute encoder” is an encoder that measures the absolute position of the encoder shaft, rather than the incremental movement (as a *quadrature encoder*) does. In this respect, absolute encoders are more similar to potentiometers than to incremental encoders. Many absolute encoders offer a simple analog output - these can be used exactly in the same way as a potentiometer, except their wiring is not generally reversible. Absolute encoders have the advantage of lacking a hard travel limit - the signal will simply reset when the shaft crosses the zero point.

Absolute encoders that do not offer a simple analog output require *more complicated communications with the RIO*.

<sup>1</sup> The way this actually works is generally by having the shaft control the position of a contact along a resistive “wiper” of fixed length along which the current flows - the resistance is proportional to the length of wiper between the contact and the end of the wiper.

### 27.3.3 Footnotes

## 27.4 Digital Inputs - Hardware

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**Note:** This section covers digital input hardware. For a software guide to digital inputs, see *Digital Inputs - Software*.

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A **digital signal** is a signal that can be in one of several discrete states. In the vast majority of cases, the signal is the voltage in a wire, and there are only two states for a digital signal - high, or low (also denoted 1 and 0, or true and false, respectively).

The roboRIO's built-in digital input-output ports (or "DIO") ports function on 5V, so "high" corresponds to a signal of 5V, and "low" to a signal of 0V<sup>12</sup>.

### 27.4.1 Connecting to the roboRIO DIO ports

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**Note:** Additional DIO ports are available through the "MXP" expansion port. To use these, a breakout board of some sort that connects to the MXP is needed.

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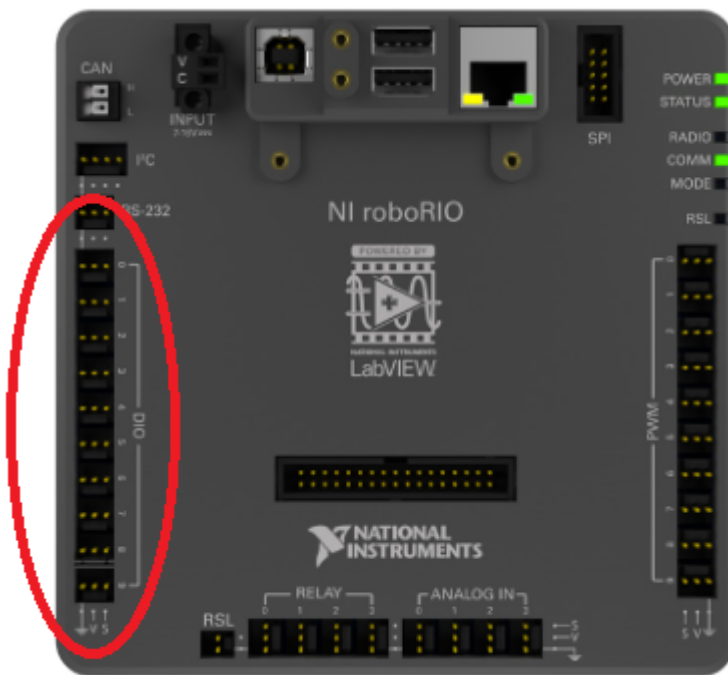
**Warning:** Always consult the technical specifications of the sensor you are using *before* wiring the sensor, to ensure that the correct wire is being connected to each pin. Failure to do so can result in damage to the device.

**Warning:** **Never** directly connect the power pin to the ground pin on any port on the roboRIO! This will trigger protection features on the roboRIO and may result in unexpected behavior.

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<sup>1</sup> More-precisely, the signal reads "high" when it rises above 2.0V, and reads "low" when it falls back below 0.8V - behavior between these two thresholds is not guaranteed to be consistent.

<sup>2</sup> The roboRIO also offers 3.3V logic via the "MXP" expansion port; however, use of this is far less-common than the 5V.



The roboRIO has 10 built-in DIO ports (numbered 0-9), as seen in the image above. Each port has three pins - signal ("S"), power ("V"), and ground ("G"). The "power" and "ground" pins are used to power the peripheral sensors that connect to the DIO ports - there is a constant 5V potential difference between the "power" and the "ground" pins<sup>3</sup> - the "power" pin corresponds to the "high" state (5V), and the "ground" to "low" (0V). The signal pin is the pin on which the signal is actually measured (or, when used as an output, the pin that sends the signal).

All DIO ports have built in "pull-up" resistors between the power pins and the signal pins - these ensure that when the signal pin is "floating" (i.e. is not connected to any circuit), they consistently remain in a "high" state.

### Connecting a simple switch to a DIO port

The simplest device that can be connected to a DIO port is a switch (such as a *limit switch*). When a switch is connected correctly to a DIO port, the port will read "high" when the circuit is open, and "low" when the circuit is closed.

A simple switch does not need to be powered, and thus only has two wires. Switches should be wired between the *signal* and the *ground* pins of the DIO port. When the switch circuit is open, the signal pin will float, and the pull-up resistor will ensure that it reads "high." When the switch circuit is closed, it will connect directly to the ground rail, and thus read "low."

<sup>3</sup> All power pins are actually connected to a single rail, as are all ground pins - there is no need to use the power/ground pins corresponding to a given signal pin.

### Connecting a powered sensor to a DIO port

Many digital sensors (such as most no-contact proximity switches) require power in order to work. A powered sensor will generally have three wires - signal, power, and ground. These should be connected to the corresponding pins of the DIO port.

### Connecting a sensor that uses multiple DIO ports

Some sensors (such as *quadrature encoders*) may need to connect to multiple DIO ports in order to function. In general, these sensors will only ever require a single power and a single ground pin - only the signal pin of the additional port(s) will be needed.

## 27.4.2 Footnotes

## 27.5 Proximity Switches - Hardware

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**Note:** This section covers proximity switch hardware. For a guide to using proximity switches in software, see *Digital Inputs - Software*.

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One of the most common sensing tasks on a robot is detecting when an object (be it a mechanism, game piece, or field element) is within a certain distance of a known point on the robot. This type of sensing is accomplished by a “proximity switch.”

### 27.5.1 Proximity switch operation

Proximity switches are switches - they operate a circuit between an “open” state (in which there is *not* connectivity across the circuit) and a “closed” one (in which there *is*). Thus, proximity switches generate a digital signal, and accordingly, they are almost always connected to the roboRIO’s *digital input* ports.

Proximity switches can be either “normally-open,” in which activating the switch closes the circuit, or “normally closed,” in which activating the switch opens the circuit. Some switches offer *both* a NO and a NC circuit connected to the same switch. In practice, the effective difference between a NO and a NC switch is the behavior of the system in the case that the wiring to the switch fails, as a wiring failure will almost always result in an open circuit. NO switches are often “safer,” in that a wiring failure causes the system to behave as if the switch were pressed - as switches are often used to prevent a mechanism from damaging itself, this mitigates the chance of damage to the mechanism in the case of a wiring fault.

### 27.5.2 Types of proximity switches

There are several types of proximity switches that are commonly-used in FRC:

- *Mechanical proximity switches (“limit switches”)*
- *Magnetic proximity switches*
- *Inductive proximity switches*

- *Photoelectric proximity switches*

### **Mechanical proximity switches (“limit switches”)**

Mechanical proximity switches (more commonly known as “limit switches”) are probably the most-commonly used proximity switch in FRC, due to their simplicity, ease-of-use, and low cost. A limit switch is quite simply a switch attached to a mechanical arm. The switch is activated when an object pushes against the switch arm, actuating the switch.

Limit switches vary in size, the geometry of the switch-arm, and in the amount of “throw” required to activate the switch. While limit switches are quite cheap, their mechanical actuation is sometimes less-reliable than no-contact alternatives. However, they are also extremely versatile, as they can be triggered by any physical object capable of moving the switch arm.

### **Magnetic proximity switches**

Magnetic proximity switches are activated when a magnet comes within a certain range of the sensor. Accordingly, they are “no-contact” switches - they do not require contact with the object being sensed.

There are two major types of magnetic proximity switches - reed switches and hall-effect sensors. In a reed switch, the magnetic field causes a pair of flexible metal contacts (the “reeds”) to touch each other, closing the circuit. A hall-effect sensor, on the other hand, detects the induced voltage transversely across a current-carrying conductor. Hall-effect sensors are generally the cheaper and more-reliable of the two.

Magnetic proximity switches may be either “unipolar,” “bipolar,” or “omnipolar.” A unipolar switch activates and deactivates depending on the presence of a given pole of the magnet (either north or south, depending on the switch). A bipolar switch activates from the proximity of one pole, and deactivates from the proximity of the opposite pole. An omnipolar switch will activate in the presence of either pole, and deactivates when no magnet is present.

While magnetic proximity switches are often more reliable than their mechanical counterparts, they require the user to mount a magnet on the object to be sensed - thus, they are mostly used for sensing mechanism location.

### **Inductive proximity switches**

Inductive proximity switches are activated when a conductor of any sort comes within a certain range of the sensor. Like magnetic proximity switches, they are “no-contact” switches.

Inductive proximity switches are used for many of the same purposes as magnetic proximity switches. Their more-general nature (activating in the presence of any conductor, rather than just a magnet) can be either a help or a hindrance, depending on the nature of the application.

### **Photoelectric proximity switches**

Photoelectric proximity switches are the last type of no-contact proximity switch in widespread use in FRC. Photoelectric proximity switches contain a light source (usually an IR laser) and a photoelectric sensor that activates the switch when the detected light (which bounces off of the sensor target) exceeds a given threshold.



Since photoelectric proximity switches rely on measuring the amount of reflected light, they are often inconsistent in their triggering range between different materials - accordingly, most photoelectric sensors have an adjustable activation point (typically controlled by turning a screw somewhere on the sensor body). On the other hand, photoelectric sensors are also extremely versatile, as they can detect a greater variety of objects than the other types of no-contact switches.

Photoelectric sensors are also often used in a “beam break” configuration, in which the emitter is separate from the sensor. These typically activate when an object is interposed between the emitter and the sensor.

## 27.6 Encoders - Hardware

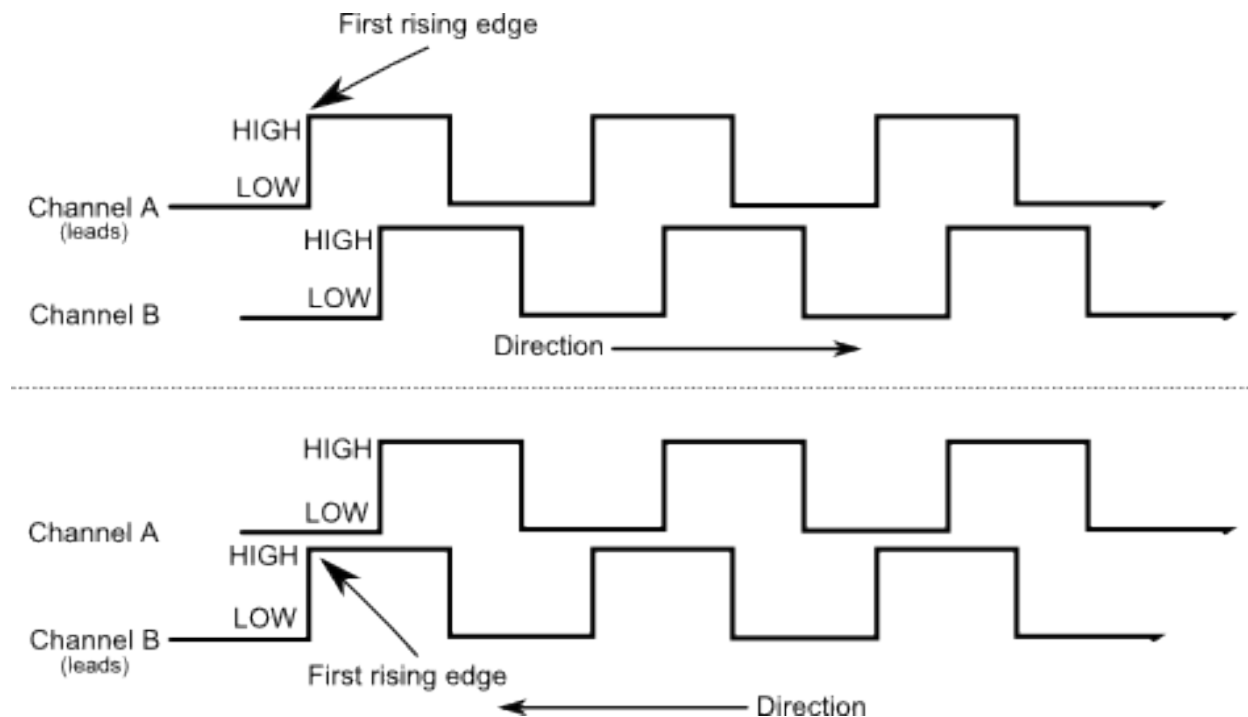
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**Note:** This section covers encoder hardware. For a software guide to encoders, see [Encoders - Software](#).

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Quadrature encoders are by far the most common method for measuring rotational motion in FRC, and for good reason - they are cheap, easy-to-use, and reliable. As they produce digital signals, they are less-prone to noise and interference than analog devices (such as *potentiometers*).

The term “quadrature” refers to the method by which the motion is measured/encoded. A quadrature encoder produces two square-wave pulses that are 90-degrees out-of-phase from each other, as seen in the picture below:



Thus, across both channels, there are four total “edges” per period (hence “quad”). The use of two out-of-phase pulses allows the direction of motion to be unambiguously determined from which pulse “leads” the other.

As each square wave pulse is a digital signal, quadrature encoders connect to the *digital input* ports on the RIO.

### 27.6.1 Types of encoders

There are three types of quadrature encoders typically used in FRC:

- *Shafted encoders*
- *On-shaft encoders*
- *Magnetic encoders*

These encoders vary in how they are mounted to the mechanism in question. In addition to these types of encoders, many FRC mechanisms come with quadrature encoders integrated into their design.

#### Shafted encoders

Shafted encoders have a sealed body with a shaft protruding out of it that must be coupled rotationally to a mechanism. This is often done with a helical beam coupling, or, more cheaply, with a length of flexible tubing (such as surgical tubing or pneumatic tubing), fastened with cable ties and/or adhesive at either end. Many commercial off-the-shelf FRC gearboxes have purpose-built mounting points for shafted encoders, such as the popular [Grayhill 63r](#).

#### On-shaft encoders

On-shaft encoders (such as the [AMT103-V](#) available through FIRST Choice) couple to a shaft by fitting *around* it, forming a friction coupling between the shaft and a rotating hub inside the encoder.

#### Magnetic encoders

Magnetic encoders require no mechanical coupling to the shaft at all; rather, they track the orientation of a magnet fixed to the shaft. The [CTRE Mag Encoder](#) is a popular option, with many FRC products offering built-in mounting options for it. While the no-contact nature of magnetic encoders can be handy, they often require precise construction in order to ensure that the magnet is positioned correctly with respect to the encoder.

### 27.6.2 Encoder resolution

**Warning:** The acronyms “CPR” and “PPR” are *both* used by varying sources to denote both edges per revolution *and* cycles per revolution, so the acronym alone is not enough to tell which is of the two is meant when by a given value. When in doubt, consult the technical manual of your specific encoder.

As encoders measure rotation with digital pulses, the accuracy of the measurement is limited by the number of pulses per given amount of rotational movement. This is known as the

“resolution” of the encoder, and is traditionally measured in one of two different ways: edges per revolution, or cycles per revolution.

*Edges per revolution* refers to the total number of transitions from high-to-low or low-to-high across both channels per revolution of the encoder shaft. A full period contains *four* edges.

*Cycles per revolution* refers to the total number of *complete periods* of both channels per revolution of the encoder shaft. A full period is *one* cycle.

Thus, a resolution stated in edges per revolution has a value four times that of the same resolution stated in cycles per revolution.

In general, the resolution of your encoder in edges-per-revolution should be somewhat finer than your smallest acceptable error in positioning. Thus, if you want to know the mechanism plus-or-minus one degree, you should have an encoder with a resolution somewhat higher than 360 edges per revolution.

## 27.7 Gyroscopes - Hardware

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**Note:** This section covers gyro hardware. For a software guide to gyros, see [Gyroscopes - Software](#).

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Gyroscopes (or “gyros”, for short) are devices that measure rate-of-rotation. These are particularly useful for stabilizing robot driving, or for measuring heading or tilt by integrating (adding-up) the rate measurements to get a measurement of total angular displacement.

Several popular FRC devices (known as “inertial measurement units,” or “IMUs”) combine both an accelerometer and a gyroscope. Some popular examples are:

- [Analog Devices ADIS16448 and ADIS 16470 IMUs](#)
- [CTRE Pigeon IMU](#)
- [Kauai Labs NavX](#)

### 27.7.1 Types of gyros

There are two types of Gyros commonly-used in FRC: single-axis gyros, and three-axis gyros.

#### Single-axis gyros

As per their name, single-axis gyros measure rotation rate around a single axis. This axis is generally specified on the physical device, and mounting the device in the proper orientation so that the desired axis is measured is highly important. Single-axis gyros generally output an analog voltage corresponding to the measured rate of rotation, and so connect to the roboRIO’s *analog input* ports.

The [Analog Devices ADXRS450 FRC Gyro Board](#) that has been in FIRST Choice in recent years is a commonly used single axis gyro.

