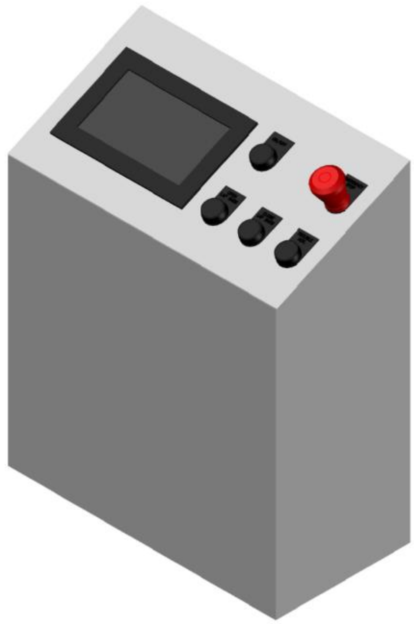

XEM

X-Car Electrical Maintenance Tool

Operations & Maintenance Manual

Alexander Washington - EE, Matthew Hunt - EE

HRRR PROJECT 80085

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1. Executive Summary

A multifunctional application specific tester will be developed for the Hollywood Rip Ride Rockit roller coaster ride vehicles at Universal Studios Orlando. The ride vehicles at Hollywood Rip Ride Rockit feature an electrical system that when entering the load and unload station, connects to the Ride Control System (RCS). The Ride Control System monitors the status the lap bars, controls the opening and closing the lap bars, monitors the current station sector the electrical system is connected to and monitors the operators request to dispatch through RFID sensors.

At distribution of this document, the Ride Control System at the Hollywood Rip Ride Rockit is the only system that interacts with the electrical system upon the ride vehicles that operate on the Hollywood Rip Ride Rockit. All system checks are performed by the Ride Control System. These system checks, however, do not provide enough information to assist with troubleshooting when a discrepancy may occur. The Ride Control System only reports a fault that it detected or did not detect a signal. The Ride Control System does not differentiate whether the signal was detected or not in report to the operator.

The connection to/from the ride vehicle completes the circuit in the RCS. From there the RCS can control and monitor components of the ride vehicle. Currently, troubleshooting abilities are sparse and often resort to replacing parts until the issues go away. This proposed tool referred to as the X-Car Electrical Maintenance tool, will provide the necessary functions to properly diagnose and provide direction towards areas needing troubleshooting. The tester will use Ohm’s laws, Kirchoff’s Laws and transmission line theories combined with software processes in order to provide detailed information about the ride vehicle circuit to the technical user. From the standpoint of the ride vehicle, the XEM will be the Ride Control System.

The hardware on the X-Car Vehicle Maintenance tool performs functions to solve for voltages, currents, resistances, power output and wire integrity. These functions are realized by manipulating voltage sources, known resistances, currents and signal propagation. Manipulating these components of the system along with using fundamental laws such as Ohm’s laws and Kirchoff’s laws allow these functions to be realized. The signal propagation is realized through digital signal processing. The analog signal propagation is estimated by taking measurements in discrete periods of time.

2. System Description

The X-Car Electrical Maintenance (XEM) tester tool was designed to be used for ride vehicles at Universal Orlando's Hollywood Rip Ride Rockit (HRRR). At HRRR, the ride vehicles are monitored and controlled for safe loading and unloading of guests. The safety is monitored through multiple redundant safety checks and controls. Due to the complexity of the system, everything must be operating within a tight tolerance in order to operate within the safety constraints.

The ride vehicle has circuitry onboard that act as a DUT to the Ride Control System (RCS) at HRRR. The onboard circuitry only acts as a DUT when traversing through load/unloading station. As a DUT, the system is checking the status of the lap bars, location in the station, operating the lap bars, and dispatch enable. When any of these DUT systems fail to operate, the RCS will stop the dispatch system for a fail-safe condition.

2.1. Motivation

At Universal Orlando in the Technical Services department, our top goals are safety and reliability. As a result, the technical services department does its best job to provide a safe and reliable environment for team members and guests. The development of this tool will allow for the Technical Services department to provide a more reliable ride system for guests and provide a safe method for the technical user to perform maintenance. The is no all-in-one tool that provides a safe technique and helps improve ride reliability for the ride system at Hollywood Rip Ride Rockit. There are several maintenance tools which operate independently at Hollywood Rip Ride Rockit. They all, however, provide limited troubleshooting capabilities and their methods are not set to official standards.

The motivation for this project is to promote the Technical Services goals of safety and reliability. By producing this design, the levels of safety and reliability will improve. This project will also provide a significant challenge to the designer to provide such functionality to the technical user. The challenge is also a motivation to the designer because of the desire to improve, learn and apply new technical and engineering skills.

2.2. Goals and Objectives

With the design of this project, the goal is to provide a maintenance tool that will help improve troubleshooting abilities in a safe and reliable way. The name of the tool will be named the X-Car Electrical Maintenance tool. The X-Car Electrical Maintenance tool will provide several means of performing electrical tests to a ride vehicle under test. The X-Car Electrical Maintenance tool will have several forms of connections in order to interface with the ride vehicle under test.

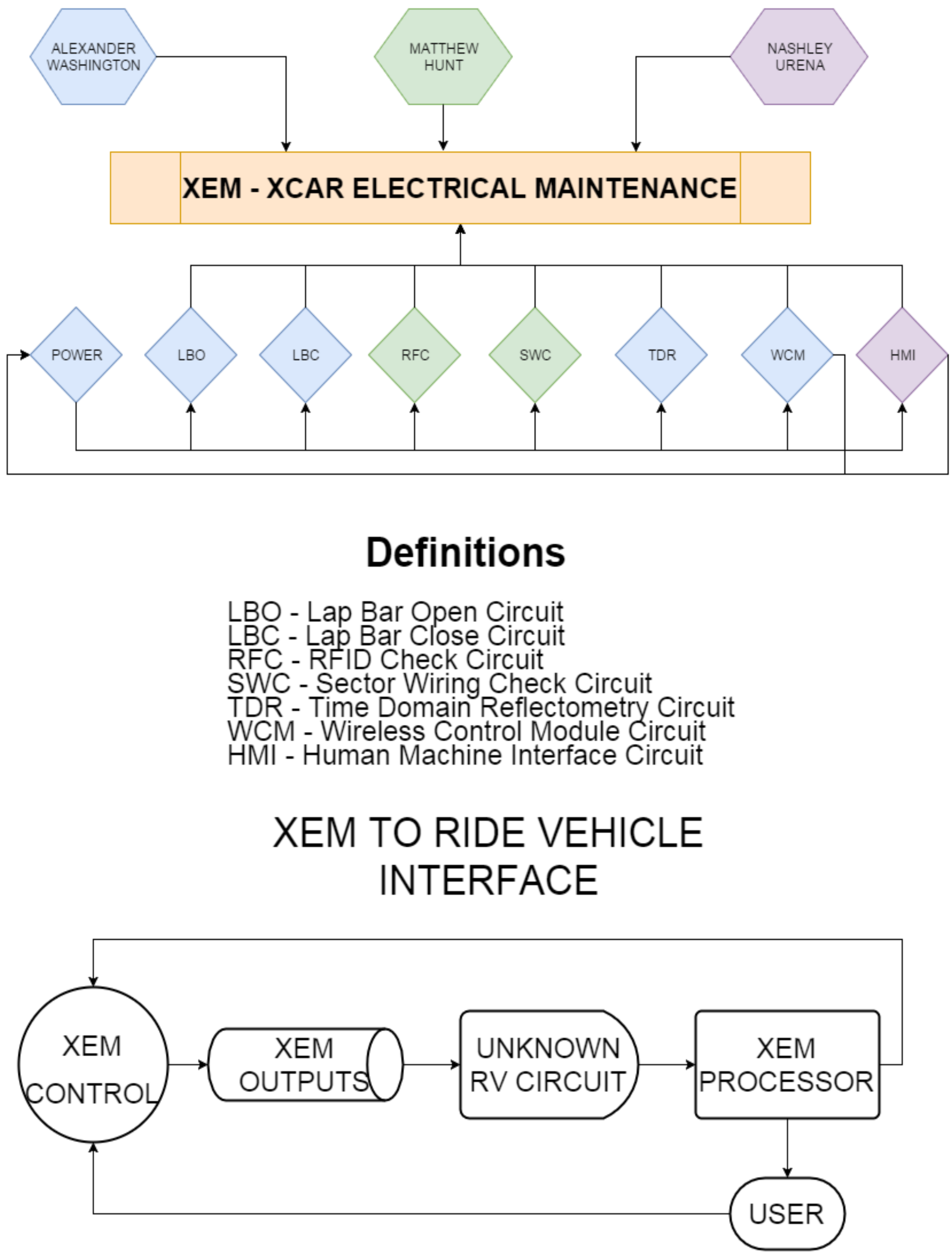

Figure 2-1: XEM System Block Diagram Overview

2.3. Overview

The X-Car Electrical Maintenance (XEM) troubleshooting tool was developed to eliminate troubleshooting bottlenecks. Current bottlenecks include a lack of high power output to operate lap bars, difficulty measuring weak connections, and testing the feedback signals from ride vehicles. The XEM will essentially simulate the RCS in the offline maintenance position allowing end users to troubleshoot more efficiently. Figure 2-1: XEM System Block Diagram Overview shows the basic overall block diagram and common terms of the system.

The RCS interfaces with the ride vehicle through use of a bus bar. The ride vehicle has current collector shoes on them which slide along the bus bar to maintain electrical connection. The ride vehicle is made up of two trains linked together with their own onboard circuitry. Each ride vehicle has 8 current collector shoes which have their own purpose. The RCS interfaces with them individually but recognizes them as a single ride vehicle. The XEM has a few different connectors which allow for troubleshooting different parts of the ride vehicle onboard circuitry. There is the Bus Bar Connector, the X21 Connector, and coaxial cable. All end user feedforward and feedback is implemented through a touch screen LCD. This LCD is referred to as the industrial standard term Human Machine Interface.

2.3.1. Bus Bar Connector

The Bus Bar Connector (BBC) interfaces with the eight current collector shoes on each train. The BBC is a pseudo bus bar that accepts collector shoes as a connection point. With the BBC, the lap bars can be operated, the RFID dispatch signal can be tested, the overall lap bar status (open/closed) can be tested, and the sector occupied status can be tested.

2.3.2. X21 Connector

The X21 Connector (X21) interfaces with seats individually. It uses a 10-pin HBE connector. There is a connector on each seat which the X21 can connect to. Through this connector the lap bar signal and the lap bar operation can be tested.

2.3.3. Coaxial Cable

The Coaxial cable is the test hook up for time domain reflectometry. This can connect to any wire not connected to a power source. It can test for bad connections, open circuits, or short circuits.

2.3.4. Human Machine Interface (HMI)

The HMI is part of the XEM which allows the end user to operate the XEM. It provides information regarding statuses, alarms, warnings, control, and safety functionality. The HMI is a 7” touch screen LCD. This is the main interface with the XEM other than the hardware push buttons. All modes, mode enables, mode triggers, and feedback information are provided to the user through the HMI. The HMI also records usage information and stores the current date and time. The HMI also provides minimal troubleshooting advice for the end user. Figure 2-2: Touch Screen LCD HMI shows the touch screen LCD that will be in use as the HMI.

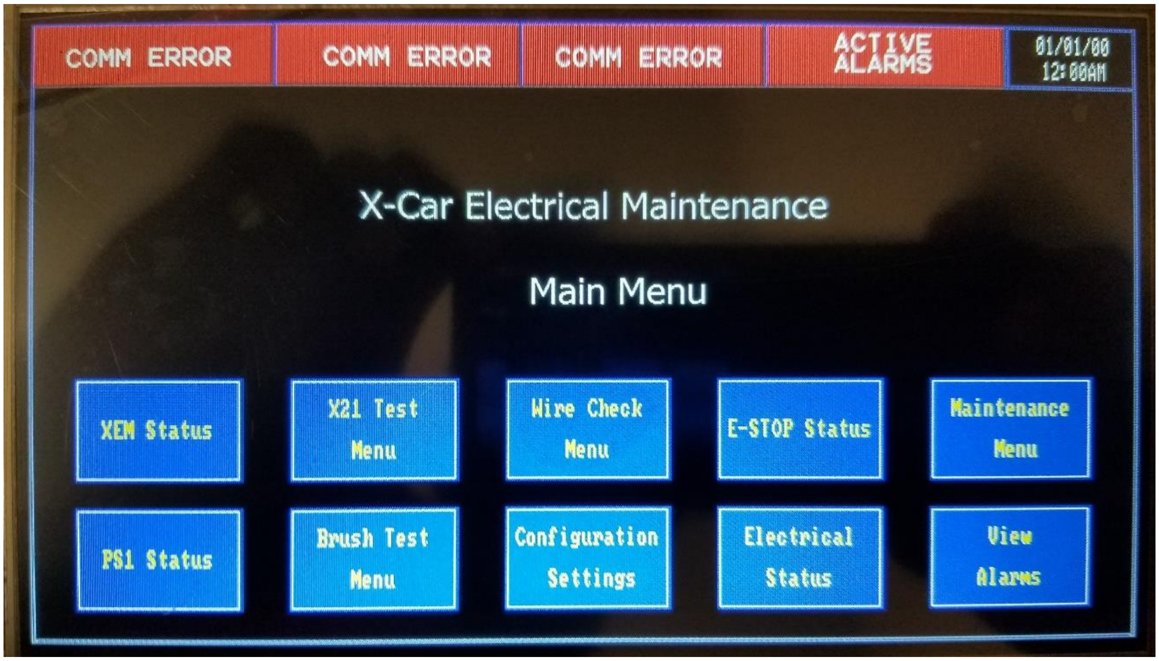

Figure 2-2: Touch Screen LCD HMI

2.4. Specifications

- The XEM will connect to the ride vehicle through busbar/collector shoes, a 10 pin HBE connector, or through a single coaxial connection point.
- The XEM will be powered by a 120V/20A socket.
- The XEM will provide 1.2kW of DC power at 24V.
- The XEM will detect resistances in the tenth of an ohm range.
- The XEM will detect voltages in the tenth of a Volt range.
- The XEM will detect voltages up to 28V.
- The XEM will detect currents up to 50A.
- The XEM will provide transmission line waveforms up to 100ft.
- The XEM will monitor 6 different control/signal lines on the ride vehicle.
- The XEM will operate the lap bar mechanism on the ride vehicle.
- The XEM will be transportable.
- The XEM will provide safety functions to prevent equipment damage and user injury.
- The XEM will provide fault monitoring of the hardware and messaging.
- The XEM lap bar operation can be controlled remotely.

