A Primer on Electronics & Wiring in FRC

The intent of this document is to teach you (the reader) enough to go and do your own research and make your own informed decisions using the muscle between your ears about motors and their use in FRC. It is not an end-all-be-all but hopefully will introduce you to the tools we'll be using throughout and teach you to use them yourself.

Tim Flynn

Special thanks to my editors & contributors (in no particular order):
Solomon (2898 Alumni), Howard Cohen, Allen Gregory, Marshall Massengill, Jordan (1902), Set (5663), Abby Petruga.

Tips, Tricks and Advice

"Steal from the best, invent the rest." - Mike Corsetto

"Trust the process, keep iterating, chase excellence." Team 148 & John V Neun

"Touch it, own it." - Fabled FRC Proverb

K.I.S.S (Keep It Simple, Stupid) - Less parts means easier to build, easier to repair, easier to operate, and the more time you can spend practicing, iterating, and improving.

“Red To Red, Black To Black” - Basic Electrical Circuits

The core of any electrical circuit is a power source, a sink, and a closed loop. This means that something generates the flow of electrons (electricity), and it has a path to traverse. An open circuit means there’s a break, the circuit doesn’t work if it’s open. A closed circuit is functional and operational, a flow from source to destination is intact.

In FRC, our electricity source is the robot battery, a sealed lead acid battery with two terminals, a positive (+) and a negative (-). They go into an Anderson SB50 (formal name for a robot battery connector), which connects to our power distribution panel. Not to get ahead of ourselves, let’s explain the stuff in the wires a little bit more, being electricity, and its properties.

Voltage (V)

If we’re describing electricity, voltage is probably the unit you’re most familiar with. You know about 1.5V batteries, AA, AAAs, and so on. Your car battery is 12V and the wall is 120V. Volts are a unit of measurement for “pressure” of electricity: the force at which it flows through a wire.

Resistance (Ω)

In hydro-mechanical terms, resistance is the width of the pipe. Just like a smaller pipe means that it takes more force for the same volume of water to flow through, a circuit with a higher resistance takes more voltage to move the same amount of electricity (current) through.

Amperage (A)

To continue the analogy of electricity being water, amperage is the unit of gallons per minute. Amperage, or “amps” for short, is a measure of electrical flow through the wire. While a circuit is forced to receive the voltage supplied to it, it can draw as many or as little amps as it needs, governed by the ability of the source to regulate voltage at higher amperages. Generally, this amperage draw is regulated by the resistance of the circuit, giving way to Ohm's Law: $V = IR$, or the number of volts supplied is equal to the number of amps drawn times the resistance of the system, in Ohms.

Wattage (W)

Together, voltage and amperage form wattage, or the total deliverable energy of both the flow and the rate. For example, the wall voltage (in the United States) is approximately 120 volts and can supply up to about 15 amps, giving us a total maximum wattage of 1,800 watts. For this reason, if someone is trying to sell you a ten thousand watt stereo system, some critical thinking lets us know this is pretty much impossible.

Wire Standards

In the world of electronics, some physical properties are universally accepted for safety and commonality reasons. This holds true in FRC, with specific colors and sizes meaning different things, indicating different purposes.

Common Wire Meanings

In electronics, there are some understandings of wires and their color codes that folks should know.

Red - The positive terminal of battery-supply electrical circuits.
Black - The negative or return terminal of battery-supply electrical circuits.

Red and black typically denote a battery connection, whether through the PDP or directly to the battery (from the PDP) if the wire is large. For thin and small wires, it sometimes is signaling devices like sensors or control wires.

If you take nothing else out from this document, do not wire red to black or vice versa. Red as positive and black as return are virtually universally everywhere.