### Three-axis gyros

Three-axis gyros measure rotation rate around all three spacial axes (typically labeled x, y, and z).

Peripheral three-axis gyros may simply output three analog voltages (and thus connect to the *analog input ports*, or (more commonly) they may communicate with one of the roboRIO's *serial buses*.

## 27.8 Ultrasonics - Hardware

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**Note:** This section covers ultrasonic sensor hardware. For a software guide to ultrasonics, see *Ultrasonics - Software*.

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Ultrasonic rangefinders are some of the most common rangefinders used in FRC. They are cheap, easy-to-use, and fairly reliable. Ultrasonic rangefinders work by emitting a pulse of high-frequency sound, and then measuring how long it takes the echo to reach the sensor after bouncing off the target. From the measured time and the speed of sound in air, it is possible to calculate the distance to the target.

### 27.8.1 Types of ultrasonics

While all ultrasonic rangefinders operate on the “ping-response” principle outlined above, they may vary in the way they communicate with the roboRIO.

#### Analog ultrasonics

Analog ultrasonics output a simple analog voltage corresponding to the distance to the target, and thus connect to an *analog input* port. The user will need to calibrate the voltage-to-distance conversion in *software*.

#### Ping-response ultrasonics

While, as mentioned, all ultrasonics are functionally ping-response devices, a “ping response” ultrasonic is one configured to connect to *both a digital input and a digital output*. The digital output is used to send the ping, while the input is used to read the response.

#### Serial ultrasonics

Some more-complicated ultrasonic sensors may communicate with the RIO over one of the *serial buses*.

## 27.8.2 Caveats

Ultrasonic sensors are generally quite easy to use, however there are a few caveats. As ultrasonics work by measuring the time between the pulse and its echo, they generally measure distance only to the *closest* target in their range. Thus, it is extremely important to pick a the right sensor for the job. The documentation for ultrasonic sensors will generally include a picture of the “beam pattern” that shows the shape of the “window” in which the ultrasonic will detect a target - pay close attention to this when selecting your sensor.

Ultrasonic sensors are also susceptible to interference from other ultrasonic sensors. In order to minimize this, the roboRIO can run ping-response ultrasonics in a “round-robin” fashion - however, in competition, there is no sure way to ensure that interference from sensors mounted on other robots does not occur.

Finally, ultrasonics may not be able to detect objects that absorb sound waves, or that redirect them in strange ways. Thus, they work best for detecting hard, flat objects.

## 27.9 Accelerometers - Hardware

Accelerometers are common sensors used to measure acceleration.

In principle, precise measurements of acceleration can be double-integrated and used to track position (similarly to how the measurement of turn rate from a gyroscope can be integrated to determine heading) - however, in practice, accelerometers that are available within the legal FRC price range are not nearly accurate for this use. However, accelerometers are still useful for a number of tasks in FRC.

The roboRIO comes with a built-in three-axis accelerometer that all teams can use, however teams seeking more-precise measurements may purchase and use a peripheral accelerometer, as well.

Several popular FRC devices (known as “inertial measurement units,” or “IMUs”) combine both an accelerometer and a gyroscope. Popular FRC example include:

- [Analog Devices ADIS16448 and ADIS 16470 IMUs](#)
- [CTRE Pigeon IMU](#)
- [Kauai Labs NavX](#)

### 27.9.1 Types of accelerometers

There are two types of accelerometers commonly-used in FRC: single-axis accelerometers, and multi-axis accelerometers.

#### Single-axis accelerometers

As per their name, single-axis accelerometers measure acceleration along a single axis. This axis is generally specified on the physical device, and mounting the device in the proper orientation so that the desired axis is measured is highly important. Single-axis accelerometers generally output an analog voltage corresponding to the measured acceleration, and so connect to the roboRIO’s *analog input* ports.

## Multi-axis accelerometers

Multi-axis accelerometers measure acceleration along all multiple spacial axes. The roboRIO's built-in accelerometer is a three-axis accelerometer.

Peripheral multi-axis accelerometers may simply output multiple analog voltages (and thus connect to the *analog input ports*, or (more commonly) they may communicate with one of the roboRIO's *serial buses*.

## 27.10 LIDAR - Hardware

LIDAR (light detection and ranging) sensors are a variety of rangefinder seeing increasing use in FRC.

LIDAR sensors work quite similarly to *ultrasonics*, but use light instead of sound. A laser is pulsed, and the sensor measures the time until the pulse bounces back.

### 27.10.1 Types of LIDAR

There are two types of LIDAR sensors commonly used in current FRC: 1-dimensional LIDAR, and 2-dimensional LIDAR.

#### 1-Dimensional LIDAR

A 1-dimensional (1D) LIDAR sensor works much like an ultrasonic sensor - it measures the distance to the nearest object more or less along a line in front of it. 1D LIDAR sensors can often be more-reliable than ultrasonics, as they have narrower "beam profiles" and are less susceptible to interference.

1D LIDAR sensors generally output an analog voltage proportional to the measured distance, and thus connect to the roboRIO's *analog input* ports.

#### 2-Dimensional LIDAR

A 2-dimensional (2D) LIDAR sensor measures distance in all directions in a plane. Generally, this is accomplished (more-or-less) by simply placing a 1D LIDAR sensor on a turntable that spins at a constant rate.

Since, by nature, 2D LIDAR sensors need to send a large amount of data back to the roboRIO, they almost always connect to one of the roboRIO's *serial buses*.

### 27.10.2 Caveats

LIDAR sensors do suffer from a few common drawbacks:

Like ultrasonics, LIDAR relies on the reflection of the emitted pulse back to the sensor. Thus, LIDAR critically depends on the reflectivity of the material in the wavelength of the laser. The FRC field wall is made of polycarbonate, which tends to be transparent in the infrared wavelength (which is what is generally legal for FRC use). Thus, LIDAR tends to struggle to detect the field barrier.

2D LIDAR sensors (at the price range legal for FRC use) tend to be quite noisy, and processing their measured data (known as a “point cloud”) can involve a lot of complex software. Additionally, there are very few 2D LIDAR sensors made specifically for FRC, so software support tends to be scarce.

As 2D LIDAR sensors rely on a turntable to work, their update rate is limited by the rate at which the turntable spins. For sensors in the price range legal for FRC, this often means that they do not update their values particularly quickly, which can be a limitation when the robot (or the targets) are moving.

Additionally, as 2D LIDAR sensors are limited in *angular* resolution, the *spatial* resolution of the point cloud is worse when targets are further away.

## 27.11 Triangulating Rangefinders

Triangulating rangefinders (often called “IR rangefinders,” as they commonly function in the infrared wavelength band) are another common type of rangefinder used in FRC.

Unlike *LIDAR*, triangulating rangefinders do not measure the time between the emission of a pulse and the receiving of a reflection. Rather, most IR rangefinders work by emitting a constant beam at a slight angle, and measuring the position of the reflected beam. The closer the point of contact of the reflected beam to the emitter, the closer the object to the sensor.

### 27.11.1 Using IR rangefinders

IR Rangefinders generally output an analog voltage proportional to the distance to the target, and thus connect to the *analog input* ports on the RIO.

### 27.11.2 Caveats

IR rangefinders suffer similar drawbacks to 1D LIDAR sensors - they are very sensitive to the reflectivity of the target in the wavelength of the emitted laser.

Additionally, while IR rangefinders tend to offer better resolution than LIDAR sensors when measuring at short distances, they are also usually more sensitive to differences in orientation of the target, *especially* if the target is highly-reflective (such as a mirror).

## 27.12 Serial Buses

In addition to the *digital* and *analog* inputs, the roboRIO also offers several methods of serial communication with peripheral devices.

Both the digital and analog inputs are highly limited in the amount of data that can be send over them. Serial buses allow users to make use of far more-robust and higher-bandwidth communications protocols with sensors that collect large amounts of data, such as inertial measurement units (IMUs) or 2D LIDAR sensors.

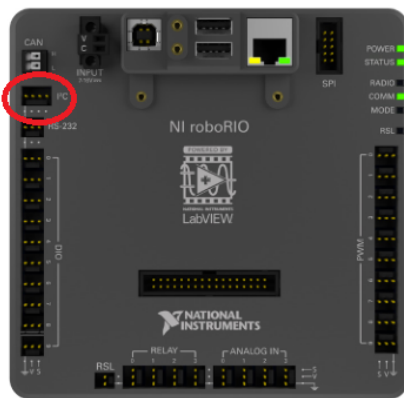
## 27.12.1 Types of supported serial buses

The roboRIO supports four basic types of serial communications:

- *I2C*
- *SPI*
- *RS-232*
- *USB*

Additionally, the roboRIO supports communications with peripheral devices over the CAN bus. However, as the FRC CAN protocol is quite idiosyncratic, relatively few peripheral sensors support it (though it is heavily used for motor controllers).

### I2C



#### I<sup>2</sup>C Port

Figure 6 and Table 5 describe the I<sup>2</sup>C port pins and signals.

Figure 6. I<sup>2</sup>C Port Pinout

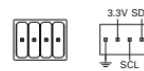


Table 5. I<sup>2</sup>C Port Signal Descriptions

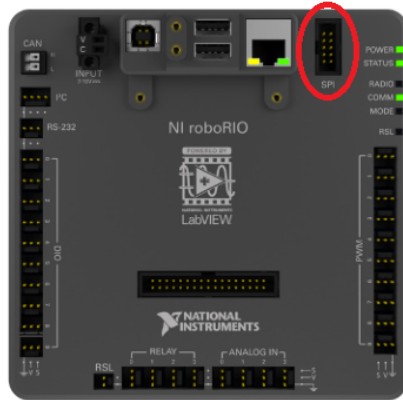
Signal Name	Direction	Description
GND	—	Reference for digital lines and +3.3 V power output.
3.3V	Output	+3.3 V power output.
SCL	Input or Output	I <sup>2</sup> C lines with 3.3 V output, 3.3 V/5 V-compatible input. Refer to the <a href="#">PC Lines</a> section for more information.
SDA	Input or Output	I <sup>2</sup> C lines with 3.3 V output, 3.3 V/5 V-compatible input. Refer to the <a href="#">PC Lines</a> section for more information.

To communicate to peripheral devices over I2C, each pin should be wired to its corresponding pin on the device. I2C allows users to wire a “chain” of slave devices to a single port, so long as those devices have separate IDs set.

The I2C bus can also be used through the [MXP expansion port](#). The I2C bus on the MXP is independent. For example, a device on the main bus can have the same ID as a device on the MXP bus.



## SPI



### SPI Port

Figure 13 and Table 12 describe the SPI port pins and signals.

Figure 13. SPI Port Pinout

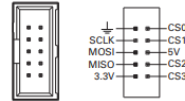


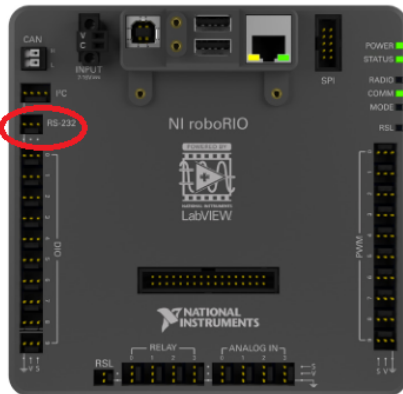
Table 12. SPI Port Signal Descriptions

Signal Name	Direction	Description
3.3V	Output	+3.3 V power output.
5V	Output	+5 V power output.
CS <0..3>	Output	SPI with 3.3 V output, 3.3 V/5 V-compatible input. Refer to the <a href="#">SPI Lines</a> section for more information.
SCLK	Output	
MOSI	Output	
MISO	Input	
GND	—	Reference for digital lines and +3.3 V and +5.5 V power output.

To communicate to peripheral devices over SPI, each pin should be wired to its corresponding pin on the device. The SPI port supports communications to up to four devices (corresponding to the Chip Select (CS) 0-3 pins on the diagram above).

The SPI bus can also be used through the [MXP expansion port](#). The MXP port provides independent clock, and input/output lines and an additional CS.

## RS-232



### RS-232 Port

Figure 7 and Table 6 describe the RS-232 port pins and signals.

Figure 7. RS-232 Serial Port Pinout

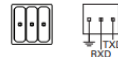


Table 6. RS-232 Serial Port Signal Descriptions

Signal Name	Direction	Description
TXD	Output	Serial transmit output with $\pm 5$ V to $\pm 15$ V signal levels. Refer to the <a href="#">UART and RS-232 Lines</a> section for more information.
RXD	Input	Serial receive input with $\pm 15$ V input voltage range. Refer to the <a href="#">UART and RS-232 Lines</a> section for more information.
GND	—	Reference for digital lines.

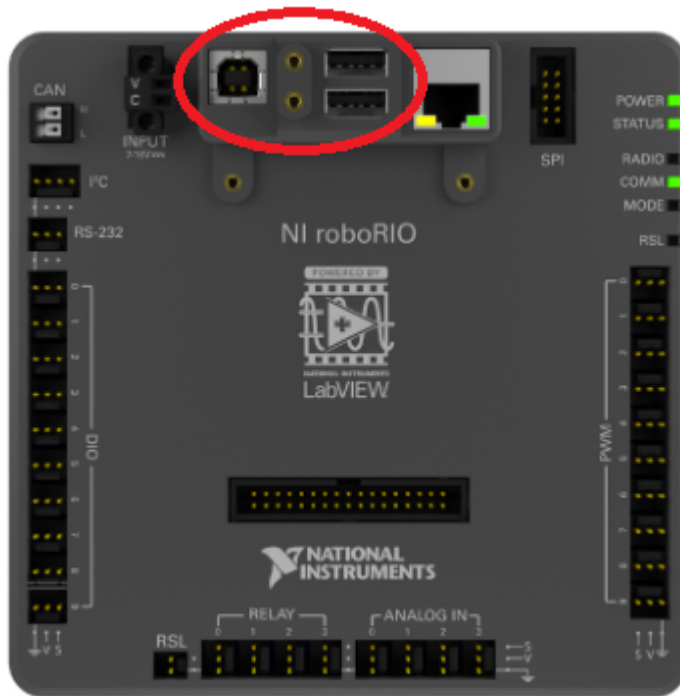
To communicate to peripheral devices over RS-232, each pin should be wired to its corresponding pin on the device.

The RS-232 bus can also be used through the [MXP expansion port](#).

The RoboRIO RS-232 serial port uses RS-232 signaling levels ( $\pm 15$ v). The MXP serial port uses CMOS signaling levels ( $\pm 3.3$ v).

**Note:** By default, the onboard RS-232 port is utilized by the roboRIO's serial console. In order to use it for an external device, the serial console must be disabled using the [Imaging Tool](#) or [roboRIO Web Dashboard](#).

## USB



The roboRIO has three USB ports: 1x USB-B, and 2x USB-A. These can be connected to devices with standard USB cables.

### 27.12.2 MXP expansion port

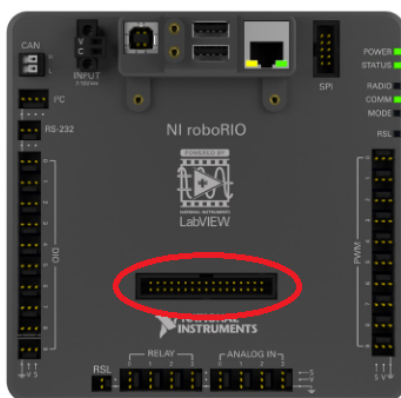


Figure 4. MXP Pinout

33	1
32	2
31	3
30	4
29	5
28	6
27	7
26	8
25	9
24	10
23	11
22	12
21	13
20	14
19	15
18	16
17	17
16	18
15	19
14	20
13	21
12	22
11	23
10	24
9	25
8	26
7	27
6	28
5	29
4	30
3	31
2	32
1	33

Several of the serial buses are also available for use through the roboRIO's MXP expansion port. This port allows users to make use of many additional *digital* and *analog* inputs, as well as the various serial buses.

Many peripheral devices attach directly to the MXP port for convenience, requiring no wiring

on the part of the user.

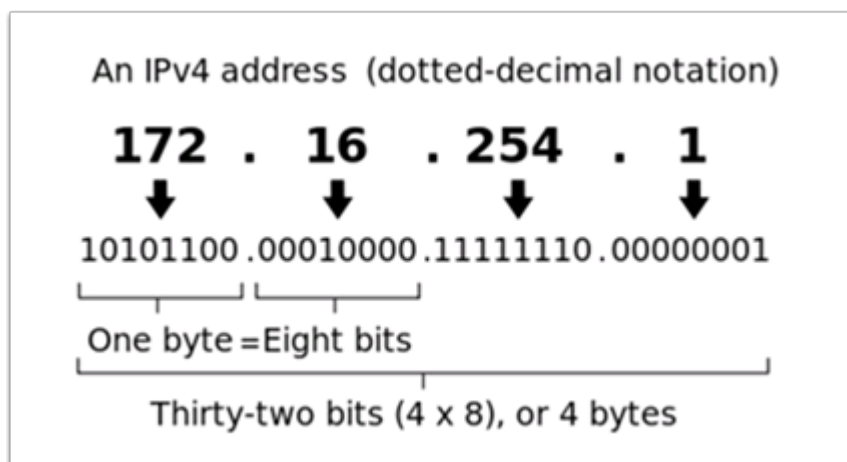
## Networking Introduction

This section outlines basic robot configuration and usage relating to communication between the driver station and roboRIO.