2.5. House of Quality

The house of quality, depicted in Figure 2-3: House of Quality; Marketing & Engineering Aspects, is used to relate Market Aspects to Engineering Aspects and help the engineering team visualize how each aspect relates to each other. The Engineering Aspects are also each related to one another and their relationship depicted.

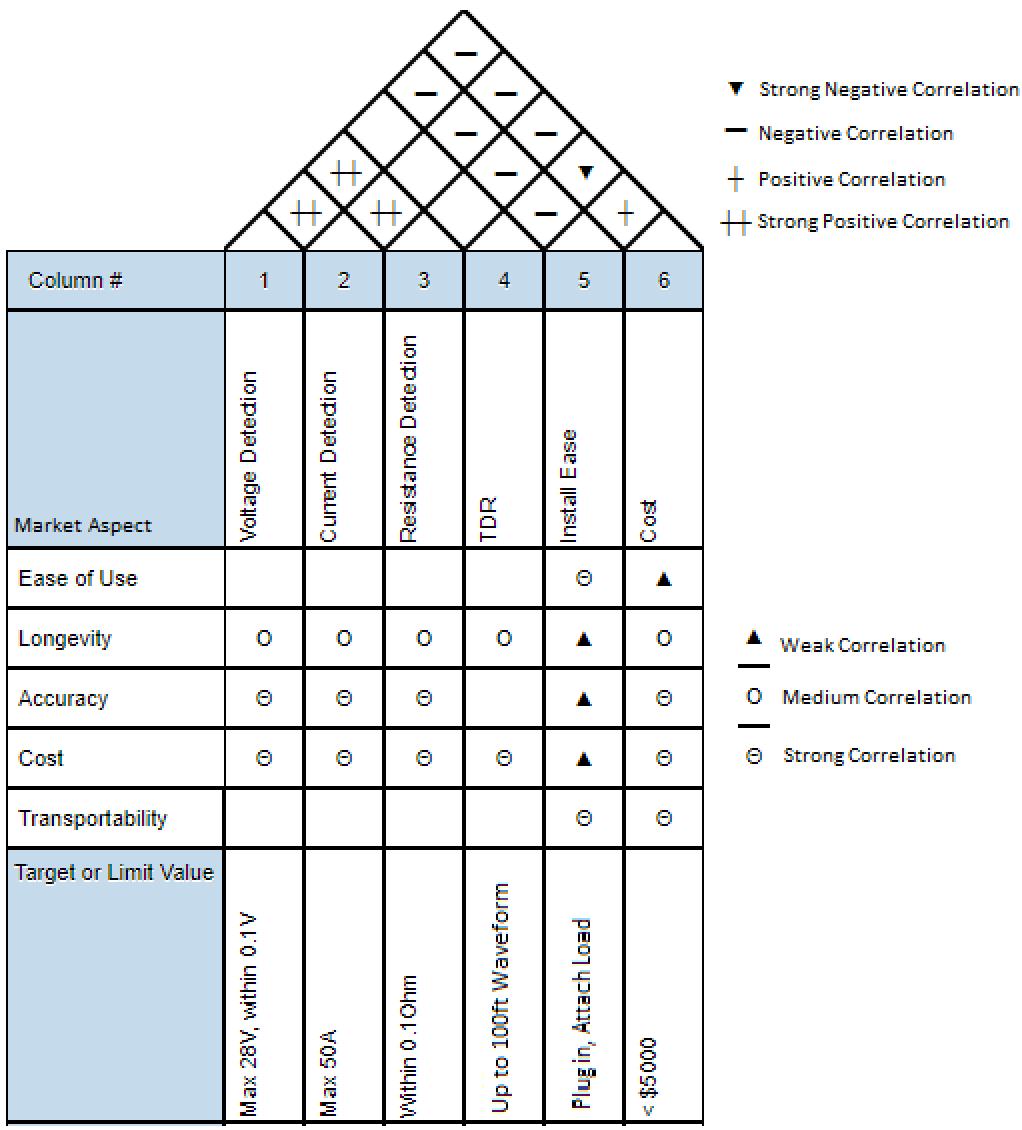

Figure 2-3: House of Quality; Marketing & Engineering Aspects

Market aspects are what a potential customer would want, or has set forth for the engineering team to meet. This could be things like minimal cost, high uptime, simple use without training, or size of the product. The Longevity of the system refers to how long the system can be used without needing service or repairs, and impacts the overall quality of parts and cost of the system. The accuracy of the system refers to how reliably the system detects and presents its reading to the user, which is directly related to the quality of the proposed voltage, resistance, and current measurement circuits. The cost of the system needs to be minimized while also keeping the validity of the system high. Finally, the system needs to be transportable, so it can be easily used on different attached systems.

The Engineering Aspects are set by the engineering team creating the system. They are similar to the Market Aspects, but are from the perspective of the engineers. The voltage detection circuit needs to be as accurate as possible and be able to measure up to twenty-eight volts within one tenth of a volt.

One of the current measurement circuits is based on the accuracy of the voltage measurement circuits, therefore the accuracy of this current measurement circuit has a high correlation to the voltage measurement circuit. The second current detection circuit is made using an application specific current sense amplifier. The current sense amplifier outputs a voltage that can be read by an analog to digital converter.

The resistance measurement can be done in two ways. One way is by combining the voltage measurement with the current measurement to determine the voltage drop over the device under test. The second resistance measurement utilizes a Wheatstone bridge circuit to measure the slight voltage difference between nodes to find the resistance.

The Time Domain Reflectometer, TDR, is a complex circuit that requires high accuracy and precision, and will negatively impact the cost of the XEM, as it is one of the most complex subsystems. Each detection circuit and the TDR all negatively impact the ease of installation as the system becomes more complex, the ideal goal would be for the XEM to be plugged into a power socket and attached to the load system for a simple installation. The cost of the system increases as all of the detection circuits become more accurate.

The voltage measurement, current measurement, and time domain reflectometer will be demonstrated, showing that each system is working and is within the set forth parameters: maximum of 28 Volt measurement within one tenth of a volt, a maximum of 50 amperes measurement, and a waveform of up to 100 feet. These will all be demonstrated on a load system that is a valid representation of the intended applicable load system.

The representative load system will have similar electrical characteristics to the actual load. The XEM will be connected to this representative system and will show that this test system is within the set forth parameters of the load system. Then different characteristics of the representative load system would be changed and measured again. After changing the characteristics of the representative load, such as by adding more resistance to the system, the XEM will run its measurement functions and then once the changed characteristics are no longer within the acceptable parameters the XEM will inform the user of the errors.

3. Research and Part Selection

Extensive research and part selection comparisons were performed in order to reach the engineering specifications. Main research was divided up in to several sections: power supply, voltage measurement hardware, resistance measurement hardware, microcontroller hardware, output controls hardware, time domain reflectometry hardware and human machine interface hardware.

3.1. Power Supply

The XEM has a multitude of power supply requirements to meet the engineering specifications. The power supply requirements were split in to two sections: high power and low power. The high power section only refers to 24V. The high power section of the 24V is spec'd out to supply 24V at 50A. The Low power section includes 24V low power, 12V low power, 5V low power and 3.3V low power.

3.1.1. High Power Selection

The high power section of the power supply specifications requires a 24V output with 1.2kW of power output. For this a power supply with minimum output of 50A at 24V was required. Due to the high power output, power efficiency is of highest constraint. Next is accuracy and ease of use and lastly safety.

The following three power supplies were researched from the electronics manufacturer Mean Well: RSP-2000-24, RCP-2000-24, and the RCP-1600-24.

Table 3-1: Power Supply Comparison; 24V High Power shows the main parameters that were compared between the power supplies. In this case the RSP-2000-24 was chosen because of the ease of use. They all match the 24V, 50A, 1.2kW power output specification but the RSP-2000-24 and the RCP-2000-24 win in this category because of the higher power output. Having a higher than necessary power output potential helps ensure that the regulated 24V is more stable and accurate. The RSP-2000-24 is a normally on power supply which is not the best configuration with safety being concerned but this can be circumvented through additional hardware.

Lastly, the connection type of the RSP-2000-24 is much more user friendly. No special connector is necessary to interface with the power supply. The connection is a screw terminal which allows any standard wire to connect. All the power supplies have the same error reporting and control. All the power supplies have roughly the same efficiency rating so this also was not a factor in the choice. All the power supplies also reach the same standards and are UL listed. All three power supplies also provide auxiliary power which is isolated from the 24V output. They each provide 5V and 12V which can be used for auxiliary components that need a constant power source.

Table 3-1: Power Supply Comparison; 24V High Power

PARAMETER	RSP-2000-24	RCP-2000-24	RCP-1600-24
MANUFACTURER	MEANWELL	MEANWELL	MEANWELL
MAX VOUT	28V	28V	30V
MIN VOUT	21V	21V	23.5V
MAX CURRENT	80A	80A	67A
MAX POWER	1920W	1920W	1608W
INPUT VOLTAGE	115VAC	115VAC	115VAC
INPUT CURRENT	16A	16A	15A
EFFICIENCY	90.50%	90.50%	91%
REGULATION	0.50%	0.50%	0.50%
SAFETY	NORMALLY ON	NORMALLY OFF	NORMALLY OFF
CONNECTION TYPE	SCREW TERMINAL	CUSTOM	CUSTOM
COST	$356.00	$365.00	$347.00

3.1.2. Low Power Supply Selection

The low power section of the power supply distribution does not explicitly have to meet an engineering specification but allows other systems of the XEM to reach specifications. The low power section has a main supply and sub-regulators to supply the correct voltages and power tolerances to systems of the XEM. There are three main low power sections required: 12V supply, 5V supply, 5V analog supply, ±5V supply, 3.3V supply and 3.3V analog supply.

The 12V supply selection is important because it is the main supply for the low power distribution. All the lower voltages, 5V supply, ±5V supply and 3.3V supplies, source their power from the 12V supply. The most important parameters that were considered for the 12V power supply were power output and form factor. For this, three power supplies were compared. The parameter comparison between each power supply is shown in Table 3-2: Power Supply Comparison; 12V Low Power Supply. All three power supplies compared have the same voltage output of 12V. All three power supplies compared have the same current output of 2.5A. All three power supplies compared have max power output of 30W. The three power supplies, however, have different efficiencies. The power efficiency of TDK-LAMBDA's DRB30121 power supply has an efficiency of 88%. The power efficiency of DELTA ELECTRONICS' DRP012V03W1AZ power supply has an efficiency of 85%. The power efficiency of PHOENIX CONTACT's 2902998 power supply has an efficiency of 87%. All three supplies have a very similar efficiency so this was not factored in the decision. All three power supplies also have output voltage adjustments. The three power supplies have different dimensions but the same mounting of the DIN rail. In the DIN rail configuration, the biggest constraint is the width. From this comparison, TDK-LAMBDA'S DRB30121 power supply was selected because it had the smallest width dimension. This leaves room for other components to be mounted within the XEM chassis.