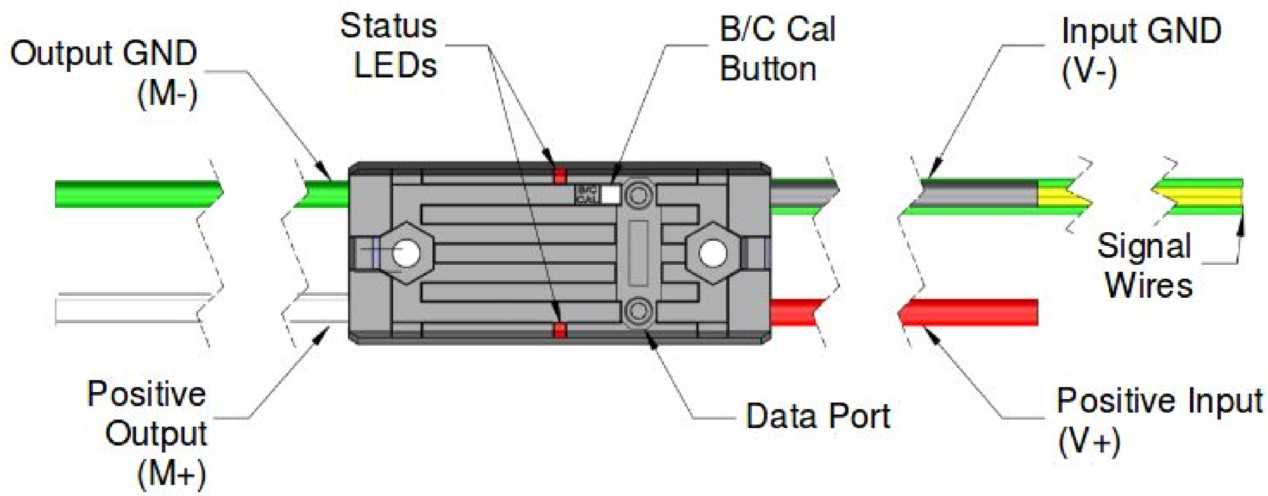
Green & Yellow

Small thin green & yellow wires are CANbus, the method of communication between portions of the FRC control system. This is distinct from larger wires in:

Green - Motor controller negative terminal. (M-)
White - Motor controller positive terminal. (M+)

The Green / White colors for wiring are typically reserved for motor controllers from Crossing The Road Electronics, but it's still useful to be familiar with.

See the CAN section for more information about CANbus.

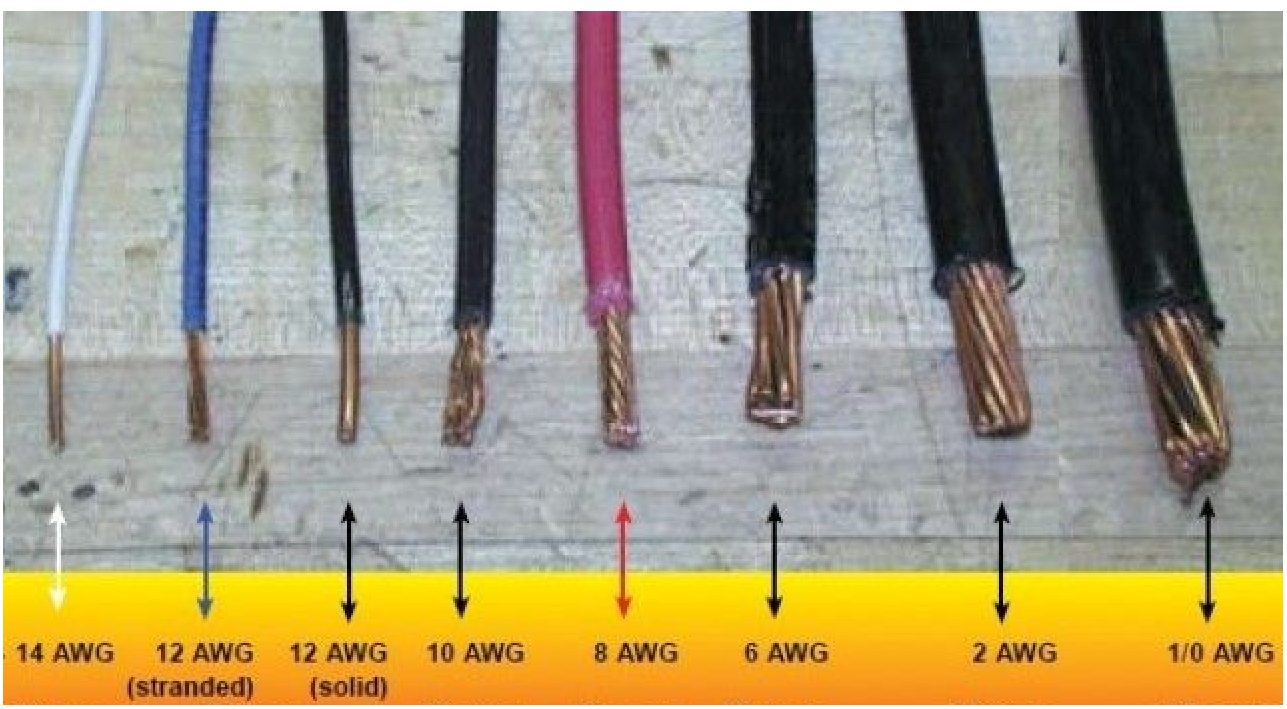


(Talon SRX, Crossing The Road Electronics)