### 28.1 Networking Basics

#### 28.1.1 What is an IP Address?

An IP address is a unique string of numbers, separated by periods that identifies each device on a network. Each IP address is divided up into 4 sections (octets) ranging from 0-255.



As shown above, this means that each IP address is a 32-bit address meaning there are  $2^{32}$  addresses, or nearly 4,300,000,000 addresses possible. However, most of these are used publicly for things like web servers.

This brings up our **first key point** of IP Addressing: Each device on the network must have a unique IP address. No two devices can have the same IP address, otherwise collisions will occur.

Since there are only 4-billion addresses, and there are more than 4-billion computers connected to the internet, we need to be as efficient as possible with giving out IP addresses.

This brings us to public vs. private addresses.

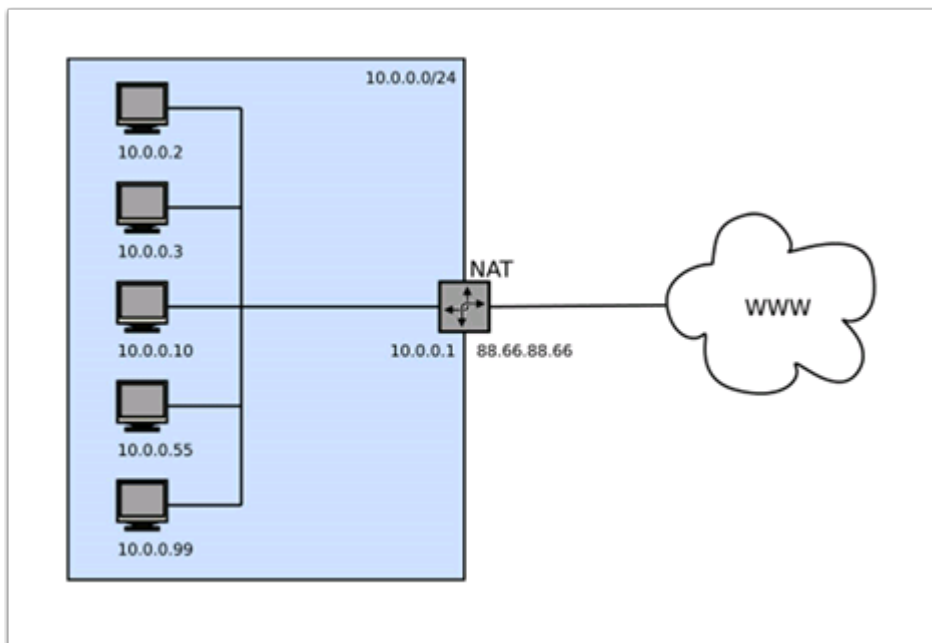
### 28.1.2 Public vs Private IP Addresses

To be efficient with using IP Addresses, the idea of “Reserved IP Ranges” was implemented. In short, this means that there are ranges of IP Addresses that will never be assigned to web servers, and will only be used for local networks, such as those in your house.

**Key point #2:** Unless you are directly connecting to your internet provider’s basic modem (no router function), your device will have an IP Address in one of these ranges. This means that at any local network, such as: your school, work office, home, etc., your device will 99% of the time have an IP address in a range listed below:

Class	Bits	Start Address	End Address	Number of Addresses
A	24	10.0.0.0	10.255.255.255	16,777,216
B	20	172.16.0.0	172.31.255.255	1,048,576
C	16	192.168.0.0	192.168.255.255	65,536

These reserved ranges let us assign one “unreserved IP Address” to an entire house, and then use multiple addresses in a reserved range to connect more than one computer to the internet. A process on the home’s internet router known as **NAT** (Network Address Translation), handles the process of keeping track which private IP is requesting data, using the public IP to request that data from the internet, and then passing the returned data back to the private IP that requested it. This allows us to use the same reserved IP addresses for many local networks, without causing any conflicts. An image of this process is presented below.



**Note:** For the FRC networks, we will use the 10.0.0.0 range. This range allows us to use the 10.TE.AM.xx format for IP addresses, whereas using the Class B or C networks would only allow a subset of teams to follow the format. An example of this formatting would be 10.17.50.1 for FRC Team 1750.

### 28.1.3 How are these addresses assigned?

We've covered the basics of what IP addresses are, and which IP addresses we will use for the FRC competition, so now we need to discuss how these addresses will get assigned to the devices on our network. We already stated above that we can't have two devices on the same network with the same IP Address, so we need a way to be sure that every device receives an address without overlapping. This can be done Dynamically (automatic), or Statically (manual).

#### Dynamically

Dynamically assigning IP addresses means that we are letting a device on the network manage the IP address assignments. This is done through the Dynamic Host Configuration Protocol (DHCP). DHCP has many components to it, but for the scope of this document, we will think of it as a service that automatically manages the network. Whenever you plug in a new device to the network, the DHCP service sees the new device, then provides it with an available IP address and the other network settings required for the device to communicate. This can mean that there are times we do not know the exact IP address of each device.

#### What is a DHCP server?

A DHCP server is a device that runs the DHCP service to monitor the network for new devices to configure. In larger businesses, this could be a dedicated computer running the DHCP service and that computer would be the DHCP server. For home networks, FRC networks, and other smaller networks, the DHCP service is usually running on the router; in this case, the router is the DHCP server.

This means that if you ever run into a situation where you need to have a DHCP server assigning IP addresses to your network devices, it's as simple as finding the closest home router, and plugging it in.

#### Statically

Statically assigning IP addresses means that we are manually telling each device on the network which IP address we want it to have. This configuration happens through a setting on each device. By disabling DHCP on the network and assigning the addresses manually, we get the benefit of knowing the exact IP address of each device on the network, but because we set each one manually and there is no service keeping track of the used IP addresses, we have to keep track of this ourselves. While statically setting IP addresses, we must be careful not to assign duplicate addresses, and must be sure we are setting the other network settings (such as subnet mask and default gateway) correctly on each device.

### 28.1.4 What is link-local?

If a device does not have an IP address, then it cannot communicate on a network. This can become an issue if we have a device that is set to dynamically acquire its address from a DHCP server, but there is no DHCP server on the network. An example of this would be when you have a laptop directly connected to a roboRIO and both are set to dynamically acquire an IP address. Neither device is a DHCP server, and since they are the only two devices on the network, they will not be assigned IP addresses automatically.

Link-local addresses give us a standard set of addresses that we can “fall-back” to if a device set to acquire dynamically is not able to acquire an address. If this happens, the device will assign itself an IP address in the 169.254.xx.yy address range; this is a link-local address. In our roboRIO and computer example above, both devices will realize they haven’t been assigned an IP address and assign themselves a link-local address. Once they are both assigned addresses in the 169.254.xx.yy range, they will be in the same network and will be able to communicate, even though they were set to dynamic and a DHCP server did not assign addresses.

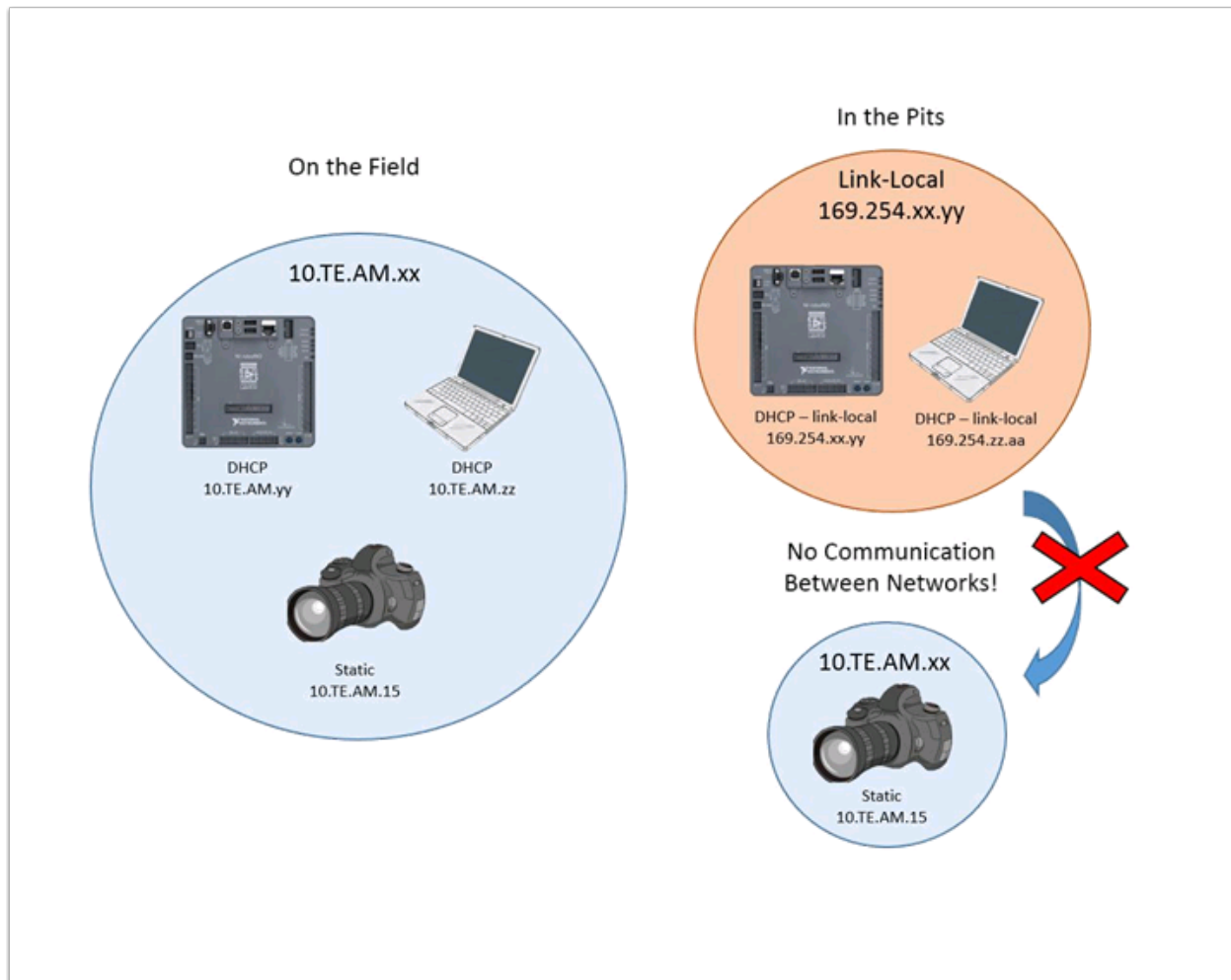
### **28.1.5 IP Addressing for FRC**

See the [\*IP Networking Article\*](#) for more information.

#### **Mixing Dynamic and Static Configurations**

While on the field, the team should not notice any issues with having devices set statically in the 10.TE.AM.xx range, and having the field assign DHCP addresses as long as there are no IP address conflicts as referred to in the section above.

In the pits, a team may encounter issues with mixing Static and DHCP devices for the following reason. As mentioned above, DHCP devices will fall back to a link-local address (169.254.xx.yy) if a server isn’t present. For static devices, the IP address will always be the same. If the DHCP server is not present and the roboRIO, driver station, and laptop fall back to link-local addresses, the statically set devices in the 10.TE.AM.xx range will be in a different network and not visible to those with link-local addresses. A visual description of this is provided below:



### 28.1.6 mDNS

mDNS, or multicast Domain Name System is a protocol that allows us to benefit from the features of DNS, without having a DNS server on the network. To make this clearer, let's take a step back and talk about what DNS is.

#### What is DNS?

DNS (Domain Name System) can become a complex topic, but for the scope of this paper, we are going to just look at the high level overview of DNS. In the most basic explanation, DNS is what allows us to relate human-friendly names for network devices to IP Addresses, and keep track of those IP addresses if they change.

Example 1: Let's look at the site [www.google.com](http://www.google.com). The IP address for this site is 172.217.164.132, however that is not very user friendly to remember!

Whenever a user types [www.google.com](http://www.google.com) into their computer, the computer contacts the DNS server (a setting provided by DHCP!) and asks what is the IP address on file for [www.google.com](http://www.google.com). The DNS server returns the IP address and then the computer is able to use that to connect to the Google web site.



Example 2: On your home network, you have a server named MYCOMPUTER that you want to connect to from your laptop. Your network uses DHCP so you don't know the IP Address of MYCOMPUTER, but DNS allows you to connect just by using the MYCOMPUTER name. Additionally, whenever the DHCP assignments refresh, MYCOMPUTER may end up with a different address, but because you're connecting by using the MYCOMPUTER name instead of a specific IP address, the DNS record was updated and you're still able to connect.

This is the second benefit to DNS, and the most relevant for FRC. With DNS, if we reference devices by their friendly name instead of IP Address, we don't have to change anything in our program if the IP Address changes. DNS will keep track of the changes and return the new address if it ever changes.

### DNS for FRC

On the field and in the pits, there is no DNS server that allows us to perform the lookups like we do for the Google web site, but we'd still like to have the benefits of not remembering every IP Address, and not having to guess at every device's address if DHCP assigns a different address than we expect. This is where mDNS comes into the picture.

mDNS provides us the same benefits as traditional DNS, but is just implemented in a way that does not require a server. Whenever a user asks to connect to a device using a friendly name, mDNS sends out a message asking the device with that name to identify itself. The device with the name then sends a return message including its IP address so all devices on the network can update their information. mDNS is what allows us to refer to our roboRIO as `roboRIO-TEAM-FRC.local` and have it connect on a DHCP network.

---

**Note:** If a device used for FRC does not support mDNS, then it will be assigned an IP Address in the 10.TE.AM.20 - 10.TE.AM.255 range, but we won't know the exact address to connect and we won't be able to use the friendly name like before. In this case, the device would need to have a static IP Address.

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### mDNS - Principles

Multicast Domain Name System (mDNS) is a system which allows for resolution of host names to IP addresses on small networks with no dedicated name server. To resolve a host name a device sends out a multicast message to the network querying for the device. The device then responds with a multicast message containing its IP. Devices on the network can store this information in a cache so subsequent requests for this address can be resolved from the cache without repeating the network query.

### mDNS - Providers

To use mDNS, an mDNS implementation is required to be installed on your PC. Here are some common mDNS implementations for each major platform:

Windows:

- **NI mDNS Responder:** Installed with the NI FRC Game Tools
- **Apple Bonjour:** Installed with iTunes

OSX:

- **Apple Bonjour:** Installed by default

Linux:

- **nss-mDNS/Avahi/Zeroconf:** Installed and enabled by default on some Linux variants (such as Ubuntu or Mint). May need to be installed or enabled on others (such as Arch)

## mDNS - Firewalls

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**Note:** Depending on your PC configuration, no changes may be required, this section is provided to assist with troubleshooting.

---

To work properly mDNS must be allowed to pass through your firewall. Because the network traffic comes from the mDNS implementation and not directly from the Driver Station or IDE, allowing those applications through may not be sufficient. There are two main ways to resolve mDNS firewall issues:

- Add an application/service exception for the mDNS implementation (NI mDNS Responder is C:\Program Files\National Instruments\Shared\mDNS Responder\nimdnsResponder.exe)
- Add a port exception for traffic to/from UDP 5353. IP Ranges:
  - 10.0.0.0 - 10.255.255.255
  - 172.16.0.0 - 172.31.255.255
  - 192.168.0.0 - 192.168.255.255
  - 169.254.0.0 - 169.254.255.255
  - 224.0.0.251

## mDNS - Browser support

Most web-browsers should be able to utilize the mDNS address to access the roboRIO web server as long as an mDNS provider is installed. These browsers include Microsoft Edge, Firefox, and Google Chrome.

### 28.1.7 USB

If using the USB interface, no network setup is required (you do need the *Installing the FRC Game Tools* installed to provide the roboRIO USB Driver). The roboRIO driver will automatically configure the IP address of the host (your computer) and roboRIO and the software listed above should be able to locate and utilize your roboRIO.

### 28.1.8 Ethernet/Wireless

The *Programming your Radio* will enable the DHCP server on the OpenMesh radio in the home use case (AP mode), if you are putting the OpenMesh in bridge mode and using a router, you can enable DHCP addressing on the router. The bridge is set to the same team based IP

address as before (10.TE.AM.1) and will hand out DHCP address from 10.TE.AM.20 to 10.TE.AM.199. When connected to the field, FMS will also hand out addresses in the same IP range.

### 28.1.9 Summary

IP Addresses are what allow us to communicate with devices on a network. For FRC, these addresses are going to be in the 10.TE.AM.xx range if we are connected to a DHCP server or if they are assigned statically, or in the link-local 169.254.xx.yy range if the devices are set to DHCP, but there is no server present. For more information on how IP Addresses work, see [this](#) article by Microsoft.

If all devices on the network support mDNS, then all devices can be set to DHCP and referred to using their friendly names (ex. roboRIO-TEAM-FRC.local). If some devices do not support mDNS, they will need to be set to use static addresses.

If all devices are set to use DHCP or Static IP assignments (with correct static settings), the communication should work in both the pit and on the field without any changes needed. If there are a mix of some Static and some DHCP devices, then the Static devices will connect on the field, but will not connect in the pit. This can be resolved by either setting all devices to static settings, or leaving the current settings and providing a DHCP server in the pit.