Table 3-2: Power Supply Comparison; 12V Low Power Supply

PARAMETER	DRB30121	DRP012V030W1AZ	2902998
MANUFACTURER	TDK-LAMBDA	DELTA ELECTRONICS	PHOENIX CONTACT
VIN	85-264VAC	85-264VAC	85-264VAC
VOUT	12V	12V	12V
CURRENT OUTPUT	2.5A	2.5A	2.5A
POWER OUTPUT	30W	30W	30W
EFFICIENCY	88%	85%	87%
LENGTH	90mm (3.54")	100.6mm (3.96")	90mm (3.54")
WIDTH	21mm (.83")	32mm (1.26")	22.5mm (.89")
HEIGHT	75mm (2.95")	100mm (3.94")	90mm (3.54")
MOUNTING	DIN RAIL	DIN RAIL	DIN RAIL
COST	$44.60	$22.45	$53.00

The 5V power supply was spec'd out to power the LCD HMI. The LCD HMI is manufactured by 4D systems and is described in section 3.9. For the 5V power supply the main constraints are power output, efficiency and form factor. There were three different regulators considered for the 5V power supply. It is necessary for the power supply to supply at least 500mA at 5V with an input voltage of 12V. The power supplies considered were RECOM's R-785.0-1.0, MICRO COMMERCIAL COMPONENT'S MC7805CT, and TEXAS INSTRUMENTS' (TI) LM340T-5.0 regulators. All three regulators produce regulate at 5V output. The main differences between the three regulators were the efficiency, regulation accuracy and cost. RECOM's regulator had the highest cost at $7.49 each. The MICRO's regulator had the lowest cost at $0.48 each. TEXAS INSTRUMENT's has a cost of $1.54 each. All three use the same pin configuration. The RECOM's voltage input limits are the lowest but the input voltage of 12V falls within limits. The MICRO'S and TI'S regulator have a high input voltage tolerance. The MICRO'S and TI'S regulator also have very good output voltage regulation having a very steady output whereas the RECOM regulator has relatively high error. In this application however, the accuracy is not detrimental to operation. The largest difference in these regulators is the efficiency. The RECOM regulator has the highest efficiency at the input voltage of 12V sitting at 91%. The other two regulators have an efficiency of 41% at 12V. With the decent current consumption on the 5V, the efficiency is of highest concern. Therefore, the RECOM regulator was selected for the 5V supply. The cost is not prohibitive in this situation.

Table 3-3: Power Supply Comparison; 5V LCD Supply

Parameter	R-785.0-1.0	MC7805CT	LM340T-5.0
MANUFACTURER	RECOM	MICRO COM CO	TEXAS INSTRUMENTS
VIN MIN	6.5	7	7.5
VIN MAX	18	35	20
VOUT	5	5	5
REGULATION %	2.00%	0.03%	0.06%
REGULATION	85mV	1.6mV	3mV
OUTPUT CURRENT	1000mA	1500mA	1000mA
EFFICIENCY @VIN=12V	91%	41%	41%
COST	$7.49	$0.48	$1.54

The ±5V supply was spec'd out to power the analog circuitry for the Time Domain Reflectometer.

The 3.3V supply was spec'd out to power the main microcontroller and all other 3.3V digital circuitry. For this supply the main concern is power output and efficiency. The digital circuitry requires around 250mA in total. A minor fluctuation in regulation is acceptable. For this 3.3V supply, three voltage regulators were considered: RECOM'S R-783.3-0.5 regulator, TI's LM1117 regulator and MICROCHIP's MCP1703 regulator. Table 3-4: Power Supply Comparison; 3.3V Digital Supply shows a comparison between the potential voltage regulators for the digital circuitry. The RECOM regulator is a switching regulator whereas TI's regulator and MICROCHIP's regulator are LDO (low dropout) regulators. All three regulators meet the specification for the VIN requirements of 12V. All three regulators meet the 3.3V specification for the VOUT requirements of 3.3V. RECOM's regulator has the highest regulation error but is suitable for the digital supply. Where the RECOM's regulator excels compared to the other two supplies is in efficiency. The RECOM regulator has an efficiency of 89% at 12V which is very good for the current draw on the digital supply. The cost however is high compared to the other two regulators. The MICROCHIP regulator has the best cost at $0.65 each but does not meet the efficiency requirements. The MICROCHIP regulator also has a max current output of 250mA which is too low for the current requirements of the 3.3V digital supply. Therefore, the RECOM regulator was selected for the 3.3V digital supply. The voltage regulation can be assisted with bypass capacitors and the noise injected in to the circuitry can be ignored due to the digital circuitry not being highly susceptible to switching noise.

Table 3-4: Power Supply Comparison; 3.3V Digital Supply

Parameter	R-783.3-0.5	LM1117	MCP1703
MANUFACTURER	RECOM	TEXAS INSTRUMENTS	MICROCHIP
VIN MIN	4.75	4.5	4
VIN MAX	32	15	16
VOUT	3.3	3.3	3.3
REGULATION %	2.00%	0.04%	0.40%
REGULATION	65mV	1mV	1.3mV
OUTPUT CURRENT	500mA	800mA	250mA
EFFICIENCY @VIN=12V	89%	28%	28%
COST	$6.81	$1.54	$0.65

The 3.3V analog supply was spec'd out to power the analog operational amplifier circuitry. For this supply, high regulation accuracy, noise immunity, and package is of highest concern. For this reason, only LDO regulators were considered. The following three LDO voltage regulators were considered: MICROCHIP's MCP1703, TI'S LM1117-3.3 and STMicroelectronic's L78L33ACUTR. Table 3-5: Power Supply Comparison; 3.3V Analog Supply shows a comparison between the potential voltage regulators for the analog circuitry. All three regulators are low dropout regulators. The power requirement for the analog circuitry is less than 100mA. All three regulators meet this specification. The STMICRO regulator however is at its limit for this specification. All three regulators have high regulation accuracy; however, the TI regulator has the best regulation abilities. The MICROCHIP has slightly worse regulation but introduces less noise on the output at 1uV. The TI regulator, however, has 99uV of noise on the output. Based on this, the MICROCHIP regulator is best for the 3.3V analog supply due to the minimal noise on the output which is recommended on analog power supplies. The package size was also of importance because of limited real estate on the circuit board. The package size from all three regulators from biggest to smallest is TI'S regulator, STMICRO's regulator and MICROCHIP's regulator. Based on the package size as well as the noise and regulation specifications for the MICROCHIP regulator, the MCP1703 was selected for the 3.3V analog supply.

Table 3-5: Power Supply Comparison; 3.3V Analog Supply

Parameter	LM1117	MCP1703	L78L33ACUTR
MANUFACTURER	TEXAS INSTRUMENTS	MICROCHIP	STMICRO
VIN MIN	4.5	4	5.5
VIN MAX	15	16	30
VOUT	3.3	3.3	3.3
REGULATION %	0.04%	0.40%	0.90%
REGULATION	1mV	1.3mV	30mV
OUTPUT CURRENT	800mA	250mA	100mA
OUTPUT NOISE	99uV	1uV	40uV
PACKAGE	TO-220	SOT23-3	SO-8
COST	$1.54	$0.65	$0.47

3.2. Input/Output Controls Hardware

The input/output controls hardware are the components that perform functions, act as switches or protect and buffer inputs within the XEM system. The input/outputs are split up in to two separate functions: high power and low power. The high power sections refer to the lap bar control circuitry and the low power sections include everything else such as the LCD power control, the WSL7 24V signal, E-Stop power control, WSL# resistance measurements control, E-Stop interlocks and input protection.

3.2.1. High Power Control

The high power control is for controlling the 24V output with high current capabilities. To control this high power output, relays were researched. There are two main types of relays that were researched, mechanical relays and solid state relays. The two relays researched were CRYDOM's D1D80 and NAIDIAN's JQX-62F-2Z. The comparison between the two relays are shown in Table 3-6: High Power Control; Relay Comparison. The benefits of solid state over electromechanical in this situation are easily observed. The solid state relay has a much higher VDC operating range such that when inductive loads are switched off, there is much lower chance of damage due to voltage spikes, the switching time from on-off and off-on is much faster, and the on state resistance is much lower. With the benefit of fast switching time, user safety is enhanced due to faster control of the high power outputs. With the benefit of low on state resistance, less power is dissipated through the relay resulting in higher efficiency in power output and as a result more accurate measurements. The solid state relay also has much lower control voltage requirements allowing for easier control circuitry. The solid state relay also does not have an inductive load on the control circuitry allowing for voltage level sensitive control components to be used without concern. The downside to all of these benefits is the high cost of the D1D80 compared to the NAIDIAN relay. The D1D80 solid state relay was chosen because of the benefits in helping meet the engineering specifications more readily.

Table 3-6: High Power Control; Relay Comparison

PARAMETER	D1D80	JQX-62F-2Z
MANUFACTURER	CRYDOM	NAIDIAN
RELAY TYPE	SOLID STATE	ELECTROMECHANICAL
MAX VDC OPERATING	100V	30V
MIN LOAD	5mA	-
MAX LOAD	80A	-
ON STATE RESISTANCE	8mOhm	100mOhm
CONTROL VOLTAGE	3.5	24
CONTROL CURRENT	10mA	53mA
TURN ON TIME	100us	25ms
TURN OFF TIME	100us	25ms
COST	127.15	21

3.2.2. Low Power Control

For low power control, which manages all switches and input buffering, only solid state components were considered because of their ease of use and minimal supporting hardware. There were two types of devices considered NPN MOSFETs and PNP MOSFETs. The comparison between the PNP MOSFETs and NPN MOSFETs are shown in Table 3-7: Low Power Control; PNP MOSFET Comparison and Table 3-8: Low Power Control; NPN MOSFET Comparison respectively.

The PNP MOSFETs being used will be multipurpose. The selected PNP MOSFET will have to account for all uses. The PNP MOSFETs will be used for input protection, relay control, and output control. To account for all uses it is necessary to have VDS (MAX) of 24V or higher, VGS of 24V or higher, low RDS(ON) and good current capabilities. All three PNP MOSFETs being compared have the same VDS (MAX) and is above 24V. All three PNP MOSFETs being compared have the same VGS (MAX) and is above 24V. The DIODES INC MOSFET and the ON SEMICONDUCTORS MOSFET both have the same VTH (MIN) but the Alpha and Omega Semiconductors has a higher turn on voltage. The RDS (ON) is also lowest for the Alpha and Omega Semiconductors MOSFET and DIODES INC MOSFET has the next lowest value. The current capabilities for the Alpha and Omega Semiconductors MOSFET is also highest but the odd package eliminated it from consideration. Therefore, DIODES INC DMP3056L-7 was chosen for the PNP MOSFET.

Table 3-7: Low Power Control; PNP MOSFET Comparison

PARAMETER	DMP3056L-7	FDC658AP	AON7401
MANUFACTURER	DIODES INC	ON SEMI	A & O
TYPE	PNP	PNP	PNP
VDS (MAX)	30V	30V	30V
VGS (MAX)	25V	25V	25V
VTH (MIN)	-1V	-1V	-1.7V
RDS(ON)	0.035	0.067	0.011
MAX CONTINOUS CURRENT	4.3A	4A	12A
PACKAGE	SOT23-3	SOT23-6	DFN3X3
COST	$0.49	$0.59	$0.68

The NPN MOSFETs will be used for multiple purposes. The selected NPN MOSFET will have to account for all uses. The NPN MOSFET will be used for controlling relays and input protection. For the NPN MOSFET the main constraint will be VDS (MAX), VGS (MAX) and RDS (ON). The NPN MOSFET needs to have low power consumption and 24V or higher voltage capabilities for VDS and VGS. The three NPN MOSFETs considered were compared with their relevant information shown in Table 3-8: Low Power Control; NPN MOSFET Comparison. All three NPN MOSFETs compared have the same VDS (MAX). The CENTRAL SEMICONDUCTOR’s MOSFET has the highest VGS (MAX) and the lowest RDS(ON). The NEXPERIA MOSFET has the highest current capability but this is not one of the constraints for the NPN MOSFET. The cost of the CENTRAL SEMICONDUCTOR’s MOSFET is highest out of the bunch but the cost is not a constraint of the selection. Therefore, the CENTRAL SEMICONDUCTOR NPN MOSFET was chosen because it has the highest VGS (MAX) and lowest RDS (ON).

Table 3-8: Low Power Control; NPN MOSFET Comparison

PARAMETER	CMPDM7002AG	2N7002,215	NTR5103NT1G
MANUFACTURER	CENTRAL SEMI	NEXPERIA	ON SEMI
TYPE	NPN	NPN	NPN
VDS (MAX)	60V	60V	60V
VGS (MAX)	40V	30V	30V
VTH (MIN)	1V	1V	1V
RDS(ON)	2	5	2.5
MAX CONTINOUS CURRENT	.280A	.300A	0.260A
PACKAGE	SOT23-3	SOT23-3	SOT23-3
COST	$0.60	$0.25	$0.15

3.3. Measurement Circuits

The XEM will have the capability to measure voltage, current, and resistance over multiple sections of the load system. The XEM will utilize voltage dividers, current sense amplifiers, precision amplifiers, and Wheatstone bridges. The measurement of each of these is needed as any one of them could indicate an error in the load system or the signs of an error in the making.

The XEM system has multiple parameters that it will measure in the load system. The XEM will utilize different circuits to measure the voltage, resistance, and current through different systems of the attached load. Each of these measurements will generate different responses to the user and depending on the severity of the measurement, depending on i it may be dangerous, then an emergency stop can be performed.

For example, if a resistance measurement was shown to have an incredibly high amount of resistance then perhaps there is a disconnection somewhere in the measured circuit. The voltage measurement of the system would help determine if something is causing a larger or smaller voltage drop, either due to a short around some component or perhaps extra resistance being gained from some error.

The XEM places accuracy of utmost importance. Each measurement circuit is designed to be within strict parameters. The measurements need to be accurate to report proper error reports and reading to the user. Proper measurements reduce the chance of the user performing erroneous repairs or emergency stops.