Wire Gauges

Electronics wires have a concept of size much like many other things, but the standard for wire size is measured in ‘AWG’, or American Wire Gauge. The uncommon attribute about the scale is the *smaller* the number is the larger the thickness of the wire. In FRC, our battery cables (traditionally) are 6AWG, our motor controller wires 12AWG, and our signaling cables 18AWG or thinner.

(Please refer to the appropriate game manual for rules reference.)



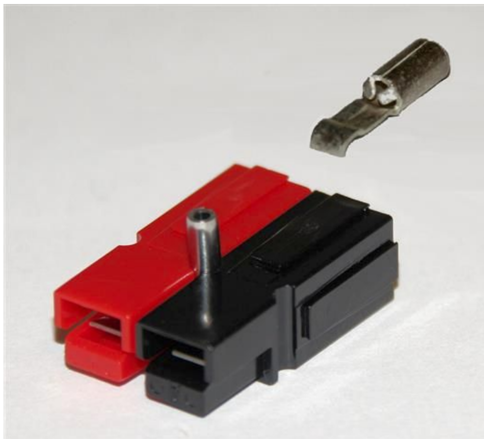
(Wire Gauge Sizes, Sonic Electronix)

Connectors & Terminals

In FRC, some connectors are frequently used for varying purposes, and a brief outline to familiarize yourself with them may prevent some headaches or breakdowns in communication. The two major types of connectors are soldered or crimped. Powerpoles, Dupont, and SB50s are all crimped connectors, relying on mechanical force for electrical connections. The XT60 family of connectors are all soldered connectors, and require a soldering iron to correctly operate.

Anderson Powerpole

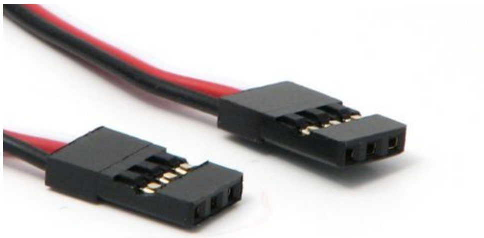
This small blocky connector is used frequently in FRC for ease of use and stock support of up to 45A circuits, with pin options available in 15 and 30A additionally. With both retaining pins and a modular design, these connectors have made it easy to not only keep wires together, but able to seperate them when you need to. A How-To-Use Guide can be found here.



(Anderson Powerpole, W2VTM)

Dupont Connector

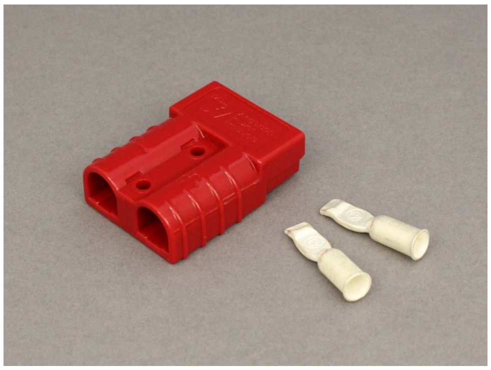
These small, lightweight terminals have made signal wiring easy to install and expand, and have found significant usage in many projects. In FRC, their primary use are for PWM connections (both on the roboRIO and motor controller), and more recently for CAN connections (on the motor controller). They're typically pre-assembled, but kits can be purchased.



(Dupont Connector, MindSensors)

Anderson SB50

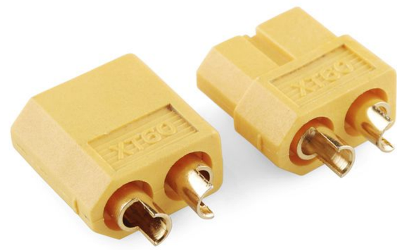
A larger variant of the Powerpoles mentioned earlier, these take 6AWG wire and are used in FRC for battery connections. Battery SB50s are typically red or pink in color. These crimped connectors typically use a hydraulic crimper to get terminals on, due to their large mechanical mass.