## 28.2 IP Configurations

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**Note:** This document describes the IP configuration used at events, both on the fields and in the pits, potential issues and workaround configurations.

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### 28.2.1 TE.AM IP Notation

The notation TE.AM is used as part of IPs in numerous places in this document. This notation refers to splitting your four digit team number into two digit pairs for the IP address octets.

Example: 10.TE.AM.2

Team 12 - 10.0.12.2

Team 122 - 10.1.22.2

Team 1212 - 10.12.12.2

Team 3456 - 10.34.56.2

### 28.2.2 On the Field

This section describes networking when connected to the Field Network for match play

### On the Field DHCP Configuration

The Field Network runs a DHCP server with pools for each team that will hand out addresses in the range of 10.TE.AM.20 and up with subnet masks

- OpenMesh OM5P-AN or OM5P-AC radio - Static 10.TE.AM.1 programmed by Kiosk
- roboRIO - DHCP 10.TE.AM.2 assigned by the Robot Radio
- Driver Station - DHCP (“Obtain an IP address automatically”) 10.TE.AM.X assigned by field
- IP camera (if used) - DHCP 10.TE.AM.Y assigned by Robot Radio
- Other devices (if used) - DHCP 10.TE.AM.Z assigned by Robot Radio

### On the Field Static Configuration

It is also possible to configure static IPs on your devices to accommodate devices or software which do not support mDNS. When doing so you want to make sure to avoid addresses that will be in use when the robot is on the field network. These addresses are 10.TE.AM.1 and 10.TE.AM.4 for the OpenMesh radio and the field access point and anything 10.TE.AM.20 and up which may be assigned to a device still configured for DHCP. The roboRIO network configuration can be set from the webdashboard.

- OpenMesh radio - Static 10.TE.AM.1 programmed by Kiosk
- roboRIO - Static 10.TE.AM.2 would be a reasonable choice, subnet mask of 255.255.255.0 (default)
- Driver Station - Static 10.TE.AM.5 would be a reasonable choice, subnet mask **must** be 255.0.0.0
- IP Camera (if used) - Static 10.TE.AM.11 would be a reasonable choice, subnet 255.255.255.0 should be fine
- Other devices - Static 10.TE.AM.6-.10 or .12-.19 (.11 if camera not present) subnet 255.255.255.0

### 28.2.3 In the Pits

---

**Note: New for 2018:** There is now a DHCP server running on the wired side of the Robot Radio in the event configuration.

---

### In the Pits DHCP Configuration

- OpenMesh radio - Static 10.TE.AM.1 programmed by Kiosk.
- roboRIO - 10.TE.AM.2, assigned by Robot Radio
- Driver Station - DHCP (“Obtain an IP address automatically”), 10.TE.AM.X, assigned by Robot Radio
- IP camera (if used) - DHCP, 10.TE.AM.Y, assigned by Robot Radio

- Other devices (if used) - DHCP, 10.TE.AM.Z, assigned by Robot Radio

### In the Pits Static Configuration

It is also possible to configure static IPs on your devices to accommodate devices or software which do not support mDNS. When doing so you want to make sure to avoid addresses that will be in use when the robot is on the field network. These addresses are 10.TE.AM.1 and 10.TE.AM.4 for the OpenMesh radio

## 28.3 roboRIO Network Troubleshooting

The roboRIO and the 2015 FRC tools use dynamic IP addresses (DHCP) for network connectivity. This article describes steps for troubleshooting networking connectivity between your PC and your roboRIO

### 28.3.1 Ping roboRIO

The first step to identifying roboRIO networking issues is to isolate if it is an application issue or a general network issue. To do this, click **Start -> type cmd -> press Enter** to open the command prompt. Type `ping roboRIO-####-FRC.local` where #### is your team number (with no leading zeroes) and press enter. If the ping succeeds, the issue is likely with the specific application, verify your team number configuration in the application, and check your firewall configuration.

### 28.3.2 USB Connection Troubleshooting

If you are attempting to troubleshoot the USB connection, try pinging the roboRIO's IP address. As long as there is only one roboRIO connected to the PC, it should be configured as 172.22.11.2. If this ping fails, make sure you have the roboRIO connected and powered, and that you have installed the NI FRC Game Tools. The game tools installs the roboRIO drivers needed for the USB connection.

If this ping succeeds, but the .local ping fails, it is likely that either the roboRIO hostname is configured incorrectly, or you are connected to a DNS server which is attempting to resolve the .local address.

- Verify that your roboRIO has been *imaged for your team number*. This sets the hostname used by mDNS.
- Disconnect your computer from all other networks including Ethernet and WiFi. It is possible that one of these networks contains a DNS server that is attempting to resolve the .local address.

## 28.3.3 Ethernet Connection

roboRIO-40 : System Configuration

Search [ ] Save Refresh

**System Settings**

Hostname: roboRIO-40

IP Address: 10.0.40.2 (Ethernet)  
172.22.11.2 (Ethernet)

DNS Name: [ ]

Vendor: National Instruments

Model: roboRIO

Serial Number: 030498A9

Firmware Revision: 2.0.0f1

Operating System: NI Linux Real-Time ARMv7-A 3.2.35-rt52-2.0.0f0

Status: Running

System Start Time: 10/1/2014 2:15:56 PM

Image Title: roboRIO Image

Image Version: FRC\_roboRIO\_2015\_v14

Comments: [ ]

Locale: English

Update Firmware

**Startup Settings**

☐ Force Safe Mode

☒ Enable Console Out

☐ Disable RT Startup App

☐ Disable FPGA Startup App

☒ Enable Secure Shell Server (sshd)

☒ LabVIEW Project Access

**System Resources**

Total Physical Memory: 232 MB

Free Physical Memory: 103 MB

Total Virtual Memory: 232 MB

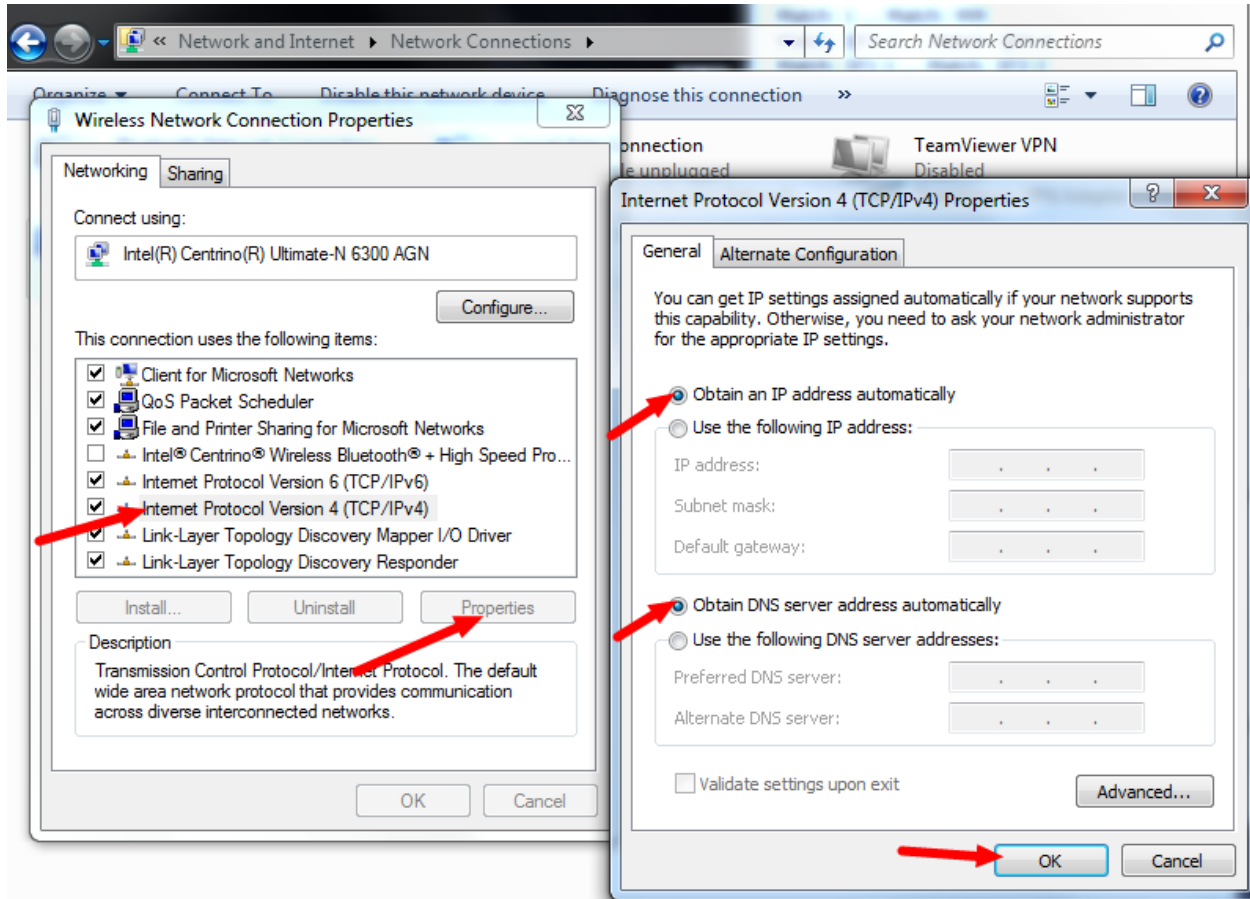
If you are troubleshooting an Ethernet connection, it may be helpful to first make sure that you can connect to the roboRIO using the USB connection. Using the USB connection, open the [roboRIO webdashboard](#) and verify that the roboRIO has an IP address on the ethernet interface. If you are tethering to the roboRIO directly this should be a self-assigned 169.\*.\*.\* address, if you are connected to the OM5P-AN radio, it should be an address of the form 10.TE.AM.XX where TEAM is your four digit FRC team number. If the only IP address here is the USB address, verify the physical roboRIO ethernet connection.

### Ping the roboRIO IP address

If there is an IP address in the step above, try pinging this IP address using the command prompt as described above. If this works, you have an issue resolving the mDNS address on your PC. The two most common causes are not having an mDNS resolver installed on the system and a DNS server on the network that is trying to resolve the .local address using regular DNS.

- Verify that you have an mDNS resolver installed on your system. On Windows, this is typically fulfilled by the NI FRC Game Tools. For more information on mDNS resolvers, see the [roboRIO Networking article](#).
- Disconnect your computer from any other networks and make sure you have the OM5P-AN configured as an access point, using the [FRC Radio Configuration Utility](#). Removing any other routers from the system will help verify that there is not a DNS server causing the issue.

## Ping fails



If pinging the IP address directly fails, you may have an issue with the network configuration of the PC. The PC should be configured to **Obtain an Address Automatically** (also known as DHCP). To check this, click **Start -> Control Panel -> Network Connections -> Change adapter settings**, then right click on the appropriate interface (usually Local Area Connection for Ethernet or Wireless Network Connection for wireless) and select **Properties**. Click **Internet Protocol Version 4**, then click **Properties**. Make sure both radio buttons are set to **Obtain automatically**.

### 28.3.4 Other things to check

Other possibilities that may cause issues include:

- Proxies. Having a proxy enabled may cause issues with the roboRIO networking.

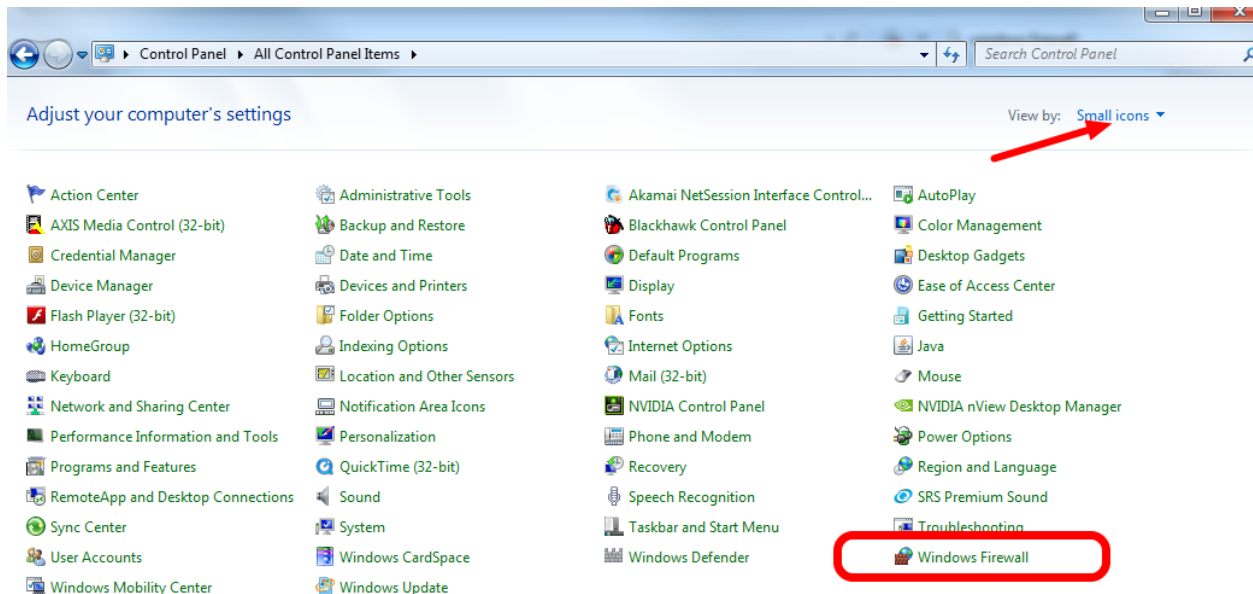
## 28.4 Windows Firewall Configuration

Many of the programming tools used in FRC need network access for various reasons. Depending on the exact configuration, the Windows Firewall may potentially interfere with this access for one or more of these programs. This document describes procedures for Windows 7, but future versions should be similar.

### 28.4.1 Disabling Windows Firewall

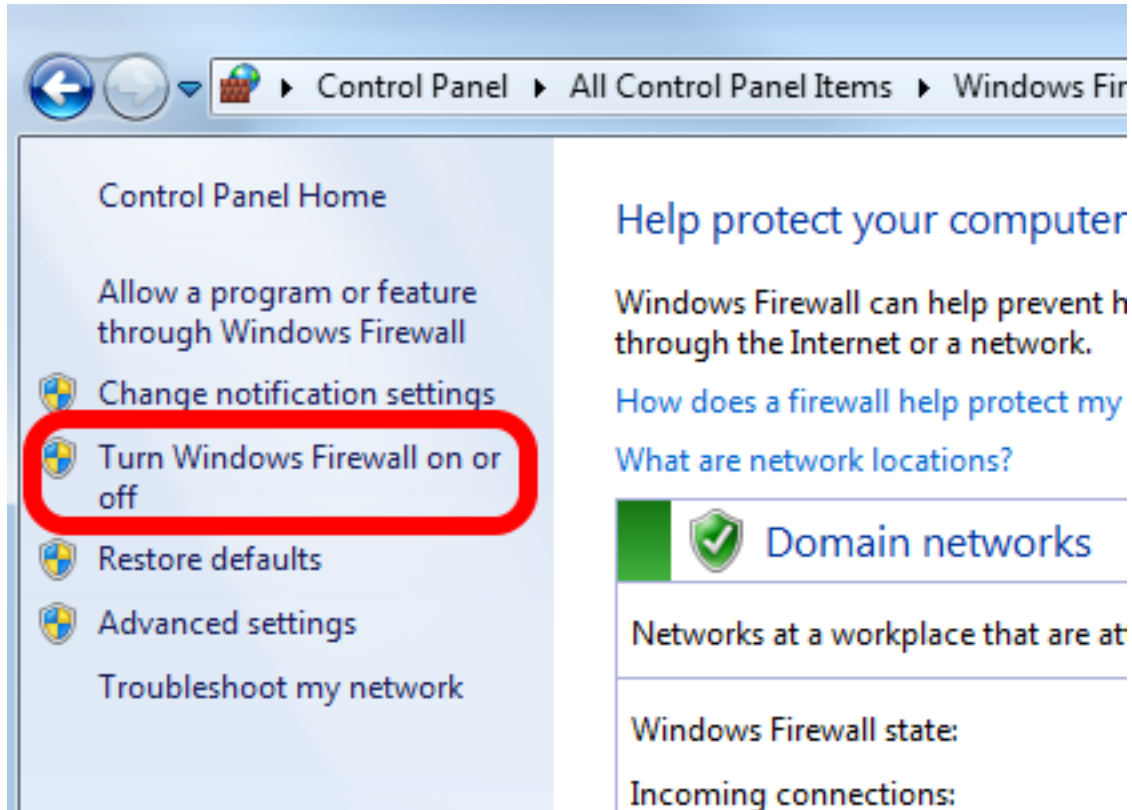
The easiest solution is to disable the Windows Firewall. Teams should beware that this does make the PC potentially more vulnerable to malware attacks if connecting to the internet.