The measurements need to be reproducible for testing the XEM against known controls to verify the stability and reliability of the XEM. If the measurement circuits do not return the same error reports under similar circumstances, then the system could have dangerous consequences.

Resistors within very small tolerances are used in many of the circuits. Precision amplifiers are used to maintain accurate measurements, either from amplification circuits or as a buffer system.

All of these circuits are important for the safety of the load system and are made using precision amplifiers and high quality parts where necessary. The purpose of the XEM is to lessen maintenance times and to provide better troubleshooting on the load system to ensure the highest safety while also saving time and money, therefore the precision and accuracy of these circuits is of high priority.

3.4. Voltage Measurement Hardware

The analog to digital converter, ADC, is the most essential part of the XEM. Without an analog to digital converter, there would be no way to measure voltage for use by the microcontroller. An ADC operates by comparing an input analog voltage, which could take any value, to a reference voltage and then representing the analog voltage as a discrete value. This value can then be used by the microcontroller. Table 3-9 compares three on-chip ADC's from three different microcontrollers.

Table 3-9: Analog to Digital Converter

Parameter	LPC1769	Mega2560	MSP430G2553
Bits	12	10	10
Steps	4096	1024	1024
Min Voltage	0	0	0
Max Voltage	3.3	5	2.5
mV/Step	0.8056	4.8828	2.4414

The LPC1769 comes equipped with an ADC. The ADC operates by comparing an input voltage to an internal reference voltage and returning a usable value to be used in the programming on the microcontroller. The ADC is a twelve-bit ADC, meaning that when the ADC compares the input voltage to the reference voltage, there are two to the twelve power number of possible return values, ranging from zero, meaning that there was no detected voltage on the input, to 4095, meaning that a voltage equal to the reference voltage was detected.

This microcontroller was selected partially because a twelve-bit ADC would allow for a high degree of precision when reading an input voltage, which is needed for accurate voltage readings, and therefore accurate resistance and current readings.

A more common development board, such as the Arduino Mega 2560, has a ten-bit ADC. The ten-bit ADC has 1024 steps in the ADC reading from zero to five volts. This gives a resolution of 4.9 millivolts per unit.

The MSP430G2553 is also constructed to have a ten-bit ADC, but the maximum voltage is 2.5 volts. The lower maximum voltage gives a more accurate measurement of voltage per steps, but having a smaller maximum voltage does not necessarily mean that it is a better choice for the XEM. A larger number of more accurate steps is needed for accurate readings.

The LCP1769 reads between zero and 3.3 volts, giving a resolution of 0.8 millivolts. The two-bit difference gives many more steps, leading to much more accurate measurements with the ADC. An ADC with more bits could have been chosen, but a twelve-bit ADC is enough for the tolerances set forth in the guidelines of the XEM.

Many of the voltages that will be measured by the chosen ADC will first be reduced by a voltage divider. This will scale the voltage down to be usable. However, voltage per step will be exacerbated based on the amount scaled. This puts an even greater emphasis on having an accurate voltage per step.

The LPC1769 has a multiplexor input on eight separate pins allowing for eight inputs to the microcontroller ADC to be selected by the programming at any one time. However, the XEM requires more than eight inputs to the ADC.

This is done by adding external multiplexors to the ADC inputs, allowing more than eight inputs to the ADC. The number of inputs needed for the XEM is much too great for the MSP430G2553 and the design already requires the use of multiplexors, so this option may be the worst choice, as expected of a board meant for learning.

The Mega2560 has an internal 16 input multiplexor. This is enough inputs for the XEM, but the most important factor of an ADC for this application is the voltage per step, so the LPC1769 meaning the best choice, despite having an appropriate number of inputs.

3.5. Resistance Measurement Hardware

Resistance measurement hardware is a combination of resistors and operational amplifiers. The resistors and operational amplifiers had to be carefully chosen for the application of measurement.

3.5.1. Operational Amplifiers

In order to choose operational amplifiers there are a few parameters to keep in mind. The input bias of the operational amplifier and the offset.

Table 3-10: Comparison of Operational Amplifiers

PARAMETER	AD8045ACPZ	AD8626ARMZ	TL084
Slew Rate (V/µS)	1350	5	5
Bandwidth	1 GHz	5 MHz	3 MHz
Max Offset µV	1000	500	15000
Max Input Bias pA	6300000	1	400

The slew rate of an operational amplifier is the rate of change in the output due to a step change in the inputs. A higher slew rate gives a faster switching between two different outputs. A high slew rate gives a faster response from a change.

For example, if a square wave input into a buffer system with a high slew rate, then the time the output takes to raise from zero to the value of the input will be lower. If the slew rate is low enough compared to the switching speed of the input, then the output may not even reach the same level of the input before the input may change. The inverse may also be true, if the input switches too quickly then it may not drop low enough to zero before starting back toward a high value. Figure 3-1: Effect of Slew Rate on Input Signal shows slew rate parameter of an operational amplifier.

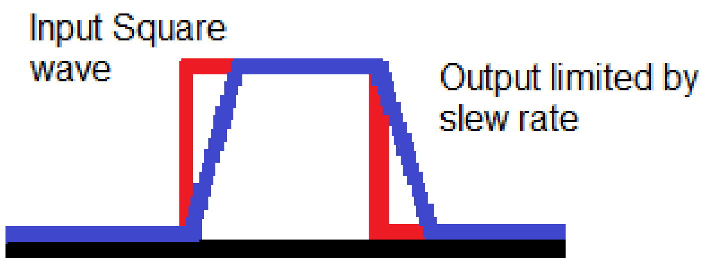

Figure 3-1: Effect of Slew Rate on Input Signal

The bandwidth of an operational amplifier is the frequency over which the voltage gain of the amplifier is above 70 percent. Past this frequency, the gain of the operational amplifier is unreliable, and begins to drop toward zero gain.

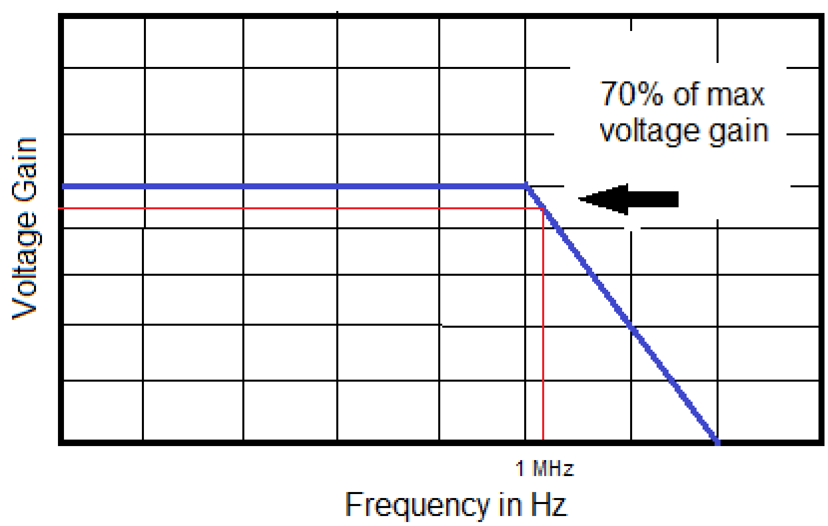

Figure 3-2: Op Amp Bandwidth Limitations

A larger bandwidth means that the operational amplifier can be used over a wider range of frequencies. An ideal operational amplifier has an infinite bandwidth. The bandwidth of an operational amplifier is limited by the Gain-Bandwidth, which is equal to the frequency where the amplifiers gain becomes unity.

Figure 3-2: Op Amp Bandwidth Limitations shows an example of the effect of the bandwidth of an operational amplifier. The amplifier proposed in the figure has a bandwidth of one megahertz.

The input bias of an operational amplifier refers to the small current that flows into the two input terminals of the operational amplifier. This small input current produces a voltage across the circuits internal resistors and if amplified along with the normal amplified voltage. The lower the input bias of an operational amplifier, the more accurate the output will be.

In our applications, when an accurate reading is wanted, a precision operational amplifier will be used. The precision operational amplifier will draw less current from the circuit to give more accurate readings.

The offset of the operational amplifier refers to the voltage difference needed between the two input terminals to receive a response in the output of the operational amplifier. If the offset is very high, then changes in voltage on one terminal will not change the output of the operational amplifier and the reading will not be accurate. When accurate readings are needed, an amplifier with a low offset will be chosen.

For our precision applications, the AD8626ARMZ operational amplifier was chosen which has a standard slew rate, no better than an operational amplifier commonly used in classrooms, because the speed at which the output will change does not need to be high.

The analog to digital converter can wait for the output of the operational amplifier to balance to its value before taking a measurement. A low slew rate could also be useful in this case, as if there is a sudden unexpected voltage change, perhaps due to some noise on the system or improper use, the reading will be close to the intended value slightly longer. However, this should not be relied upon as there are much better ways to deal with noise and unexpected situations on a circuit.

The chosen operational amplifier also has a comparatively low bandwidth when compared to a high speed operational amplifier. The input to the operational amplifier will be a direct current and will not have a high switching speed, therefore a high bandwidth is not necessary.

The offset voltage of the chosen amplifier has the smallest value because when measuring the inputs, the accuracy need to be as high as possible. The smaller offset voltage allows for measuring the smallest difference across the inputs to be passed to the analog to digital converter for use by the microcontroller.

A more precise operational amplifier will allow for more precise readings, meeting parameters of the system, and reporting accurate errors or information to the user.

The input bias of the operational amplifier chosen for the precision circuits is the lowest of the compared operational amplifiers. The low current draw into the operational amplifier help to maintain the voltage across the connected system.

If the current draw was too large, then it would interfere with the voltage across the measured terminals by pulling current into the operational amplifier and changing the voltage division on the attached circuit. This would give inaccurate readings and compromise the reliability of the measurement circuits.

3.5.2. Resistor Types

When choosing resistors for a circuit, not only does the value of the resistor need to be calculated and the power dissipation taken into consideration, but the actual construction of the resistor as well. Resistors come in multiple varieties, such as thin film, thick film, and wirewound.

3.5.2.1. Thin Film

A thin film resistor is made from a uniform dense allow, such as Nichrome. The strength of this allow allows the resistor to undergo a laser trimming process to finely adjust the resistor without introducing imperfections in the resistor. This allows thin firm resistors to achieve low tolerances, low noise, low parasitic inductance, and low capacitance.

These properties lend thin film resistors to applications that need a high stability, high accuracy, or a low noise factor. Thin film resistors can also have a cylindrical shape. If the resistor has this sort of shape, then the inductance will be much higher than typical thin film resistors.

Thin film resistors also have a lower temperature coefficient. The temperature coefficient of a resistor is one of the main parameters that characterizes a resistor. A lower temperature coefficient corresponds to a lessened effect of temperature on the resistance. Thin film resistors typically have temperature coefficients less than 50, represented in ppm/K, parts per million/Kelvin.

3.5.2.2. Thick Film

A thick film resistor is the general purpose resistor used in any application. These resistors are made by applying a paste to a ceramic plate. It is then fired and comes to a glass-like finish. The glass-like finish does help in environments with high humidity.

The process does not produce a resistor with comparable parameters to thin film resistors. However, thick film resistors are much cheaper, and so are used for any general purpose. The temperature coefficient of thick film resistors is at best close to the worst of thin film resistors. A thick film resistor can reach temperature coefficients of 200.

3.5.2.3. De-rating

De-rating a component like a resistor is then the designer decides to use a resistor with higher parameters for a simpler application, such as using a resistor that is rater for two watts for an application that is not expected to exceed one watt. This help prolong the lifetime of the components by not using them to their max conditions. [4]Figure 3-3 shows the de-rating curve for a typical resistor.

This technique also helps to protect systems and components in situations where the application may have unexpected changed in electrical characteristics. For example, by having a component rated for a higher power dissipation there would be less damage to the system is that component suddenly had more power going through it.

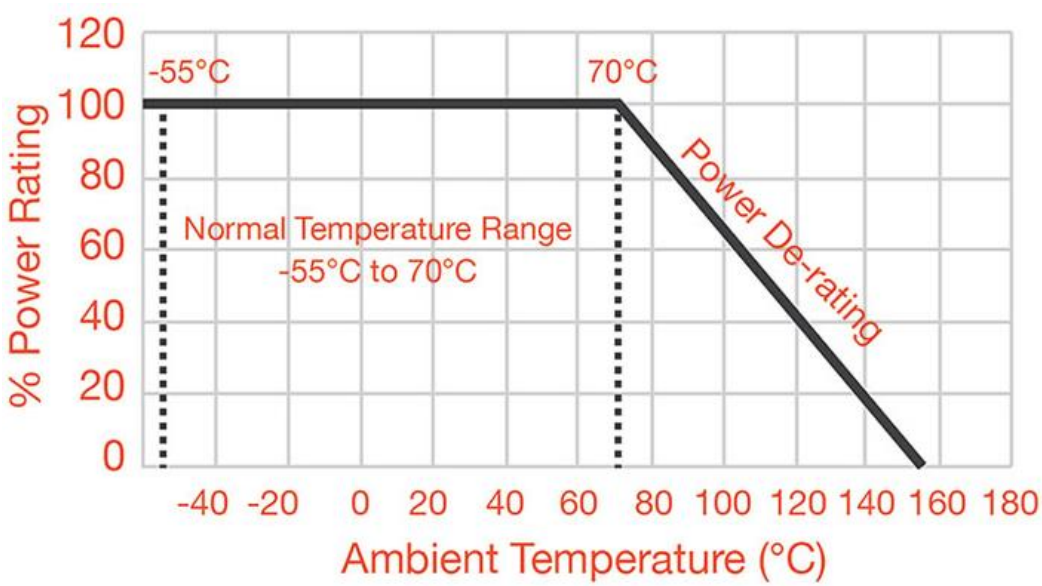

Figure 3-3: Resistor De-Rating Curve

3.5.2.4. Wire Wound

A wirewound resistor is created by wrapping a resistive material, such as copper, silver, or nickel alloys around an insulating core. The resistance of the final produce is dependent on the resistivity of the wire being used, the diameter of the core, the cross section, and the length of wire. Because each of these resistors can be accurately controlled, wirewound resistors are very highly accurate.