(SB50, 12 Volt Planet)

XT60

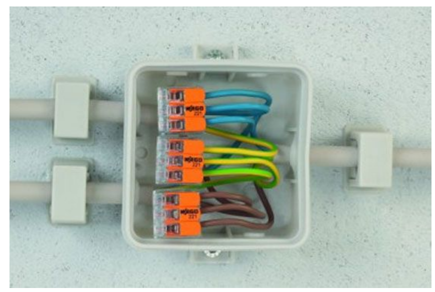
The XT60 is a versatile connector typically used in model and remote control aircraft. These soldered and polarized connectors can only be done one way, but prevents issues like plugging motor controllers in backwards or to other motor controllers (and subsequently breaking them).



(XT60, SparkFun)

Wago Lever Nut

The Wago locking terminal enables teams to connect wires electrically both quickly and easily, and without soldering. Also known as "lever nuts", these work in a pinch for smaller wires but for thicker wires many teams advise against using them. You stick a few wires in, flip the levers, and they're now electrically connected.



(Wago Levernut, ToolGuyD)

Screw Terminals

While not as common as other connectors, the FRC Control System requires the use of "screw terminals", where wire is stuck into a hole and a screw is tightened to apply mechanical force to it to have electrical contact. The two most common places you'll see this is the roboRIO power harness and the Robot Signal Light's wiring.

(RSL, ScreenStepsLive)

Ferrules

Ferrules are off-the shelf terminals for wires to be inserted into designated ports, without fear of fraying wires shorting or other issues. They're incredibly helpful for multitudes of adjacent connectors, like the PCM or VRM. These can come in a variety of colors and sizes.

(Ferrules, FerrulesDirect)

Tools Of The Trade

There are several tools that are always essential to use in FRC electronics, even though many teams aren't familiar with them. These can make your life significantly easier throughout the process of building up the control systems on a robot. More information on electrical tooling can be found in the Spectrum FRC Electrical Guide.

Multimeter

(Multimeter, Wikipedia)

The multimeter is a venerated tool of electronics, capable of metering voltage, current draw, and resistance across two points (acting as an ohmmeter). Having one in your toolkit is an easy way to check continuity between two wires in a connector chain, that a PDP port is functional, and lots of other critical tasks' status.

Crimper

A crimper is a tool used to close a mechanical connection between contact pins in electrical connectors and wires. They often can take a variety of shapes and sizes, anywhere from thin, small wires to large lugs for batteries. Due to the large variation in need and relatively low frequency, they can vary in cost significantly.

Strippers & Cutters

Wire strippers are responsible for removing the insulating outer layer of a wire. They're appropriately sized to the wire gauge, typically in ranges of 12-20 and 12-6 due to the size distribution and typically being hand-held tools. Using the right gauge on the wire stripper is essential to getting a good electrical contact in a crimper. Cutters are useful for flat, precision cuts when stripping wires, as typically a bad cut can prevent you from easily using strippers, or using ferrules.

Zip Ties & Fasteners

While not strictly a "tool", zip ties and other fasteners are essential for the layout of your electrical system. Zip ties can offer mechanical support or simply keep wires out of the way, and reclosable fasteners like Dual-Lock or Velcro (hook and loop) can easily secure larger components and electronics, as well as keep them out of the way and not prone to being damaged on the field. Keep this in mind throughout the design phase of your robot, not as an afterthought. Power doesn't get transferred wirelessly.

The FRC Electrical Flow

Each and every robot in FRC has a set of common components that generally have to be met to not only be legal, but functional as a robot in the eyes of the rules. For that reason ***please check the rules of the game you're playing and use it as your final authority, not this document.***

Control Systems Components

There are some components that all robots will have, and you *will* need to be able to compete. Any one of these not working severely impedes your ability to compete.

RoboRIO

The RoboRIO is the brains of your robot, emitting all control systems signals for servos, sensors, motor controllers, the works. It's what runs your robot code and breaks at the most inopportune times. It takes a 12V input off of a dedicated fuse on the PDP, connects to the Radio over Ethernet, and to your motors over PWM and / or CAN.

PDP

The Power Distribution Panel (PDP) is responsible for the dispersal of electrical signals from the robot battery to all motor controllers and control systems components. All electricity on the robot must first pass through the PDP. It has 16 black and red "clamp style" slots for wires to be inserted, and two fuse holders and a Weidmueller connector block for the electrical paths to the VRM, RoboRIO, and PCM. A good bit of advice with the PDP is to cover the open and unused fuse ports with tape such that metal fragments don't land in it and cause a short.