#### Control Panel



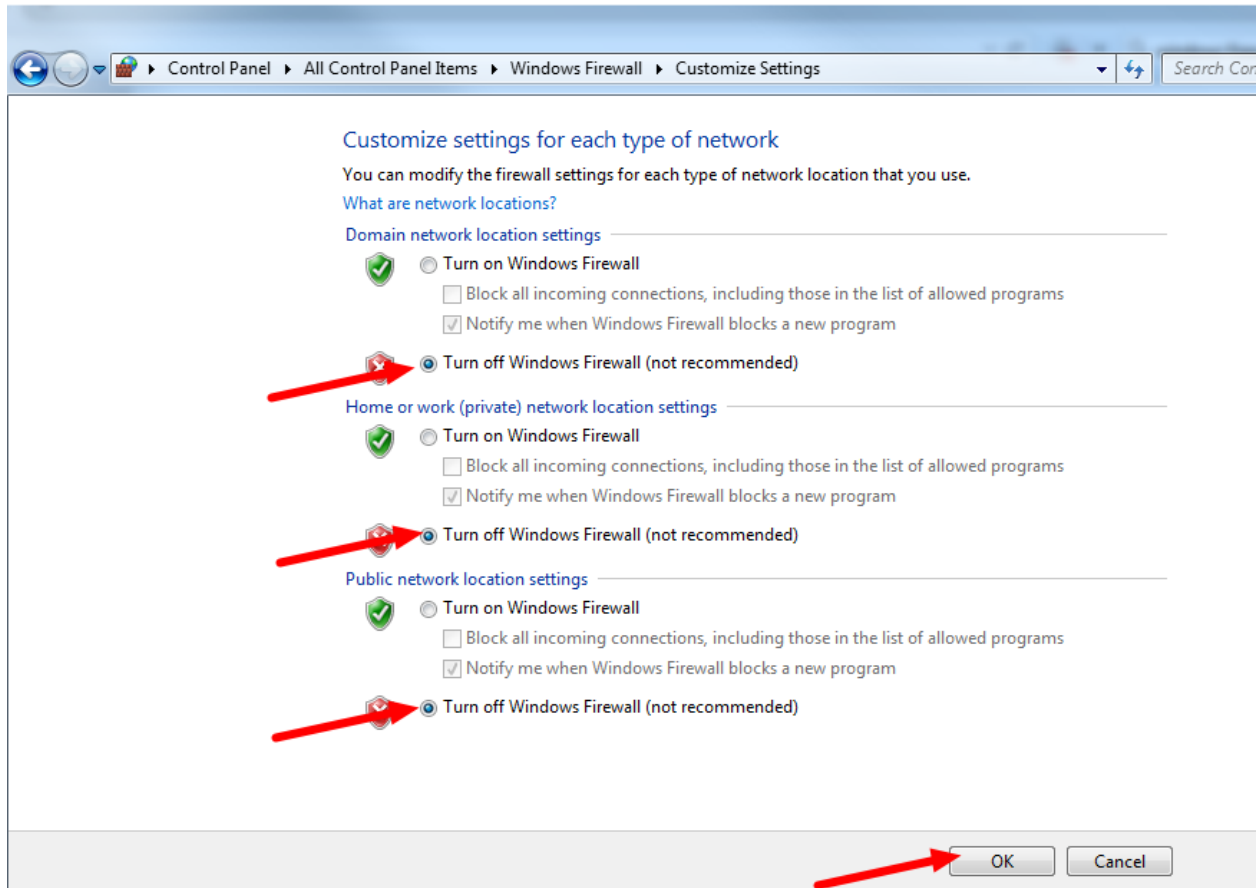
Click Start -> Control Panel to open the Control Panel. Click the dropdown next to View by: and select Small icons then click Windows Defender Firewall.



**Turn Windows Firewall on or off**

In the left pane, click Turn Windows Defender Firewall on or off, and click yes. Enter your Administrator password if a dialog appears.

## Disable the Firewall

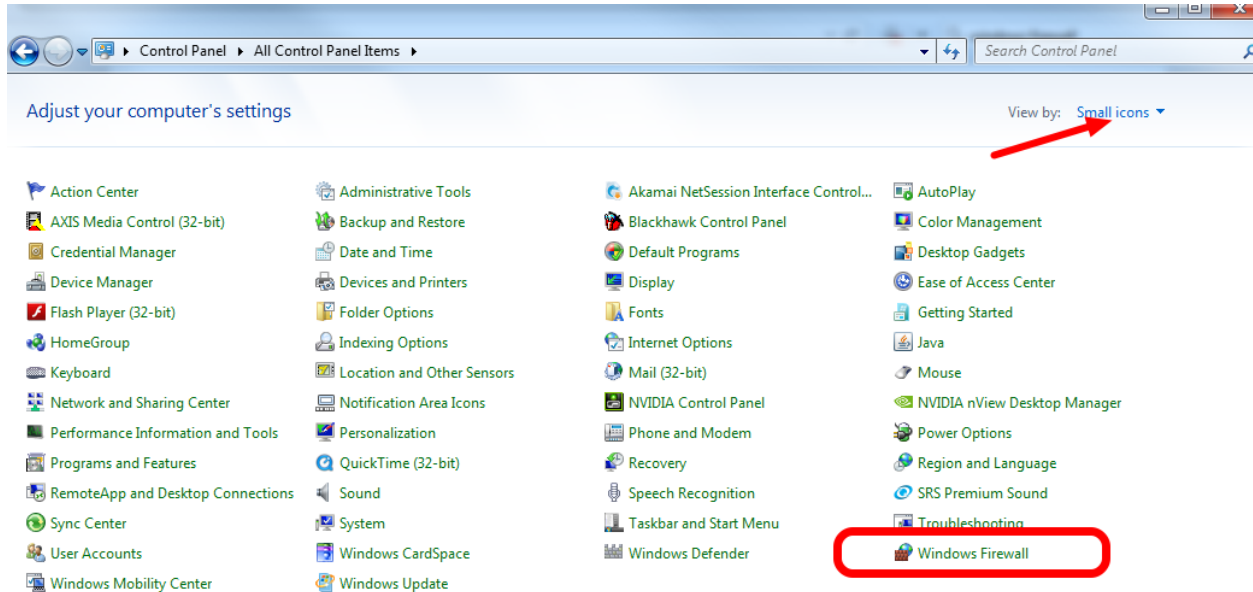


For each category, select the radio button to Turn off Windows Defender Firewall. Then click OK.

### 28.4.2 Configure the firewall

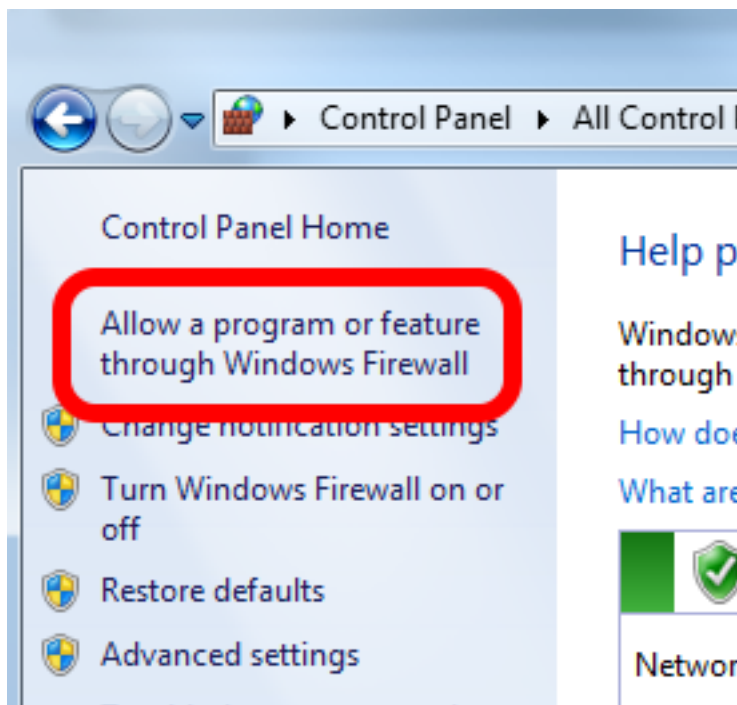
Alternatively, you can add exceptions to the Firewall for any FRC programs you are having issues with.

### Open Control Panel



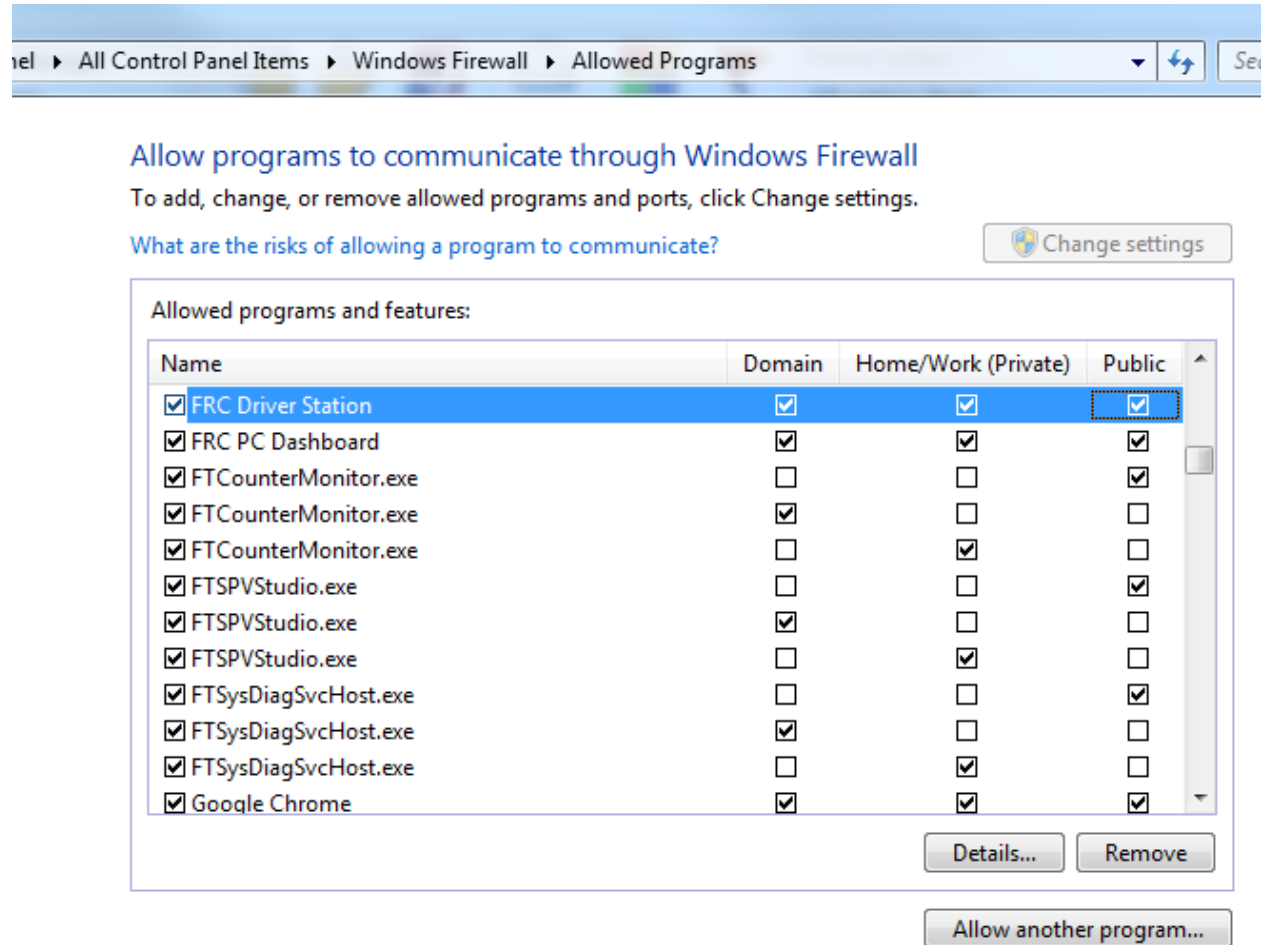
Click Start -> Control Panel to open the Control Panel. Click the dropdown next to View by: and select Small icons then click Windows Defender Firewall.

### Allow a program...



In the left pane, click Allow a program or feature through Windows Defender Firewall

## Allowed Programs



For each FRC program you are having an issue with, make sure that it appears in the list and that it has a check in each of the 3 columns. If you need to change a setting, you made need to click the [Change settings](#) button in the top right before changing the settings. If the program is not in the list at all, click the [Allow another program...](#) button and browse to the location of the program to add it.

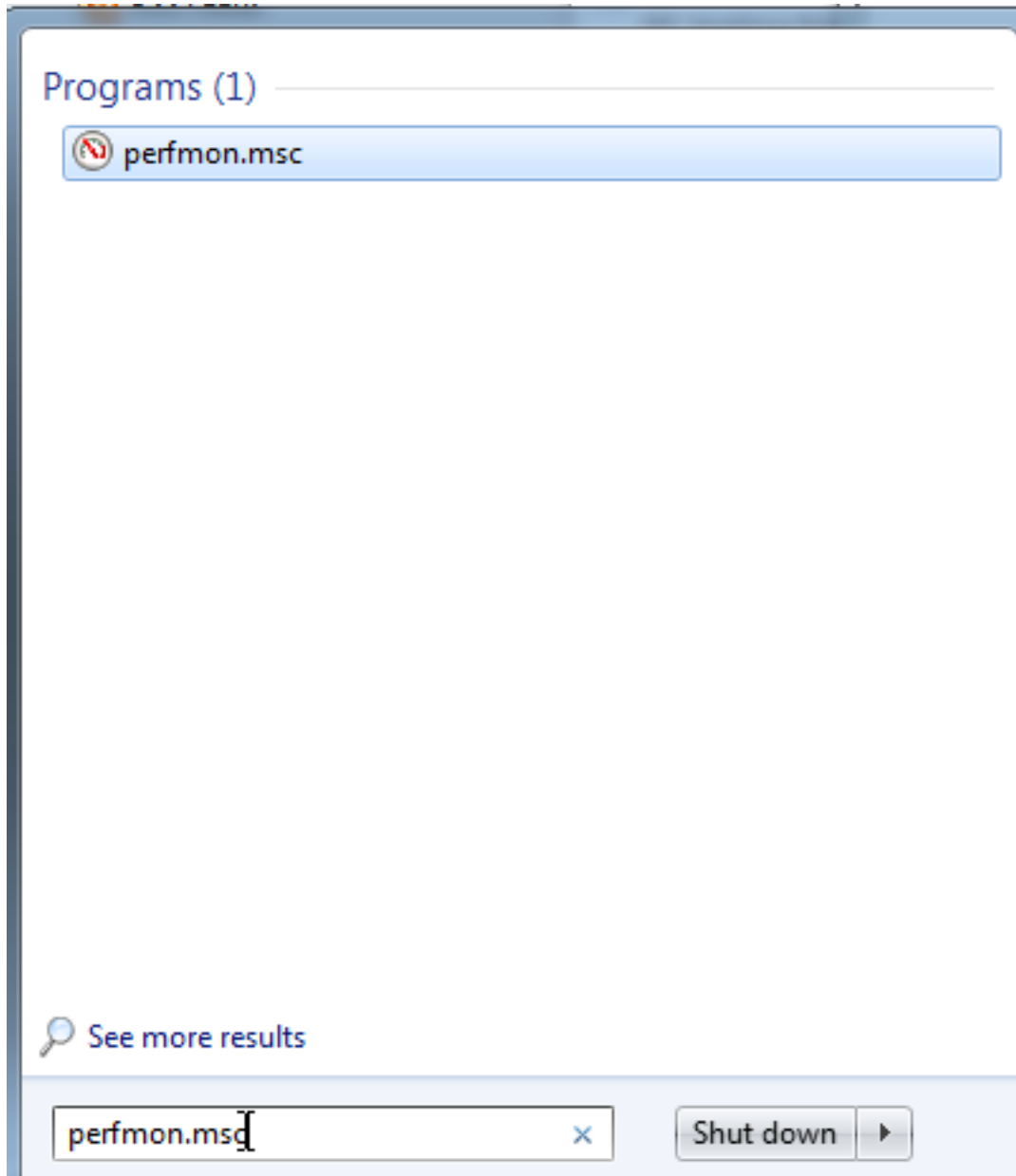
## 28.5 Measuring Bandwidth Usage

On the FRC Field (and at home when the radio is configured using the FRC Bridge Configuration Utility) each team is limited to 4Mb/s of network traffic (see the [FMS Whitepaper](#) for more details). The FMS Whitepaper provides information on determining the bandwidth usage of the Axis camera, but some teams may wish to measure their overall bandwidth consumption. This document details how to make that measurement.