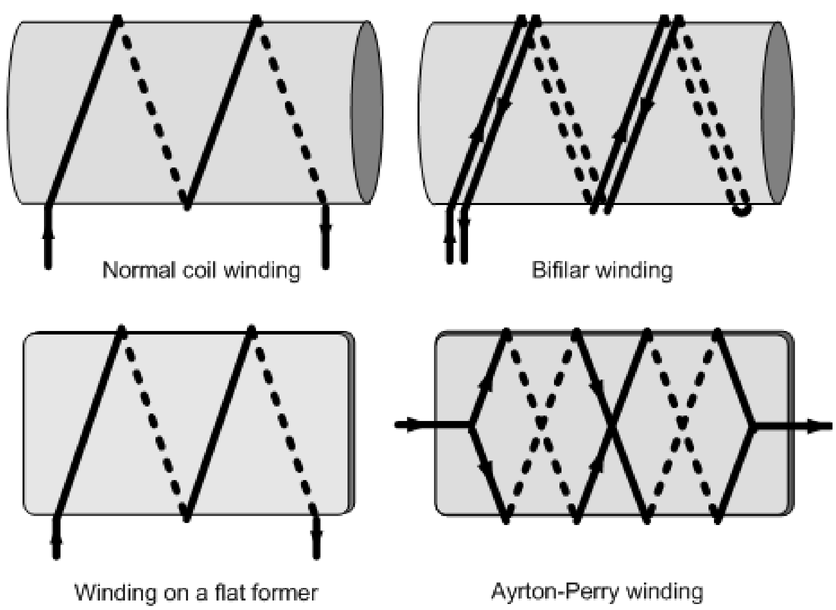

Figure 3-4:Illustration of Wire Wound Methods

There are multiple methods to creating a wire wound resistor; multiple winding patterns. Depending on the method by which the resistor is wound the characteristics of the resistor change. [11]Figure 3-4 shows examples of wirewound resistor techniques.

A bifilar winding is made by doubling the wire over, so the winding begins and ends in the same location. By doing this the winding gives low self inductance, but the parasitic capacitance between the wires is larger.

The winding can also be wound around a flat core, as opposed to the standard round core. The flatter core lessens the distance between the sires on the two sides of the core. The lessened distance helps to cancel the magnetic field between the wires, lessening the resistors inductance.

The most complex winding is Ayrton Perry winding, as depicted in the in figure #. This method of winding is the most robust method. The self inductance and capacitance is at the lowest of the types of wire wound resistors, due to the flat shape of the core and the splitting pattern used. It combines the inductance lessening properties of the flat core and opposite winding in both direction to lower capacitance.

These resistors are essentially inductors, as they are wire wound around a core. This leads to the worst inductance of all resistor types. A precision wirewound resistor is typically used in measuring bridges and calibration equipment because the typical tolerance of these kinds of resistors is 0.1% or better. These resistors can reach even better tolerances, as manufactures may account for the decay over time of a resistor. These wire wound resistors are very finely made, reaching tolerances of 0.01%.

A wire wound resistor can have a high power tolerance. A wire wound resistor built for higher power applications will be physically larger as more wire is needed to achieve the proper power dissipation across the entire resistor as to maintain reliability. By having a larger resistor, the error in the resistance is higher.

3.5.2.5. Resistor Applications

In the XEM, thick film resistors will be used for the majority of applications. When a current is needed, but not very accurately, such as supplying current to the gate of a MOSFET or limiting the current through an LED, a thick film resistor could be used to provide a current limiting component that does not need any specific parameters. Other resistances, such as the sense resistor on the MAX9929 needs a more accurate resistor.

The Wheatstone bridge circuit needs accurate resistors to function properly, as both sides of the bridge need to have equal resistances made from multiple resistors. If the resistances are not close enough together, then the differential voltage will not be accurately propagated to the ADC. Ideally, the most accurate resistor would be used, however the cost increases with the accuracy, and the power dissipation across the sense resistor is also an issue when selecting a resistor, as different types of resistor have different power ratings.

3.6. Microcontroller Hardware

The RCS simulator consists of a Microcontroller which provides all logic and post hardware processing. The Microcontroller must agree with our estimated requirements for the overall system. A microcontroller with a large number of GPIO and analog inputs will be considered thus limiting the search to high pin count microcontrollers. Three well-known and highly used microcontrollers were considered. The three microcontrollers being compared are shown in Table 3-11. The first one is the Arm microcontroller LPC1769 ARM Cortex-M3 FBD 100,551 Microcontroller. The second one is the AVR microcontroller ATmega2560. The third is the MSP430, this microcontroller was looked at due to its familiarity and availability.

Table 3-11: Microcontroller Comparison

PARAMETERS	ATmega2560 basic	LPC 1769 cortex M3 FBD 100, 551	MSP430G2553
CORE	AVR	ARM	MSP430
DATA BUS WIDTH	8	32	16
MAX CLOCK FREQUENCY	16MHz	120MHz	16MHz
IO AVAILABLE	54	70	16
ADC RESOLUTION	10-bit	12-bit	10-bit
MIN VOLTAGE	4.5	2.4	1.8
MAX VOLTAGE	5.5	3.6	3.6
RAM	8kB of SRAM	32kB of SRAM	512B SRAM
EEPROM	4KB of EEPROM	-	-
FLASH	64kB	512kB	16kB

The AVR Microcontroller is an integrated circuit that is built using a complementary metal-oxide semiconductor, it uses a low powered 8-bit structure [5]. This microcontroller focuses on the power consumption and lacks in processing speed. With 32 general purpose working registers [5] connected to the arithmetic logic Unit, in one clock cycle two registers may be accessed in one instruction allowing for more efficient code than basic CISO microcontrollers. Other features pertaining to this microcontroller not mentioned in table 310 above are the Real Time Counter, Timer/Counters, USAERs, Serial Interface, 16-channel, programmable watchdog Timer with oscillator, SPI serial Port, JTAG test interface, and six power saving modes [5]. The power saving modes stop the Oscillator and save the registers while disabling the other functions on the chip until the next interrupt and/or Reset.

The asynchronous timer runs continuously even in the power save mode so the timer can be maintained even while the device is sleeping [5]. The Crystal/Resonator Oscillator stays on while in standby mode which provides low power consumption and fast start-up. The QTouch library offered by Atmel assists in embedding capacitive touch button functionality on to the microcontrollers. The Atmega2560 AVR programs can be written in the C-language, since online sources provide C compilers [5].

The MSP430 is a low power microcontroller that can be used in transportable measurement applications. In less than 1 µs the digital controlled oscillator can allow wake-up from low power modes [10]. The CPU has a 16-bit RISC architecture. This microcontroller incorporates the von-Neumann common memory address bus and memory data bus [10]. It has a high-performance analog that helps in precision measurement; timers are comparator-gated which is ideal for calculating resistive elements. MSP430 has a bootstrap loader which allows for users to program RAM and or flash memory using the UART serial interface [10]. In this microcontroller the peripherals are connected to the CPU by control buses, data, and addresses [10].

The clock system uses a low-frequency auxiliary clock and is most commonly used and designed for battery-powered applications [10]. The microcontroller also has an embedded emulation logic that is accessed by the JTAG so that no other system resources are utilized [10]. The Interrupts for this device are fixed, and defined; there are three types of interrupts consisting of the system reset, non-maskable NMI, and lastly the maskable NMI.

The Arm cortex-M3 is a microcontroller that has high level integration and low power consumption [7]. The CPU uses a three stage; pipeline and Harvard architecture [7]. With this microcontroller there are three Advanced high-performance buses one of which being the system bus, the other the I-code bus and lastly the D-bus [7]. The I and D buses are relatively faster than the system bus [7]. The I bus is mainly used for instruction fetch and the D bus is used for data access. The ARM cortex M3 has a memory protection unit (MPU) that allows protection of critical data within the user application. The LPC 1769 has a nested vectored interrupt controller (NVIC) [7] this helps prevent some interrupt delays and assists in processing any late arriving interrupts.

An Ethernet controller is available for the LPC 1769 it can support bus clock rates of up to 100 MHz [7]. Another aspect of this microcontroller is the USB interface. The USB controller can be host, device, and or OTG controller [7]. Controller Area Network controllers are also available for the LPC 1769 this controller can make the device into a switch, and or router. The ADC has eight channels, with 12-bits. The ADC has a 12 bit; conversion rate of 200 kHz [7].

For the XEM having a higher port count is important, so this eliminates the well-known and studied MSP430. The XEM relies heavily on recorded voltages and current. For this reason, it is important to have a high performance; ADC. The ARM Microcontroller has 70 GPIO ports and the highest bit ADC out of all the microcontrollers mentioned. The intentions for the GPIO pins are to indicate input and outputs to the user and device. Another aspect that was considered was the interrupt. It is vital for the XEM to have properly working interrupts with little delay, and so the LPC 1769 has the NVIC that was previously mentioned which prevents delays and helps in processing late interrupts.

The SPI serial controller in the LPC 1769 is a duplex serial interface that handles multiple masters and slaves to a bus [7]. The ARM microcontroller also has the most memory space when compared to the others on the table. More memory space may provide more coding flexibility when programing our requirements on the board. The last and most important reason for choosing the LPC 1769 is its cost, it is not the cheapest ($11.74 according to Mouser Electronics) microcontroller, but since its capabilities outweigh the msp430 (cheapest at $9.99, already owned) and AVRs ($38.50 according to Mouser Electronics); It stands up to key requirements and will aid the XEMs performance.

3.7. Current Sense Amplifier Comparison

A current sense amplifier is needed to realize the current measurement circuit. A current sense amplifier uses the subtle changes on a either side of a sense resistor to output either a current or a voltage. The internal components of a current sense amplifier utilize the small voltage drop across the sense resistor to create a current through the amplifier.

Table 3-12: Current Sense Amplifier Comparison

PARAMETER	MAX9929	LTC6101	INA282	CS30AL
Manufacturer	Maxim integrated	Linear Technology	Texas Instruments	Life Augmented
Load Side	High	High	Either	High
Range, V	-0.1 to 28	4 to 60	-14 to 80	2.8 to 30
Gain	50V/V	Configurable	50V/V	20V/V
Max Output	2.85V	1mA	4.6V	25V
Price	2.18	2	3.62	0.65

The MAX9929, manufactured by Maxim Integrated, is a high side current sense amplifier. The maximum voltage input range on the MAX9929 is 28 volts. The maximum voltage through the load system attached to the MEX is 28 volts. The MAX9929 has a gain of 50 volts per volt, amplifying the voltage difference across the current sense resistor. The maximum output of the MAX9929 is 2.85 volts. A similar current sense amplifier, the MAX9928 by the same manufacturer, has an output current, as opposed to an output voltage. The MAX9929 has an internal resistance to produce the output voltage.

The LTC6101, manufactured by Linear Technology, is also a high side current sense amplifier. The input voltage range of the LTC6101 has a much higher maximum. However, the higher maximum is unnecessary for our applications. The XEM does not need to read up to 60 volts. The lower voltage on the range is four volts. The XEM is likely to have a smaller voltage difference across the sense resistor, therefore a lower voltage of this size is not acceptable. The output of the LTC6101 is a current output, which can still be used to implementing an external resistor on the output before the ADC.

The INA282, manufactured by Texas Instruments, can be used as either a high side or a low side current sense resistor. The voltage range for the INA282 extends into the negative range and well above the necessary voltage required for the XEM. The gain of the system is also 50 volts per volt. The output current of this current sense amplifier is 4.6 volts. The INA282 meets and exceeds the requirements set forth in the parameters. This component has a higher maximum output voltage that is above the maximum voltage that the analog to digital converter can handle, so extra components or care when selecting components would need to be taken.

If the voltage range extends out of the maximum value for the analog to digital converter then it may be damaged. The upper voltage output being above the maximum value for the analog to digital converter also means that there would be a portion of voltage above the max capabilities of the analog to digital converter that would not be accurately read, and therefore the reports generated by the XEM would be inaccurate.

The output voltage could be changed to be usable by the analog to digital converter, but this could implement unnecessary error by scaling voltages or compounding tolerance errors of components. On the other hand, the MAX9929 also meets the requirements and is a cheaper component, therefore although the INA282 would meet requirements, it is not the most efficient choice.