VRM

The Voltage Regulator Module (VRM) is responsible for conditioning the input of the robot battery's voltage and keeping it steady to run low-current but essential parts of the control system, like your robot radio and other delicate circuits through 12V and 5V Weidmuller connectors.

PCM

The Pneumatics Control Module (PCM) is responsible for the control of solenoids and pneumatics on your robot. It offers twelve Weidmuller connectors for solenoids, and a 24V voltage supply should you choose to use it. The control signals are sent to the PCM from the roboRIO over CAN, and must be connected correctly to be used in competition or it'll be non-functional.

You are not required to have a PCM on your robot if you're not using pneumatics.

PWM

PWM is less of a component of the Control System and more a type of information conveyance. PWM stands for "Pulse Width Modulation", sending data in the form of a signal turning off and on at an arbitrary rate. This rate, and changes in it, convey data to output devices, typically motor controllers, on how fast to spin a motor, and in what direction. This is expressed by a signal being between a high and low range, with a "deadband" of not-spinning in the middle of those two ranges. In FRC, we occupy the same ranges regardless of control system code or motor controller, and as such don't need to worry about the range itself. Outside of FRC however, the ranges are non-standardized and maybecome more of an issue.

CAN

CAN stands for "Control Area Network" and is significantly more difficult to explain than PWM. Rather than express information in the form of a signal being turned on and off quickly like PWM, CAN is a network protocol over the green-and-yellow twisted pair on your robot. This is more akin to Ethernet than anything else, and as such, has many more features. In FRC, CAN enables us to have sensor data sent back from motor controllers whereas PWM is a monodirectional transfer of information.

Additionally, CAN is a bus protocol, meaning that rather than having to turn every device on the CAN network back to a central point, you can connect the end of one device to the start of another, offering a chain-like solution to connectivity, saving space and time.

Radio

The robot radio is one of the most important parts of your robot. It sends data back and forth between your driver station and the robot, especially on the field. It is essential that it be tested, checked, and properly working both before and at competition. The 2018 radio models have two ethernet ports, and one power jack. Power can be delivered to the radio via Power over Ethernet (PoE Injector) as provided in the 2018 Kit of Parts, or via Barrel Jack, with either of them connected to the VRM.

Breakers & Fuses

Breakers and fuses are components of the FRC electrical flow that ensure that your robot doesn't use more energy than it should. As described in "Amperage", you can pull more energy out of a circuit than can be supplied by it, causing all sorts of issues. Fuses and breakers keep both individual components like motors, and the overall robot, from exceeding limits on current draw. The largest individual fuse is 40A, and the legal FRC breaker is 120A. Your systems can briefly exceed this, but shouldn't be designed around doing so.

The fuses in your PDP are self-resetting, meaning if tripped they'll automatically come back on fractions of seconds later. However, the main robot breaker is not. If you trip it during the match, it won't turn back on until you can go to the robot and flip the breaker. A toggle of both of them reduces their overall lifespan significantly, and be sure to test and check old fuses before putting them on your robot. You can avoid some of the damage by using current limiting on your motor controllers, should they support it.

Sensors

To get data for use in FRC, there are a slew of sensors that may be useful to teams, especially for a given game task. All of them require some programming to use properly, and usually connect to the DIO pins on your roboRIO or some other input section on your robot.

Encoders

Encoders are small electrical components that count the angle of an input shaft. This is useful for measuring distances on drivetrains, speed of shooter assemblies, and countless other things. The major variety used in FRC is a rotary encoder, and have additional subvarieties that can be used. Some commonly used ones are Greyhill 63Rs and SRX Mag Encoders.

(SRX Mag Encoder, VEXpro)

Ultrasonic Sensor

An ultrasonic sensor relies on the principle of sound, sending out a precise tone on one half and listening for it on the second half. Using the known idea of the speed of sound, it can relatively accurately measure how far away something is.

(Ultrasonic Sensor, RobotShop)

Switches

Through the use of buttons, large and small, we can detect whether a mechanical assembly is in a place it's supposed to be, or has hit its limit. The most common variety of these are limit switches, small forced-based options connected to motors to prevent driving them beyond limits of an assembly. For newer solutions some teams have taken to using VEX Bumper Switches, for observation in a code-friendly place.