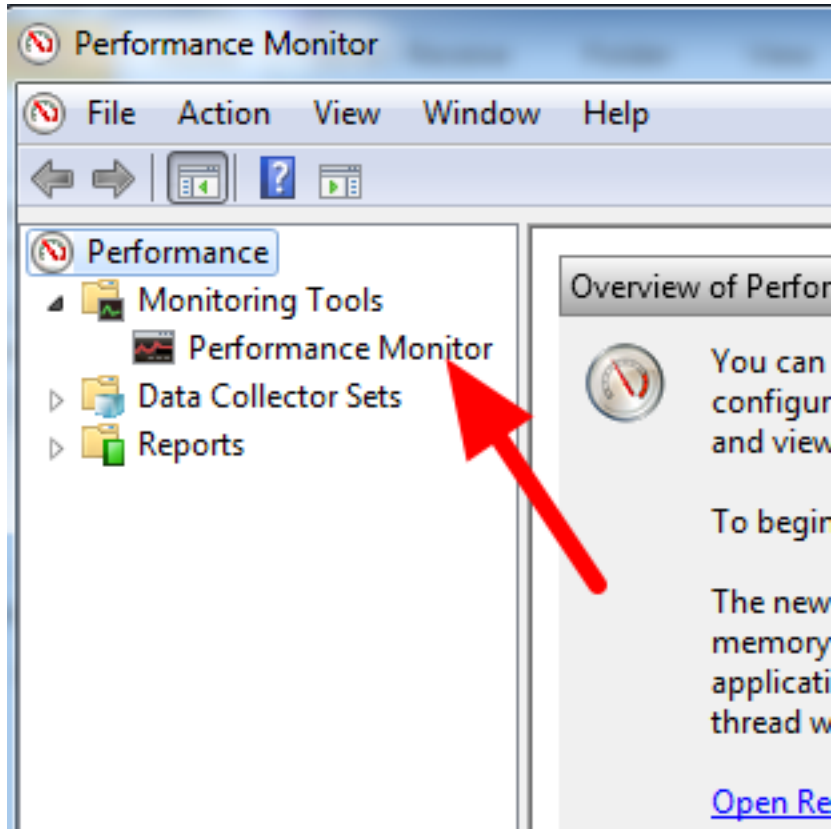
### **28.5.1 Measuring Bandwidth Using the Performance Monitor (Win 7 only)**

Windows 7 contains a built-in tool called the Performance Monitor that can be used to monitor the bandwidth usage over a network interface.

#### **Launching the Performance Monitor**

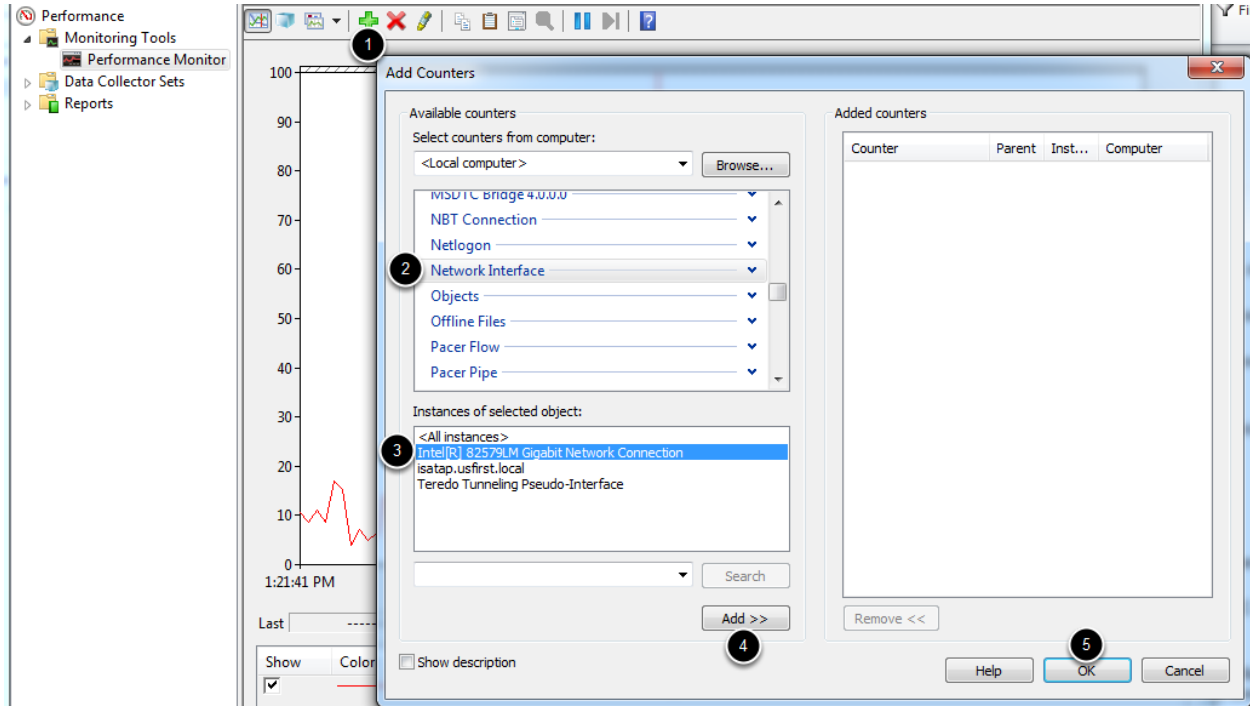


Click Start and in the search box, type `perfmon.msc` and press Enter.

**Open Real-Time Monitor**

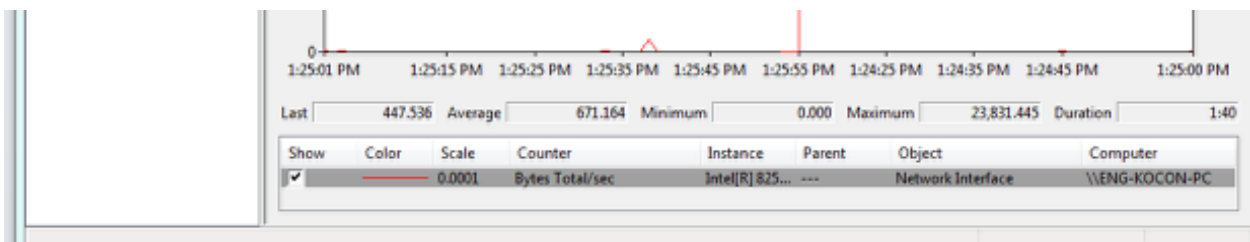
In the left pane, click Performance Monitor to display the real-time monitor.

## Add Network Counter

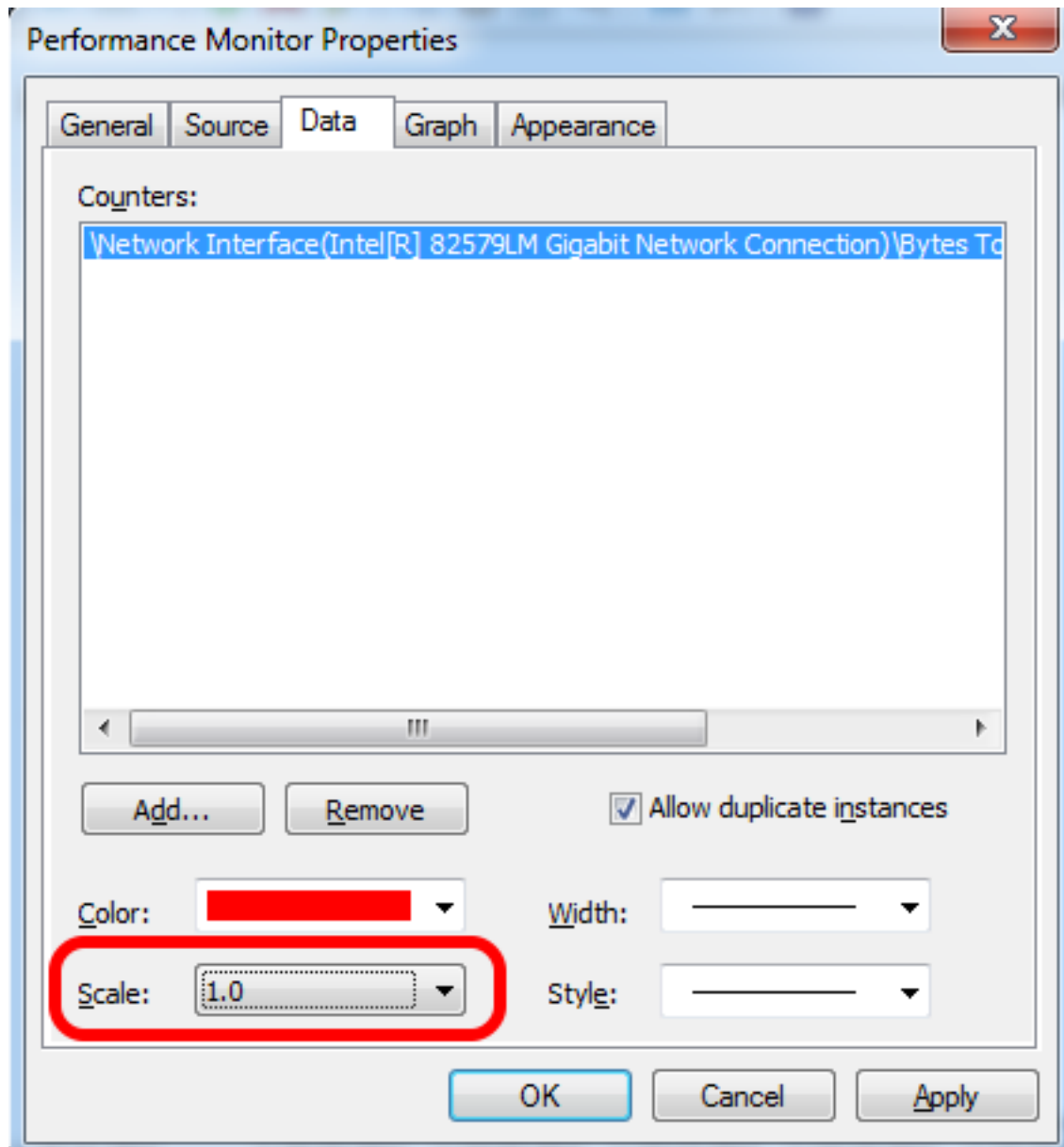


1. Click the green plus near the top of the screen to add a counter
2. In the top left pane, locate and click on Network Interface to select it
3. In the bottom left pane, locate the desired network interface (or use All instances to monitor all interfaces)
4. Click Add>> to add the counter to the right pane.
5. Click OK to add the counters to the graph.

## Remove Extra Counters



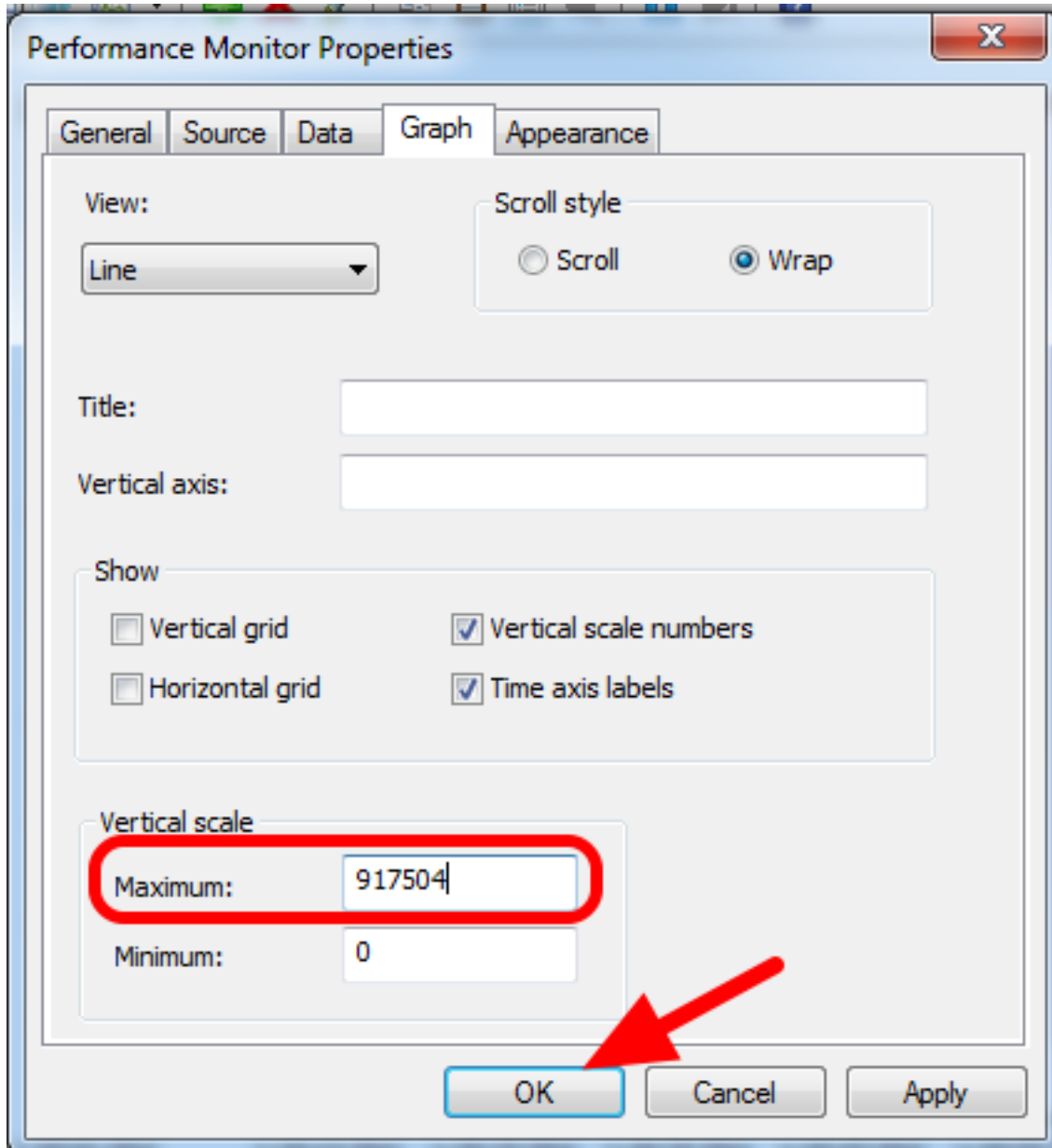
In the bottom pane, select each counter other than Bytes Total/sec and press the Delete key. The Bytes Total/sec entry should be the only entry remaining in the pane.

**Configure Data Properties**

Press Ctrl+Q to bring up the Properties window. Click on the dropdown next to Scale and select 1.0. Then click on the Graph tab.

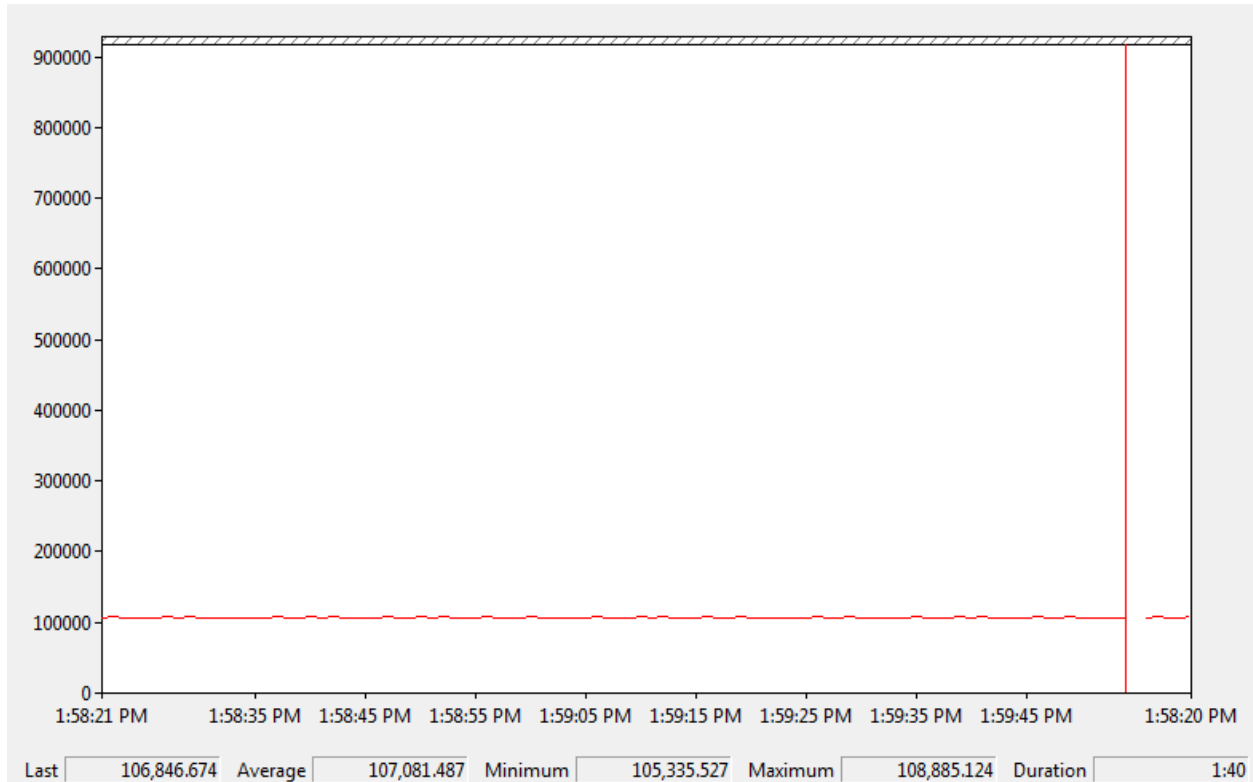


## Configure Graph Properties



In the Maximum Box under Vertical Scale enter 917504 (this is 7 Megabits converted to Bytes). If desired, turn on the horizontal grid by checking the box. Then click OK to close the dialog.