The CS30AL, manufactured by Life.Augmented, is also a high side current sense amplifier. The low range voltage is 2.8 volts. Again, the low range voltage is too high for use, as there may be much smaller voltage changes. The gain is 20 volts per volt. This is the cheapest of the proposed current sense amplifiers.

The MAX9929 is the best choice when considering performance and cost. It meets all the parameters and has a reasonable cost. The MAX9929 requires a sense resistor, the value of which will be determined in the section explaining the implementation of the MAX9929. The output of the MAX9929 is a voltage due to the internal output resistor. This removed the need for an external output resistor and allows for a connection to the analog to digital converter.

3.7.1. Sense Resistor Selection

The R_{sense} resistor needs to be carefully selected due to the high voltage and current through it. A high R_{sense} value will cause a larger voltage drop across the R_{sense} resistor. However, a higher R_{sense} value allows for a lower current to be measured more accurately. The offsets become more acceptable at a higher resistance value. A high current through the R_{sense} resistor will be inefficient and dissipate more power. The heat from too much power dissipation could also affect the operation of the MAX9929. With reason to take both a higher and a lower resistance value, a comparison needs to be made.

Table 52: Resistor Value Choice Comparison

	Ω				
Parameter	**100**	**2500**	**5700**	**8000**	**10000**
mV	237.624	9.596	4.21	3	2.4
Gain sense	47524.75	1919.232	841.958	599.925	479.952
mV/mΩ	0.238	0.01	0.004	0.003	0.002
mV/mΩ gain	47.524	1.919	0.842	0.6	0.48
Steps/mΩ	58.973	2.382	1.045	0.744	0.596
mA	237.62	9.6	4.21	3	2.4
mW sense	56.47	0.09	0.02	0.01	0.01
mW resistor	5646.51	230.22	101.02	71.98	57.59
Error mΩ	0.21	5.21	11.877	16.669	20.835

Table 52: Resistor Value Choice Comparison shows that given a constant voltage, which will be provided, as the resistance increases the power dissipated across the resistor decreases. However, error of the system will increase with a larger R_{sense} resistor. The value chosen for the R_{sense} is 5700 ohms. This value was chosen after weighing all the different factors together.

The required resistance is also going to be split over two different resistors to split the power dissipation among the two resistors. Splitting the power dissipation across two resistors makes it easier to find resistors that can handle the heat that will be emitted from the resistor. The chosen resistor value will need to be within one percent of the chosen value to maintain accuracy of the current sense system. An inaccurate resistor will defeat the purpose of using this circuit.

3.8. Time Domain Reflectometry Hardware

The time domain reflectometer is the hardware which measures signals in the time domain. It samples signals with respect to time and stores the data with timestamps. When reviewed this data can be shown in a voltage verses time graph. To develop the time domain reflectometer, many components and functions are required. The time domain reflectometer is made up of three major functional components: pulse generator, data sampler, and data processor. These three functional components are critical and require utmost care with the design. To design a useable time domain reflectometer, the sampling periods must be very short. This requires high speed, high frequency components which are very sensitive to proper design.

The data sampler in reference to the time domain reflectometer is the analog digital converter. Ideally the data sampler would have an infinitely small data sample period. Unfortunately, the data sample rate is limited by technologies available. For analog digital converters, there are three common types: Delta-Sigma, Successive Approximation and Flash. Each have their own respective pros and cons. The guide supplied by [9] Texas Instruments was used in researching the different analog to digital conversion methods. Table 3-13 is an overview of the three topologies researched.

Delta-Sigma analog to digital converters determine the analog value by converting the analog signal from the time domain in to the frequency domain. Once the signal is in the frequency domain a digital filter converts the signal in to a sum of Dirac delta functions at the sample rate of the analog digital converter. From there the Dirac delta functions are further filtered in to the final binary value at the data rate of the analog digital converter. Figure 3-5, image by [9] TI, shows a graphical method to how the digital filter creates the Dirac delta representation of the analog signal and is then sampled to the useable binary value. The Delta-Sigma methodology works very well to high resolutions. The downside of the Delta-Sigma methodology is that it is slow and works best with low frequency signals. Delta-Sigma analog digital converters are best used with DC signals. A very high resolution such as 24 bits can be used with this method of conversion without much influx of noise.

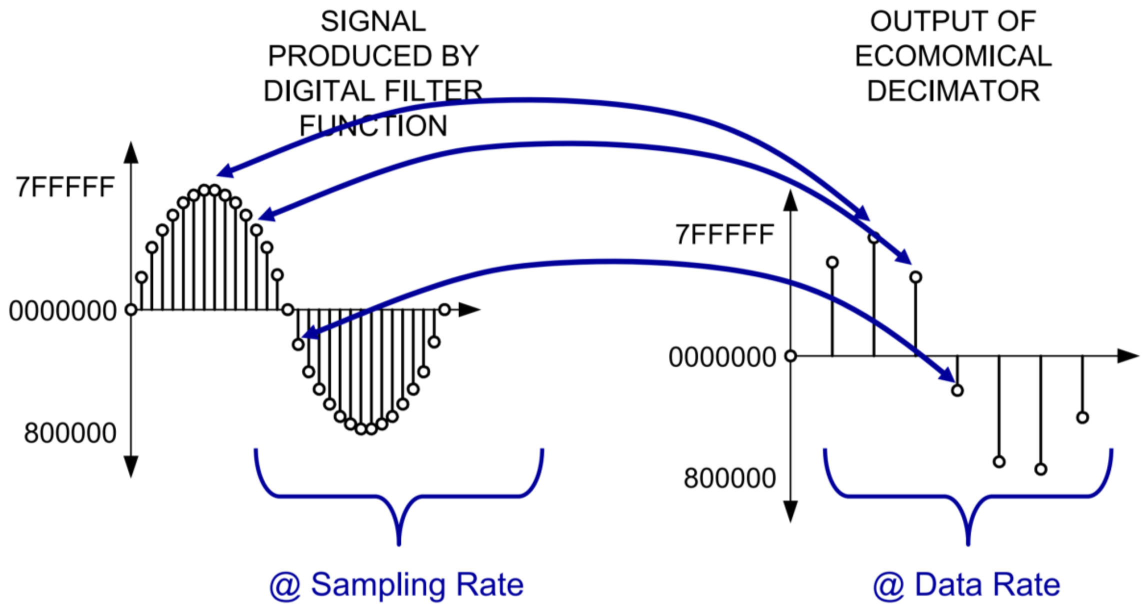

Figure 3-5: Delta-Sigma Conversion Method

Successive approximation analog to digital converters determine the analog value by sampling the analog signal and comparing it to reference signals. The analog to digital converter uses a reference voltage to determine the analog signal. The analog to digital converter has a set number of resolution bits. The successive approximation method starts by checking the MSB. The MSB represents the half scale voltage level based on the reference voltage. If the analog input signal is higher than half the reference voltage then the MSB is a 1, otherwise the MSB is a 0. From there on it successively compares different scales of the reference voltage with the analog input signal. Due to the nature of the successive approximation method, the resolution cannot be too high otherwise the data sample will be lost before the approximation is complete. At the same time however, the speed of successive approximation can be high. The main bandwidth limiter is the time it takes for the analog signal to be sampled.

Flash analog to digital converters determine the analog signal by direct hardware implementation using comparators and logic gates. Due to the direct hardware nature, the speed of the flash analog to digital converter is limited simply by propagation delay of the hardware used. This allows for very high speed up in the giga-samples per second. The downside is that the amount of hardware required for a limited number of bits is exponential compared to the other topologies.

Table 3-13: ADC Topology Comparison

TOPOLOGY	Δ-∑	SAR	FLASH
SAMPLE RATE	100KSPS	100MSPS	1GSPS++
RESOLUTION	up to 24bits	up to 18bits	8 bits
SIZE	Medium	Medium	Very Large
LATENCY	5 CYCLE	1 CYCLE	Propagation
POWER	MEDIUM	LOW	HIGH
COST	LOW	MEDIUM	VERY HIGH

Due to the high speed requirement for the time domain reflectometer, the flash type analog to digital converter will be used. The resolution will be low and cost is high but the sample rate is at the level needed to capture the transmission line waveform. The specific analog to digital converter to be used is made by Texas Instruments and is named the ADC08B3000. This analog to digital converter has two 1.5GSPS flash type analog to digital converters that can be interleaved to achieve 3GSPS rate. The ADC08B3000 also incorporates a data buffer which stores the data samples. This chip takes the role of the data sampler and data processor which makes integration easy. The ADC08B3000 does, however, require differential inputs thus requires much external hardware to function properly. With the use of differential inputs, a rail-to-rail supply is necessary. The ADC08B3000 also has a voltage specification of 1.9V. This is an off-ball voltage requirement. This means it will require its own power supply and voltage signals to be converted to tolerable levels.

The next important function of the time domain reflectometer is the pulse generator. The most important constraint for the pulse generator is speed. The next being power output. The pulse generator will be made of logic gates performing the output function. The pulse generator ideally needs to create an infinitely small pulse length. Due to physics, this is not possible in reality. There are a few logic gate design technologies that will be researched: AUC, AVLC and AVC. Table 3-14 shows the parameters for each technology.

Table 3-14: Logic Gate Technologies

PARAMETER	AUC	ALVC	AHC
VOLTAGE	2.5V	3.3V	5V
SLEW RATE	2V/ns	1.3V/ns	0.8V/ns
PROPAGATION DELAY	1.5ns	2ns	5.5ns
OUTPUT CURRENT	9mA	24mA	24mA

The AUC technology has the best performance which is necessary here in terms of speed but the output current is low and not enough to drive the transmission line. Therefore, the next best technology will be used which is ALVC. The ALVC has a high slew rate and also decent output driver for the transmission line. The AHC has good voltage output but is a weak performer in the high speed category. The propagation delay is also easy to compensate for with the AUC with it being only 1.5ns but the ALVC comes in at a close second place.

3.9. Human Machine Interface Hardware

As a viable output and input display for the user, an LCD will be chosen; The LCDs of choice are 3 specific touch screen LCD the 7" TFT LCD Touch, 4Dsystem 4Duino TFTLCD, and 4D Systems Armadillo. The comparison between these devices are shown in Table 314 [1,2,3]not

Table 3-15.

The 4D system 4Duino is the cheapest but also has the lowest resolution and dimensions. The 4d system also is compatible with the Arduino. This LCD would have been an ideal choice when paired with the AVR microcontroller, but this is not the case with the ARM microcontroller chosen. The 4Dsystem armadillo is the second cheapest, and slightly bigger than the 4Duino systems, but it lacks display resolution. The top choice for the XEM will be the 7" TFT LCD Touch w Diablo16 processor, since it has larger dimensions, screen, and that it has the highest display resolution regardless of the price.

.

Table 3-15: Potential LCD Comparison

PARAMETERS	**7" TFT LCD**	**2.4" TFT LCD IoT**	**4D Systems Armadillo**
MANUFACTURER	4D SYSTEMS		
DISPLAY RESOLUTION	800 x 480	240x320	480x272
TOUCH INPUTS	yes	yes	yes
DIMENSIONS	179.9 mm x 100 mm x 15.5 mm	72.8x53.3x14.6 mm	120.7 x 69.6 x 16.5mm
VOLTAGE REQUIRED	5V	5V	5V
COST	$179.00	$79.00	$99.00

3.10. Bill of Materials

All the components spec'd out for the XEM Tool are listed below. The XEM Main circuit board BOM was summarized due to the extensive length of the bill of materials for that circuit. The BOM is split into sections of component type. Table 3-16 is a summary of the XEM main circuit board BOM. The resistors are standard thick film resistors or thin film precision resistors or thick film high wattage resistors. There is one resistor that acts as a resettable fuse. All of the capacitors are ceramic type capacitors. The capacitors are all X5r type capacitors. The capacitors exhibit low ESR and are good for filtering. The values of the capacitors range from 0.1uF to 10uF. Their use is for decoupling the power traces. The MOSFETs are of PNP or NPN type variety. The regulators are linear type or switching type. The digital circuitry includes the microcontroller, buffers and logic gates. The operational amplifiers are a variety of instrument amplifiers or precision amplifiers. The diodes are all schottky type diodes. The relays are electromechanical relays with a low profile and low current handling capabilities.

Table 3-16: XEM Main Circuit Board BOM - Summary

COMPONENT TYPE	QUANTITY	COST
RESISTORS	82	$34.81
CAPACITORS	48	$8.36
MOSFETS	39	$16.89
TERMINAL CONNECTORS	13	$10.35
REGULATORS	4	$15.44
DIGITAL CIRCUITRY	8	$23.59
OPERATIONAL AMPLIFIERS	12	$52.80
DIODES	18	$5.39
RELAYS	2	$7.74
TOTAL	**226**	**$175.37**

In Table 3-17, the components that are in and make up the XEM chassis are listed. These components include relays, mounting equipment, power supplies, circuit breakers and other equipment. The relays are high current solid state relays. One of the solid state relays are rated for 80A continuous. This relay is used to provide current for the open lap bar circuit. The other solid state relay is rated for 12A continuous. That relay is used to provide current for the close lap bar circuit. The solid state relays do not include transient protection therefore the protection diode made by LittleFuse was used. This diode can handle up to 70V reverse voltage with 15kW of power dissipation. The mounting equipment is an enclosure made by Hammond Manufacturing. It is stainless steel and has mounting points for electrical components. There is also fuses included in the XEM Chassis and that is to protect circuitry from over currents. There is also the 24V power supply as described in the high power section of section 3. The power supply is made by MeanWell and supplies 24V at 50A capacity. Also included in the XEM Chassis is the 12V power supply. The 12V power supply is what supplies power for the low power circuitry. This includes the 5V suppy and 3.3V supplies. The XEM Chassis also houses circuit breakers. These circuit breakers are for the high power devices. The incoming 120VAC is on a 20A circuit breaker and the 24V high power output is on a 50A circuit breaker. The XEM Chassis also houses the touch screen 7” LCD. This is the main interface for the XEM system. The other hardware in the XEM Chassis deals with wire management. The wire management is handled with wire ducts produced by Panduit.