Troubleshooting

The troubleshooting process is no easy topic to go about documenting, but it's an important one. When something inevitably goes wrong with your electronics at competition, there is a process one can follow to make troubleshooting easier and faster. You'll almost always want to start from the top of your circuit, so let's start there. In addition, the FRC Inspection Checklist might be a helpful document to review during the build season.

Isolation

The concept of electrical isolation isn't new to FRC, but it is an important one. Given that both conductors need to be functional for a circuit to work, and electricity tries to take the path of least resistance, a badly stripped pair of wires with whiskers (thin strands sticking out) can cause all sorts of issues, hence the use of ferrules. For bare metal exposed in things like battery lugs, heat shrink tubing is incredibly helpful to prevent a dropped tool from bridging terminals.

Improper/ poor wiring and isolation is a leading cause for damaging electrical components.

"Tug-Testing" Wires

Because wires in most connectors rely on a strong mechanical connection, a simple way to see if they're functioning properly is to tug on the wire. If the terminal, connector, or any part easily falls out, then you likely need to re-do the assembly.

Static Damage

In the 2018 and 2009 FRC games, the field had pieces that when rubbed against would generate massive amounts of static electricity with a high potential to damage your control system components. Try to avoid having plastics in direct contact with the field carpet, and / or ground your frame with a drag chain. During troubleshooting, never discount the possibility of a failed component, and having spares is most likely for the best.

Troubleshooting Checklist

- ❏ Battery
    - ❏ Check all of your SB50s.
        - ❏ Tug test, are they loose?
        - ❏ Is there gunk on the terminals preventing contact?
        - ❏ Is the connector housing damaged at all?
    - ❏ Check the wires.
        - ❏ Are they connected at both ends?

        - Are they damaged at all?
    - Check the main breaker.
        - Tap the switch lightly to see if your electronics go on and off.
    - Check voltage of battery after several minutes of removal from charger.
        - If you have a battery beak, use it.
- PDP
    - Is the PDP connected to the SB50?
    - Are the PDP status lights on?
    - Are your fuses seated properly?
    - Are all wires connected properly?
        - Tug test, are they loose?
    - Is the CAN wire connected to your CAN chain?
- VRM
    - Is the VRM connected to the PDP?
        - Tug test both ends.
    - Are both the 5V and the 12V lights on?
    - Are the peripherals connected to the 5 and 12V rails on?
- Radio
    - Are the status lights on?
    - Is your radio connected to the VRM?
    - Is your radio connected to the RoboRIO?
    - Is the radio reprogrammedfor the event you're at?
    - Is your driver station configured correctly?
- RoboRIO
    - Is the roboRIO on when the robot is on?
    - Has the roboRIO been imaged for the competition season?
    - Has any additional software (CTRE libraries) been installed as needed?
    - Does your driver station report any errors?
    - Has robot code been pushed to the robot? (run at start-up for java/C)

While the above list is far from comprehensive, it should help with *some* of the issues you'll face at competition. The most common technique for troubleshooting is to "split the system" when troubleshooting. Follow the path from start to finish and see what works or doesn't.

For a motor controller, the path might be:
Battery -> SB50 -> PDP -> Fuse -> Anderson -> Motor Controller -> Motor
If your failure is at the motor controller step, everything leading up to it might work, but the motor won't. Be wary that phantom symptoms might show up in places you don't expect, but may not be the root cause.

References

Wire Standards

- Common Wire Meanings
  - Talon SRX (Crossing The Road Electronics, Talon User Guide pg. 4)
  - Wire Gauge Sizes (Sonic Electronix)

Connectors & Terminals

- Anderson Powerpole (W2VTM) / How-To-Guide (Grin Tech)
- Dupont Connector (MindSensors)
- SB50 (12 Volt Planet)
- XT60 (SparkFun)
- Wago Lever nut (ToolGuyD)
- Screw Terminal (ScreenStepsLive)
- Ferrules (FerrulesDirect)

Tools Of The Trade

- Spectrum FRC Electrical Guide (FRC 3847)
- Multimeter (Wikipedia)

The FRC Electrical Flow

- Control Systems Components
  - RoboRIO (Manual, National Instruments)
- Sensors
  - SRX Mag Encoder (VEXpro)
  - Limit Switches (FIRST Choice by AndyMark) / (Wikipedia)
  - Bumper Switches (VEX EDR)
- Troubleshooting
  - FRC Inspection Checklist (2018 *FIRST*)