## Viewing Bandwidth Usage

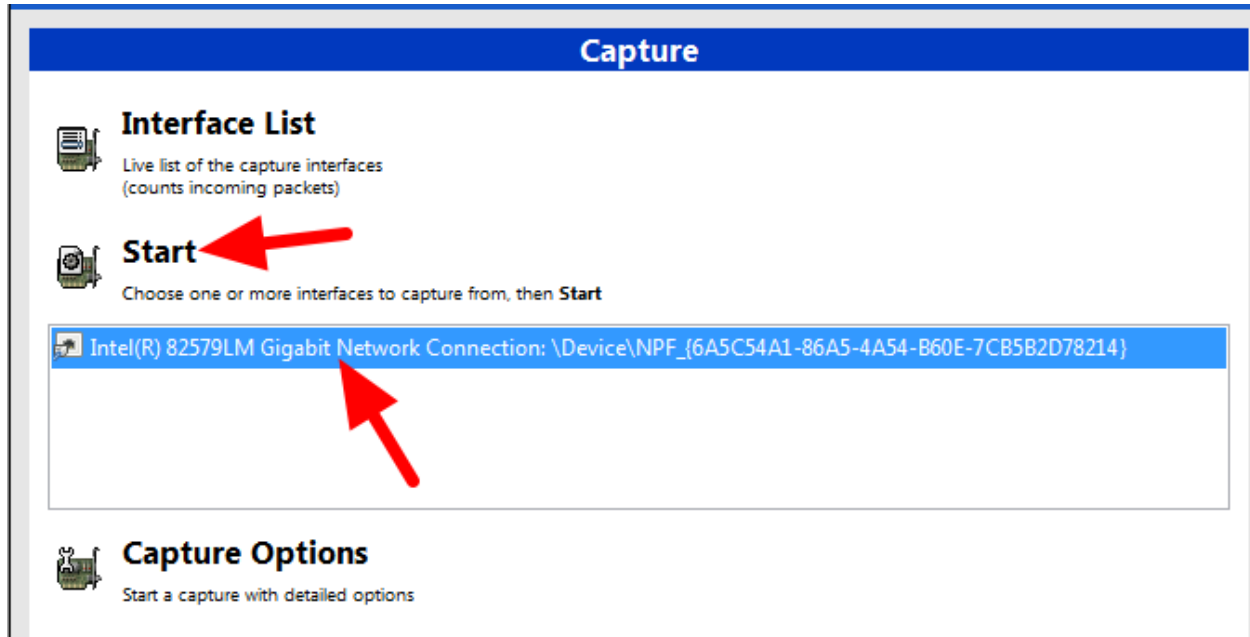


You may now connect to your robot as normal over the selected interface (if you haven't done so already). The graph will show the total bandwidth usage of the connection, with the bandwidth cap at the top of the graph. The Last, Average, Min and Max values are also displayed at the bottom of the graph. Note that these values are in Bytes/Second meaning the cap is 917,504. With just the Driver Station open you should see a flat line at ~100000 Bytes/Second.

### 28.5.2 Measuring Bandwidth Usage using Wireshark

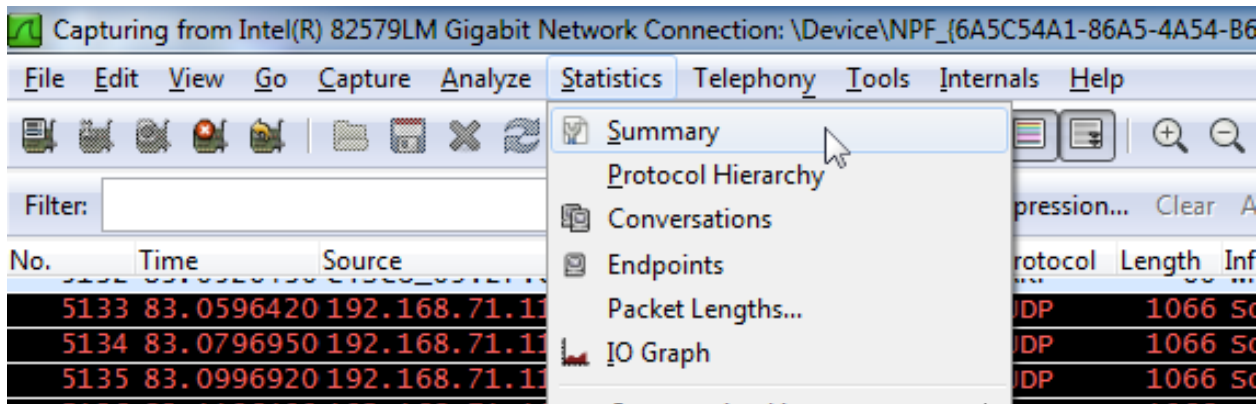
If you are not using Windows 7, you will need to install a 3rd party program to monitor bandwidth usage. One program that can be used for this purpose is Wireshark. Download and install the latest version of Wireshark for your version of Windows. After installation is complete, locate and open Wireshark. Connect your computer to your robot, open the Driver Station and any Dashboard or custom programs you may be using.

### Select the interface and Start capture



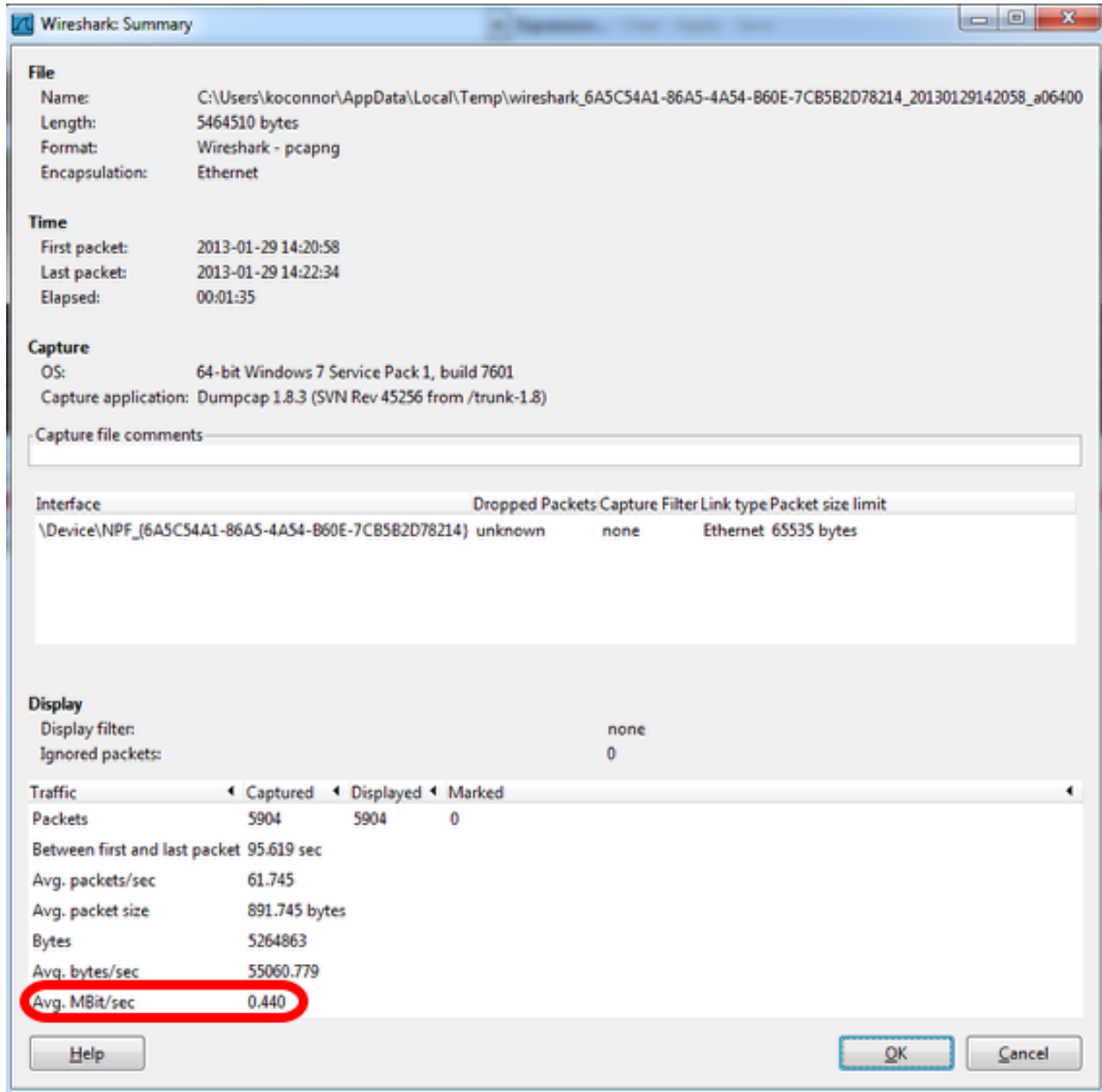
In the Wireshark program on the left side, select the interface you are using to connect to the robot and click Start.

### Open Statistics Summary



Let the capture run for at least 1 minute, then click Statistics then Summary.

## View Bandwidth Usage



Average bandwidth usage, in Megabits/Second is displayed near the bottom of the summary window.

## 28.6 OM5P-AC Radio Modification

The intended use case for the OM5P-AC radio does not subject it to the same shocks and forces as it sees in the FRC environment. If the radio is subjected to significant pressure on the bottom of the case, it is possible to cause a radio reboot by shorting a metal shield at the bottom of the radio to some exposed metal leads on the bottom of the board. This article details a modification to the radio to prevent this scenario.

**Warning:** It takes significant pressure applied to the bottom of the case to cause a reboot in this manner. Most FRC radio reboot issues can be traced to the power path in some form. We recommend mitigating this risk via strategic mounting of the radio rather than opening and modifying the radio (and risk damaging delicate internal components):

- Avoid using the “mounting tab” features on the bottom of the radio)
- You may wish to mount the radio to allow for some shock absorption. A little can go a long way, mounting the radio using hook and loop fastener or to a robot surface with a small amount of flex (plastic or sheet metal sheet, etc.) can significantly reduce the forces experienced by the radio.

### 28.6.1 Opening the Radio

**Note:** The OpenMesh OM5P-AC is not designed to be a user serviceable device. Users perform this modification at their own risk. Make sure to work slowly and carefully to avoid damaging internal components such as radio antenna cables.

---

#### Case Screws





Locate the two rubber feet on the front side of the radio then pry them off the radio using fingernails, small flat screwdriver, etc. Using a small Phillips screwdriver, remove the two screws under the feet.

### Side Latches



There is a small latch on the lid of the radio near the middle of each long edge (you can see these latches more clearly in the next picture). Using a fingernail or very thin tool, slide along the gap between the lid and case from front to back towards the middle of the radio, you should hear a small pop as you near the middle of radio. Repeat on the other side (note: it's not hard to accidentally re-latch the first side while doing this, make sure both sides are unlatched before proceeding). The radio lid should now be slightly open on the front side as shown in the image above.

### Remove Lid

**Warning:** The board may stick to the lid as you remove it due to the heatsink pads. Look through the vents of the radio as you remove the lid to see if the board is coming with it, if it is you may need to insert a small tool to hold the board down to separate it from the lid. We recommend a small screwdriver or similar tool that fits through the vents, applied through the front corner on the barrel jack side, right above the screw hole. You can scroll down to the picture with the lid removed to see what the board looks like in this area.

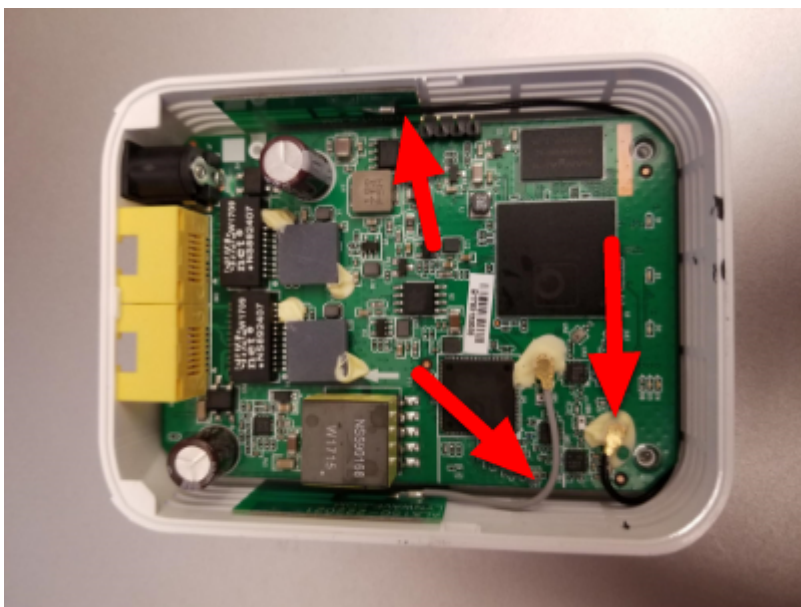


To begin removing the lid, slide it forward (lifting slightly) until the screw holders hit the case front (you may need to apply pressure on the latch areas while doing this).



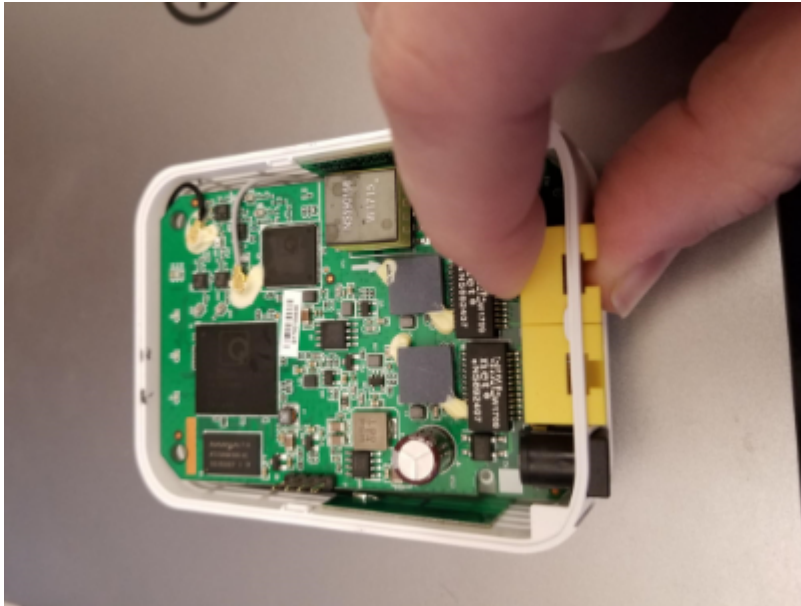
Next, begin rotating the lid slightly away from the barrel jack side, as shown while continuing to lift. This will unhook the lid from the small triangle visible in the top right corner. Continue to rotate slightly in this direction while pushing the top left corner towards the barrel jack (don't try to lift further in this step) to unhook a similar feature in the top left corner. Then lift the lid completely away from the body.

### Remove Board

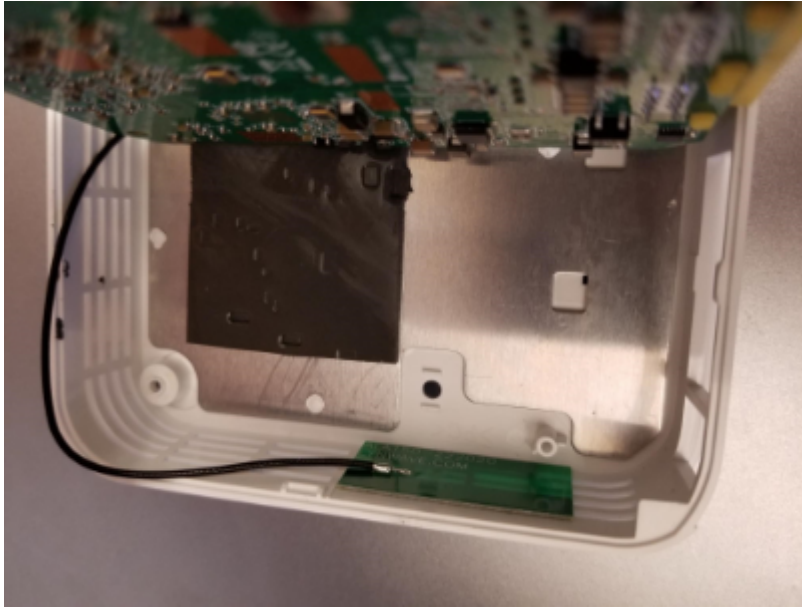




**Warning:** Note the antenna wires shown in the image above. These wires, and their connectors, are fragile, take care not to damage them while performing the next steps.



To remove the board, we recommend grasping one or both network ports with your fingers (as shown) and pushing inward (toward the front of the radio) and upward until the network ports and barrel jack are free from the case.



Tilt the board up (towards the short grey antenna cable) to expose the metal shield underneath.

**Note:** When you perform this step, you may notice that there is a small reset button on the underside of the board that is larger than the hole in the case. Note that pressing the reset button with the FRC firmware installed has no effect and that drilling the case of the radio is not a permitted modification.

### 28.6.2 Apply Tape



Apply a piece of electrical tape to the metal shield in the area just inside of the network port/barrel jack openings. This will prevent the exposed leads on the underside of the board

from short circuiting on this plate.

### **28.6.3 Re-assemble Radio**

Re-assemble the radio by reversing the instructions to open it:

- Lay the board back down, making sure it aligns with the screw holes near the front and seats securely
- Slide the lid onto the back left retaining feature by moving it in from right to left. Take care of the capacitor in this area
- Rotate the lid, press downwards and slide the back right retaining feature in
- Press down firmly on the front/middle of the lid to seat the latches
- Replace 2 screws in front feet
- Replace front feet

## 29.1 Port Forwarding

This class provides an easy way to forward local ports to another host/port. This is useful to provide a way to access Ethernet-connected devices from a computer tethered to the roboRIO USB port. This class acts as a raw TCP port forwarder, this means you can forward connections such as SSH.