Table 3-17: XEM Main Chassis BOM

ITEM	MANUFACTURER	ITEM NUMBER	QUANTITY
12V DIN RAIL SUPPLY	TDK	DRB30121	1
24V SUPPLY	MEAN WELL	RSP-2000-24	1
7" TOUCH LCD	4D SYSTEMS	uLCD-70DT	1
PROTECTION DIODE	LITTLEFUSE	15KPA70A	5
SS Relay 80A	CRYDOM	D1D80	1
SS Relay 12A	CRYDOM	D1D12L	1
ENCLOSRE PANEL	HAMMOND	18P1313	1
ENCLOSRE	HAMMOND	HWST16168S16	1
FUSE 10A SLO BLO 6.3X32MM	SCHURTER	0034.5245	5
FUSE 1A FAST BLO 5X20MM	BUSSMAN	0216001.MXP	5
20AMP CB	WEIDMULLER	BR1C20AC	1
TERMINAL BLOCK 8AWG	WAGO	284-101	5
TERMINAL BLOCK PLATE	WAGO	280-301	2
TERMINAL BLOCK JUMPER 8AWG	WAGO	284-402	4
HD CONNECTOR BASE	ILME	CHI10	1
HD CONNECTOR FEMALE	ILME	CSHF10	1
50AMP CB	SQUARE D	QOU150	1
DIN RAIL	WEIDMULLER	913917	4
END COVER ST2.5 3L	PHOENIX CONTACT	3036660	2
END BLOCK	PHOENIX CONTACT	800886	6
WIRE DUCT 1.5"X2"X6'	PANDUIT	G1.5X2WH6	6
WIRE DUCT COVER 1.5"	PANDUIT	C1.5WH6	6
WIRE DUCT 1"X2"X6'	PANDUIT	G1X2WH6	6
WIRE DUCT COVER 1"	PANDUIT	C1WH6	6
		TOTAL	72

3.11. Breadboard and Prototyping

In order to prototype the circuitry, the development board of the LPC1769 was acquired. The development board was connected to the 4D Systems LCD which is being used as the HMI as a test. The devices and their test configuration are shown in Figure 3-6.

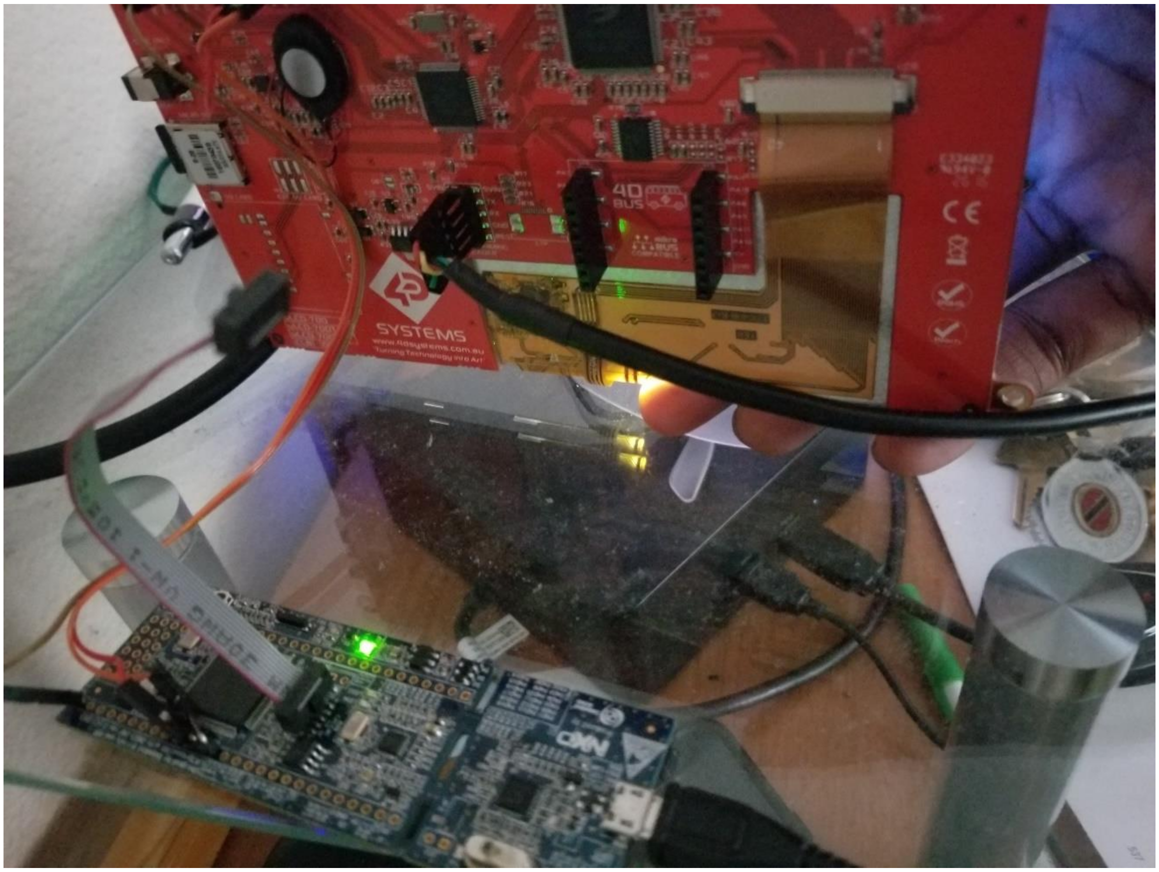

Figure 3-6: LCD Prototyping with LPC1769 DEV. BOARD

The prototyping shown above was to acclimate the LCD software with the XEM software. This allowed the HMI to interact with the XEM without any relevant control hardware connected. Here the HMI screens, software buttons and communications were established and confirmed. Each screen was programmed and developed using this setup. Then each button on each screen was tested. Then software on the XEM which communicates with the LCD was tested. An accurate and reliable baud rate was selected. The baud rate chosen was 625k. This is because the clock on the LPC1769 and the clock on the LCD both have a <.1% baud rate error at this speed. It is also a very fast baud rate allowing large amounts of data to be shared between the LCD and the LPC1769 without clogging up the bandwidth.

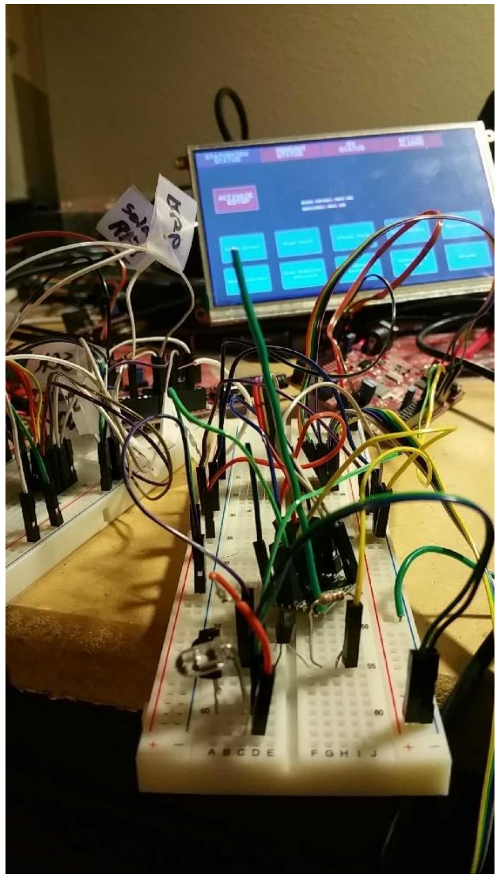

Figure 3-7: Hardware Testing Breadboard

Figure 3-8 are images of parts acquired for the XEM Chassis. Figure 3-9 is the high power PS1. Figure 3-10 is the custom circuit board prototype which has all the components for the XEM Main circuit board. This board was used for testing I/O and microcontroller design. With this board it was determined what was necessary to make a functional circuit board.

Figure 3-8: XEM Chassis with Components Attached

Figure 3-9: High Power PS1

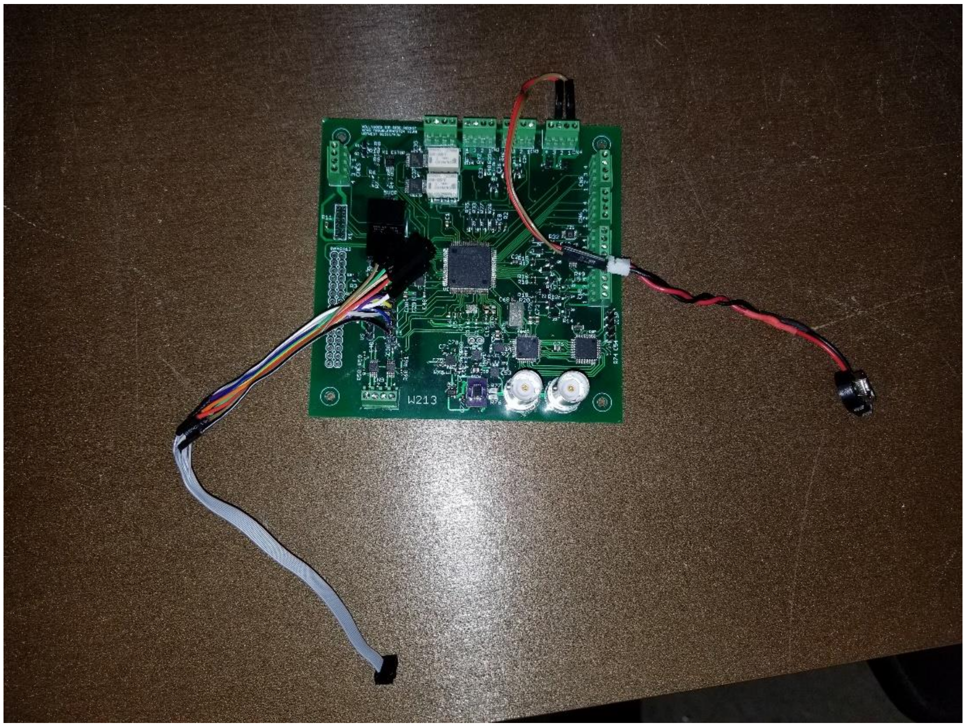

Figure 3-10: Main XEM Parts

4. Standards and Constraints

Within the industrial world, safety is a frequent topic of concern. The goal of safety in the industrial world is to provide a safe work environment for end users. It is impossible to rid all dangers from the workplace but it possible to minimize them to reasonable levels. That is the approach taken within all aspects of safety.

Some examples of potential hazards are electrical shock, fire, explosion, burn, radiation, pinching, falling, and tripping. Some examples of consequential failure are mechanical breakdown, electrical breakdown, subsequent component failures and non-recoverable hardware conditions.

In this specific application, the main hazards involved are electrical shock and burns. This is due to the high power output of the device. The device requires a high power output so the device will not detect a fault until a direct short is detected. This can allow the end user to be potentially burned or shocked if the device is used improperly. To circumvent this, the outputs are protected by hardware means of circuit breakers and/or fuses. As a back-up, there is also an emergency stop circuit which is handled by a hardware push button in conjunction with a software monitored hardware combination. The software will attempt to stop an output from causing a potential hazard before the hardware fail-safe trips.

Safety ratings in industrial applications are typically based on the SIL (Safety Integrity Level) rating and/or the PL (Performance Level) rating. These ratings are different ways of measuring the safety and reliability of a device to perform up to its specifications without failure. In this application, the PL required rating will be used and the SIL rating will be measured. Although it is best to have a high safety rating, it is also probably not the most efficient way for a circuit to perform if such high level of safety is required. In this case, a moderate safety level will be pursued. In any form, safety ratings are based on FMEA.

The following two figures, Figure 4-1 and Figure 4-2, were provided by Keyence America[6] and help explain the performance level standards.