### 29.1.1 Forwarding a Remote Port

Often teams may wish to connect directly to the roboRIO for controlling their robot. The PortForwarding class can be used to forward the Raspberry Pi connection for usage during these times. The PortForwarding class establishes a bridge between the remote and the client. To forward a port, simply do `PortForwarder.add(int port, String remoteName, int remotePort)`.

Java

```
@Override
public void robotInit() {
    PortForwarder.add(8888, "frcvision.local", 80);
}
```

C++

```
void Robot::RobotInit {
    wpi::PortForwarder::GetInstance().Add(8888, "frcvision.local", 80);
}
```

---

**Important:** You **can not** use a port less than 1024 as your local forwarded port. It is also important to note that you **can not** use full URLs (`http://frcvision.local`) and should only use IP Addresses or DNS names.

---

### 29.1.2 Removing a Forwarded Port

To stop forwarding on a specified port, simply call `remove(int port)` with `port` being the port number. If you call `remove()` on a port that is not being forwarded, nothing will happen.

Java

```
@Override
public void robotInit() {
    PortForwarder.remove(8888);
}
```

C++

```
void Robot::RobotInit {
    wpi::PortForwarder::GetInstance().Remove(8888);
}
```

## Contribution Guidelines

Welcome to the contribution guidelines for the frc-docs project. If you are unfamiliar to writing in the reStructuredText format, please read up on it [here](#).

---

**Important:** *FIRST*® retains all rights to documentation and images provided. Credit for articles/updates will be in the [Github commit history](#).

---

### 30.1 Mission Statement

The WPILib Mission is to enable *FIRST* Robotics teams to focus on writing game-specific software rather than focusing on hardware details - “raise the floor, don’t lower the ceiling”. We work to enable teams with limited programming knowledge and/or mentor experience to be as successful as possible, while not hampering the abilities of teams with more advanced programming capabilities. We support Kit of Parts control system components directly in the library. We also strive to keep parity between major features of each language (Java, C++, and NI’s LabVIEW), so that teams aren’t at a disadvantage for choosing a specific programming language.

These docs serve to provide a learning ground for all *FIRST* Robotics Competition teams. Contributions to the project must follow these core principles.

- Community-led documentation. Documentation sources are hosted publicly and the community are able to make contributions
- Structured, well-formatted, clean documentation. Documentation should be clean and easy to read, from both a source and release standpoint
- Relevant. Documentation should be focused on the *FIRST* Robotics Competition.

Please see the [Style Guide](#) for information on styling your documentation.

### 30.2 Note on New Articles

All new articles will undergo a review process before being merged into the repository. This review process will be done by members of the WPILib team. New Articles must be on official

*FIRST* supported Software and Hardware. Documentation on unofficial libraries or sensors *will not* be accepted. This process may take some time to review, please be patient.

Minor revisions and rewrites will be accepted at a more generous rate.

This document contains the various RST/Sphinx specific guidelines for the frc-docs project. For guidelines related to the various WPILib code projects, see [the WPILib Github](#)

## 31.1 Filenames

Use only lowercase alphanumeric characters and - (minus) symbol.

For documents that will have an identical software/hardware name, append “Hardware” or “Software” to the end of the document name. IE, ultrasonics-hardware.rst

Suffix filenames with the .rst extension.

---

**Note:** If you are having issues editing files with the .rst extension, the recommended text editor is [Notepad++](#). Please make sure that [tabs are replaced with spaces](#), and the space indentation is set to 3.

---

## 31.2 Page References

Pages references will be auto-generated based on the page filename and section title.

For example, given the following file `contributing.rst` and a section called Page References, you would reference this by doing `:ref:`contributing:Page References``

---

**Note:** Please note that document structure is preserved in references, with the root being the location of the `conf.py` file. To access documents in sub-folders, simply prepend the folder path before the filename. IE, `:ref:`docs/software/sensors/ultrasonics-sensors:Ultrasonics - Sensors``

---



## 31.3 Text

All text content should be on the same line, if you need readability, use the word-wrap function of your editor.

Use the following case for these terms:

- roboRIO (not RoboRIO, roboRio, or RoboRio)
- LabVIEW (not labview or LabView)
- Visual Studio Code (VS Code) (not vscode, VScode, vs code, etc)
- macOS (not Mac OS, Mac OSX, Mac OS X, Mac, Mac OS, etc.)

Use the ASCII character set for English text. For special characters (e.g. Greek symbols) use the [standard character entity sets](#).

Use `.. math::` for standalone equations and `:math:` for inline equations. A useful LaTeX equation cheat sheet can be found [here](#).

Use literals for filenames, function, and variable names.

Use of the registered trademarks *FIRST*® and FRC® should follow the Policy from [this page](#). Specifically, where possible (i.e. not nested inside other markup or in a document title), the first use of the trademarks should have the ® symbol and all instances of *FIRST* should be italicized. The ® symbol can be added by using `.. include:: <isonum.txt>` at the top of the document and then using `*FIRST*\ |reg|` or `FRC\ |reg|`.

## 31.4 Whitespace

### 31.4.1 Indentation

Indentation should *always* match the previous level of indentation *unless* you are creating a new content block.

Indentation of content directives as new line `.. toctree::` should be 3 spaces.

### 31.4.2 Blank Lines

There should be 1 blank lines separating basic text blocks and section titles. There *should* be 1 blank line separating text blocks *and* content directives.

### 31.4.3 Interior Whitespace

Use one space between sentences.

## 31.5 Headings

Headings should be in the following structure. Heading underlines should match the same number of characters as the heading itself.

1. = for document titles. *Do not* use this more than *once* per article.
2. - for document sections
3. ^ for document sub-sections
4. ~ for document sub-sub-sections
5. If you need to use any lower levels of structure, you're doing things wrong.

Use title case for headings.

## 31.6 Lists

Lists should have a new line in between each indent level. The highest indent should have 0 indentation, and subsequent sublists should have an indentation starting at the first character of the previous indentation.

```
- Block one
- Block two
- Block three

  - Sub 1
  - Sub 2

- Block four
```

## 31.7 Code blocks

All code blocks should have a language specified.

1. Exception: Content where formatting must be preserved and has no language. Instead use text.

Follow the [WPILib style guide](#) for C++ and Java example code. For example, use two spaces for indentation in C++ and Java.

## 31.8 Admonitions

Admonitions (list [here](#)) should have their text on the same line as the admonition itself. There are exceptions to this rule however, when having multiple sections of content inside of admonition. Generally having multiple sections of content inside of an admonition is not recommended.

Use

```
.. warning:: This is a warning!
```

NOT

```
.. warning::
  This is a warning!
```

## 31.9 Links

It is preferred to format links as anonymous hyperlinks. The important thing to note is the **two** underscores appending the text. In the situation that only one underscore is used, issues may arise when compiling the document.

```
Hi there, `this is a link <https://example.com>`__ and it's pretty cool!
```

However, in some cases where the same link must be referenced multiple times, the syntax below is accepted.

```
Hi there, `this is a link`_ and it's pretty cool!
```

```
.. _this is a link: https://example.com
```

## 31.10 Images

Images should be created with 1 new line separating content and directive.

```
.. image:: images/image-1.png
```

### 31.10.1 Image Files

Image files should be stored in the document directory, sub-directory of `images`

They should follow the naming scheme of `document-title-1.png` so on and so forth.

They should be of the `.png` or `.jpg` image extension. `.gif` is unacceptable due to lack of Sphinx support.

## 31.11 Table of Contents (TOC)

Each category should contain an `index.rst`. This index file should contain a `maxdepth` of 1. Sub-categories are acceptable, with a `maxdepth` of 1.

The category `index.rst` file can then be added to the root index file located at `source/index.rst`.

## 31.12 Examples

```
Title
=====
This is an example article

.. code-block:: java
```

(continues on next page)

(continued from previous page)

```
System.out.println("Hello World");
```

Section

-----

This is a section!

## **31.13 Important Note!**

This list is not exhaustive and administrators reserve the right to make changes. Changes will be reflected in this document.



## Build Instructions

This document contains information on how to build the HTML, PDF, and EPUB versions of the frc-docs site. frc-docs uses Sphinx as the documentation generator. This document also assumes you have basic knowledge of [Git](#) and console commands.

### 32.1 Prerequisites

Ensure that [Git](#) is installed and that the frc-docs repository is cloned by using `git clone https://github.com/wpilibsuite/frc-docs.git`.

#### 32.1.1 Windows

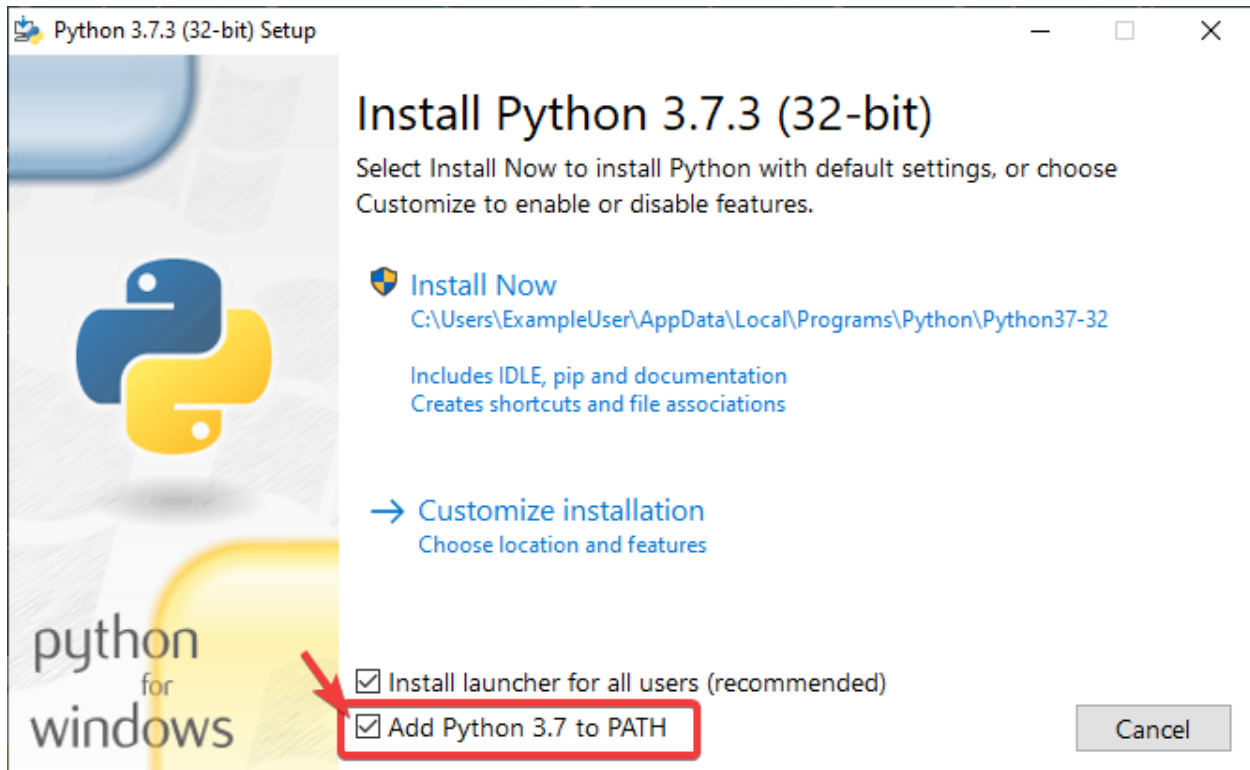
---

**Note:** The majority of MikTeX packages are not required for building HTML, additional packages may be required for building PDF and EPUB.

---

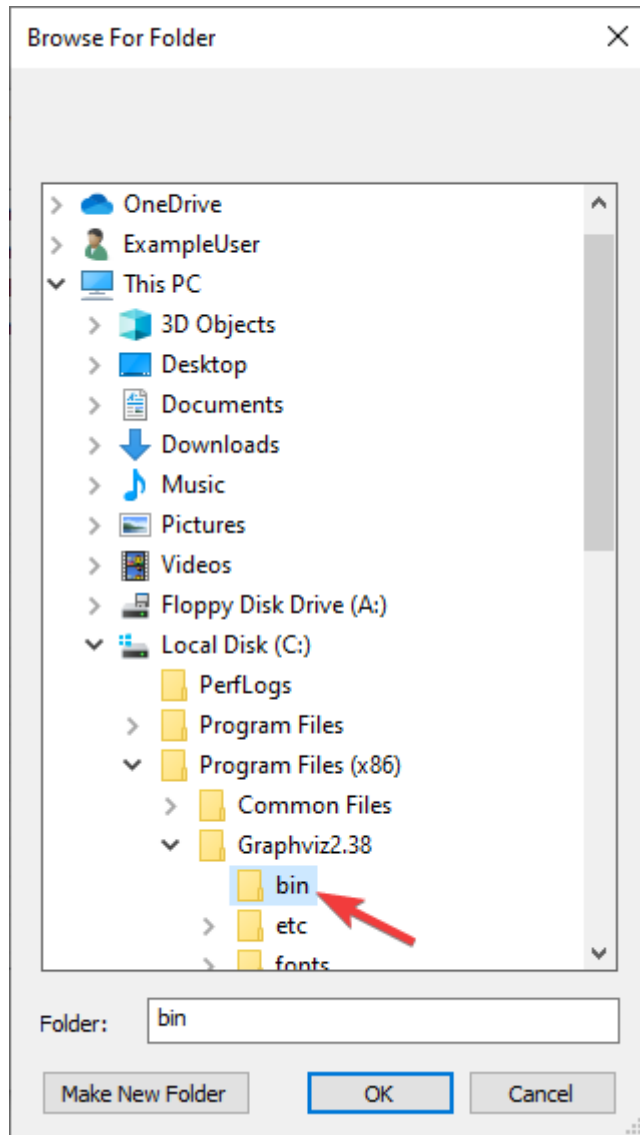
- [Python 3.6 or greater](#)
- [MiKTeX](#)
- [GraphViz](#)
- [Perl](#)

Ensure that Python is in your Path by selecting the **Add Python to PATH** toggle when installing Python.



Once Python is installed, open up Powershell. Then navigate to the frc-docs directory. Run the following command: `pip install -r source/requirements.txt`

Ensure that the GraphViz bin folder is correctly linked in your [Path](#). By default, this folder is located at `C:\Program Files (x86)\Graphviz2.38\bin`.



Install the missing MikTeX packages by navigating to the frc-docs directory, then running the following command from Powershell: `mpm --verbose --require=@miktex-packages.txt`

### 32.1.2 Linux (Ubuntu)

```
$ sudo apt update
$ sudo apt install python3 python3-pip
$ python3 -m pip install -U pip setuptools wheel
$ python3 -m pip install -r source/requirements.txt
$ sudo apt install -y texlive-latex-recommended texlive-fonts-recommended texlive-
↳ latex-extra latexmk texlive-lang-greek texlive-luatex texlive-xetex texlive-fonts-
↳ extra dvipng graphviz
```



## 32.2 Building

Open up a Powershell Window or terminal and navigate to the frc-docs directory that was cloned.

```
PS > cd "%USERPROFILE%\Documents"
PS C:\Users\Example\Documents> git clone https://github.com/wpilibsuite/frc-docs.git
Cloning into 'frc-docs'...
remote: Enumerating objects: 217, done.
remote: Counting objects: 100% (217/217), done.
remote: Compressing objects: 100% (196/196), done.
remote: Total 2587 (delta 50), reused 68 (delta 21), pack-reused 2370
Receiving objects: 100% (2587/2587), 42.68MiB | 20.32 MiB/s, done.
Receiving deltas: 100% (1138/1138), done/
PS C:\Users\Example\Documents> cd frc-docs
PS C:\Users\Example\Documents\frc-docs>
```

### 32.2.1 Lint Check

---

**Note:** Lint Check will not check line endings on Windows due to a bug with line endings. See [this issue](#) for more information.

---

It's encouraged to check any changes you make with the linter. This **will** fail the buildbot if it does not pass. To check, run `.\make lint`

### 32.2.2 Link Check

The link checker makes sure that all links in the documentation resolve. This **will** fail the buildbot if it does not pass. To check, run `.\make linkcheck`

### 32.2.3 Building HTML

Type the command `.\make html` to generate HTML content. The content is located in the `build/html` directory at the root of the repository.

## 32.3 Building PDF

Type the command `.\make latexpdf` to generate PDF content. The PDF is located in the `build/latex` directory at the root of the repository.

## 32.4 Building EPUB

Type the command `.\make epub` to generate EPUB content. The EPUB is located in the `build/epub` directory at the root of the repository.

**Top Contributors**

- [Daltz333](#) - 230 contributions
- [Oblarg](#) - 98 contributions
- [sciencewhiz](#) - 72 contributions
- [prateekma](#) - 30 contributions
- [AustinShalit](#) - 19 contributions
- [Kevin-OConnor](#) - 16 contributions
- [yellowjaguar5](#) - 9 contributions
- [ThadHouse](#) - 8 contributions
- [mcm001](#) - 7 contributions
- [PeterJohnson](#) - 7 contributions



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