Performance Level (PL)	Probability of Dangerous Failure per Hour (PFHd) 1/h
a	$\geq 10^{-5}$ and $<10^{-4}$ 〈0.001% to 0.01%〉
b	$\geq 3 \times 10^{-6}$ and $<10^{-5}$ 〈0.0003% to 0.001%〉
c	$\geq 10^{-6}$ and $<3 \times 10^{-6}$ 〈0.0001% to 0.0003%〉
d	$\geq 10^{-7}$ and $<10^{-6}$ 〈0.00001% to 0.0001%〉
e	$\geq 10^{-8}$ and $<10^{-7}$ 〈0.000001% to 0.00001%〉

Figure 4-1: Performance Level Ratings

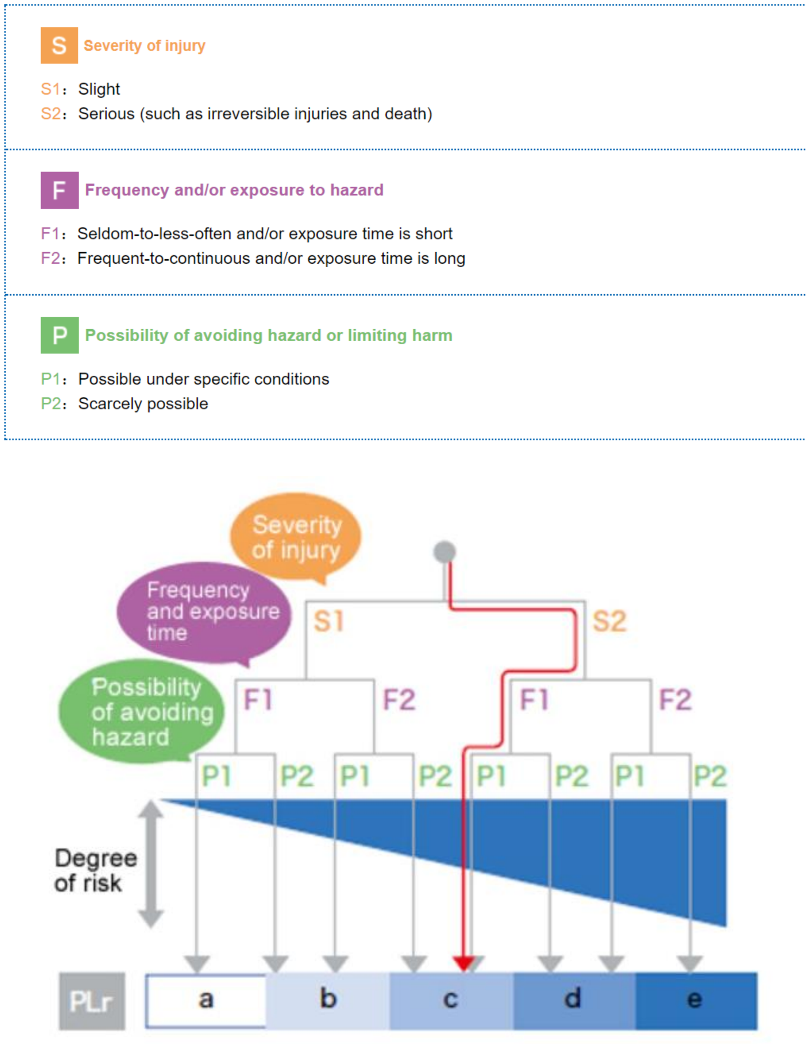

Figure 4-2: Performance Level Requirements

According to the Figures provided by Keyence America[6], the performance level requirement is S1-F1-P1 which is PLa. According to ISO 13849-1[6], the system behavior for a PLa rated system is that the occurrence of a fault can lead to the loss of the safety function. Sections 4.1 and 4.2 detail potential faults that can lead to hazards and their result. The XEM safety system (composed of hardware and software) responds to all system faults with a fail-safe response whether or not the fault is detected. This is to the level of PLd.

4.1. Failure Mode and Effects Analysis

Failure mode and effects analysis (FMEA) is a technique used to analyze the safety performance level of a system. Its purpose is to define the worst case scenario and how it is handled by a system. In this application the FMEA is shown in Table 4-1.

Table 4-1: Figure Mode and Effects Analysis

Element	Function	Failure Mode	Hazard	Consequence
Open Lap Bar Button	Sends command to open lap bar	Button stuck, NO Contact failure, NC Contact failure, output short circuit, input short circuit	Electrical Shock, Burns	Circuit breaker trip, Power Supply Disable, open lap bar disable
Close Lap Bar Button	Sends command to open lap bar	Button stuck, NO Contact failure, NC Contact failure, output short circuit, input short circuit	Electrical Shock, Burns	Fuse trip, Power Supply Disable, open lap bar disable
E- Stop Button	Disables Power Supply and all outputs	NC1 Contact failure, NC2 Contact failure, input short circuit	Electrical Shock, Burns	Power Supply Disable, outputs disabled
WSL4 Relay	Output 24V WSL4	Stuck on, Stuck off	Electrical Shock, Burns	Power Supply Disable, outputs disabled
WSL8 Relay	Output 24V WSL8	Stuck on, Stuck off	Electrical Shock, Burns	Power Supply Disable, outputs disabled
WSL7 Relay	Output 24V WSL7	Stuck on, Stuck off	No Hazard	Power Supply Disable, outputs disabled
Trouble Ack. Button	Acknowledges active faults	Stuck on, Stuck off	No Hazard	Unable to reset fault
Power Button	Turns on / off XEM	Stuck on, Stuck off	No Hazard	Unable to turn on

4.2. Safety Circuit

The safety circuit is the emergency stop circuit. The emergency stop circuit disrupts the high power output from PS1. The emergency stop circuit requires 4 inputs in order to be active. This reduces the risk of a safety hazard due to failure to interrupt the high power output. A loss of any input will activate an emergency stop condition. The truth table shown in Table 4-2 are the inputs that are necessary for the PS1 high power output to be active.

Table 4-2: Safety Circuit Truth Table

ENABLE K1 ON	ENABLE K2 ON	ESTOP PB NC1	ESTOP PB NC2	PS1 ON
0	0	0	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	0
0	1	1	0	0
0	1	1	1	0
1	0	0	0	0
1	0	0	1	0
1	0	1	0	0
1	0	1	1	0
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1

The PS1 enable circuit is based on an all or nothing voting system. If any votes are not for enabling the PS1, the PS1 will not be enabled. The simplified PS1 off truth table shown in Table 4-3 shows how any input being 0 (LOW) will prevent the PS1 high power outputs from being enabled. Through circuitry the vote of one input will influence the others to remove their vote as well (as described in the technical section). Therefore, the fail-safe condition is ensured. If any input or wire is missing the fail-safe condition is PS1 disabled. For this reason, the PLd rating is maintained. Even if a control of the fail-safe condition is lost, the fail-safe condition is still maintained through redundant outputs and inputs.

Table 4-3: Safety Circuit PS1 Disable

ENABLE K1 ON	ENABLE K2 ON	ESTOP PB NC1	ESTOP PB NC2	PS1 ON
0	x	x	x	0
x	0	x	x	0
x	x	0	x	0
x	x	x	0	0

4.3. Communication Standards

The X-Car Electrical Maintenance tool will use different standardized communication protocols in order to collect, distribute and display information. The X-Car Electrical Maintenance tool uses both wired and wireless communication protocols. The XEM uses some very common methods of communication. The wired communication protocol used is the Universal Asynchronous Receiver Transmitter (UART). The wireless communication protocol used is Frequency Shift Keying. These two protocols are standardized such that any device using this standard will be able to communicate efficiently.

The Universal Asynchronous Receiver Transmitter protocol (UART) is a well-known communication standard. The basics of this protocol is that two devices only need three connections to communicate: Rx (receive), Tx (transmit), and ground. With these three connections, any two devices that use the UART standard will be able to communicate with each other. In addition to this, the UART of each device must have a clock of its own. This clock is also referred to the baudrate. Each device must set up a baudrate matching setting. There are industry standards for common baudrates such as 115k. In this instance, the XEM uses 115k between the Main XEM circuit and the TDR circuit. The main XEM also uses 600k between itself and the HMI.

The Frequency Shift Keying protocol is a common standard within wireless communications. The basics of this protocol is that two devices share the same modulation frequency and have their demodulators tuned for that frequency. With a matching modulation frequency and their demodulators tuned for a specific frequency, two or more devices are able to communicate. The Frequency Shift Keying protocol works by placing a data signal on to a carrier frequency by which the receive can remove the carrier frequency from the signal and extrapolate the data. The two devices must be in sync for the Frequency Shift Keying protocol to perform correctly. They must share the same carrier frequency and know each other’s data rate. The importance of the synchronization between devices leads to needing a standardized protocol.

4.4. Design Constraints

The main constraints of the project were to provide a safe and reliable tool. In order to meet these constraints, many layers of fault detection and fault response had to be added to the system. To maintain reliability, high quality, high accuracy components had to be used. This increased cost and complexity considerably. Another constraint for the project is that it MUST conform to the ride system that which already exists. The XEM must not do or cause any harm to the ride vehicle equipment. A major concern is that the XEM could provide a voltage or current that exceeds the specifications for the ride vehicle equipment. This is not allowed. The safety of the user is also important. If any fault that could expose the user to any safety hazard can occur, it must be monitored. If any fault that could potentially damage equipment can occur, it must be monitored and responded to accordingly.

5. Technical Data – Design

In this chapter, the theoretical design will be discussed. The part selection and reasoning for selected the components will be explained. The schematics and layout will also be discussed. Types of components used and their purpose is also discussed. Partial limitation of these components will also briefly be explained. The overall schematic, Figure 5-1, for the main XEM circuit is shown below and will be discussed further.

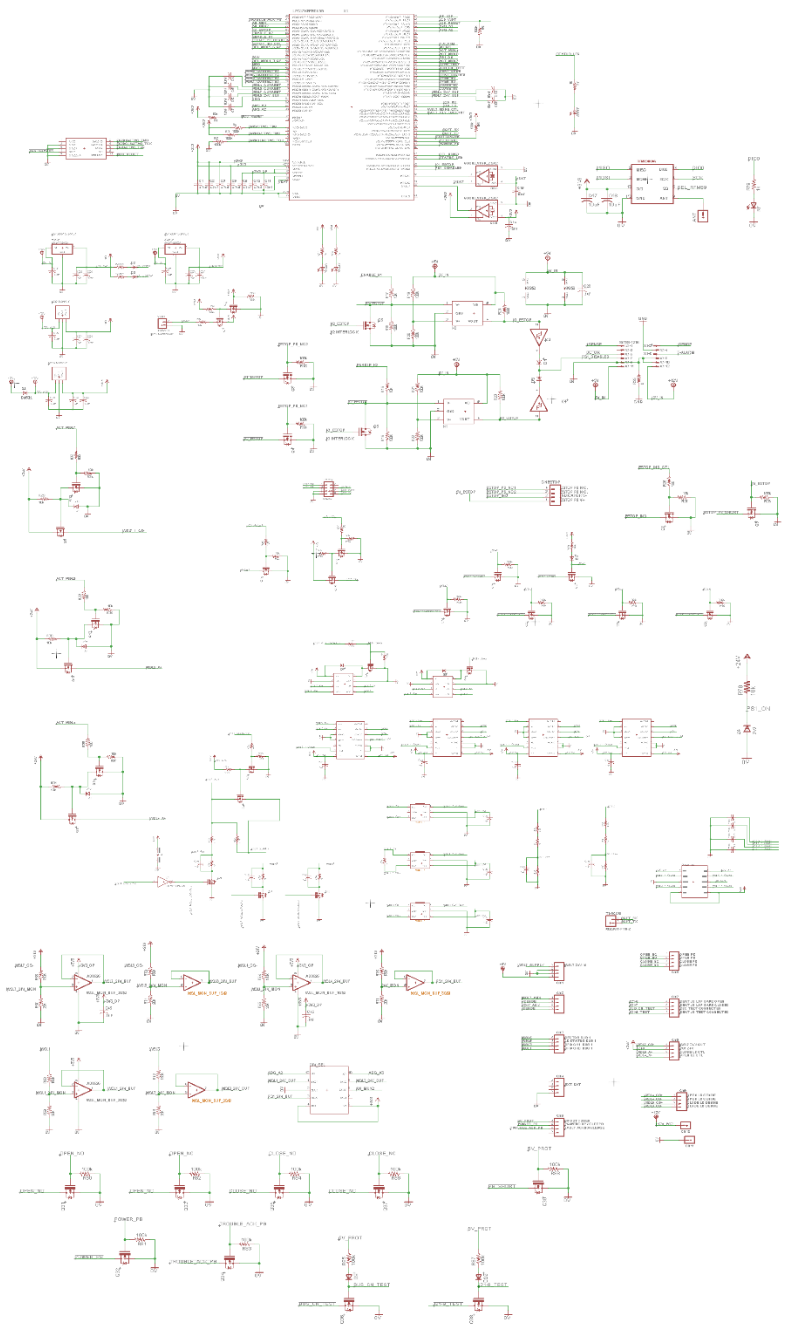

Figure 5-1: Overall Main XEM Schematic

5.1. Low Voltage Power Supplies

The low voltage power supplies refer to any voltage supply under 24V on the XEM. This includes the 3.3V power supply for the microcontrollers, the 3.3V power supply for the operational amplifiers, the 5V power supply for the HMI, the 5V power supply for the operation amplifiers, the 5V power supplied by the PS1, the 12V power supplied by the PS1, and the 12V power supplied by the PS2.

5.1.1. MCU Power Supply

The MCU power supply was chosen to be a DC-DC buck converter made by RECOM called the R-783.3-0.5. Its max output is 1.6W at 3.3V. This is 500mA at 3.3V. A buck converter was chosen because of its efficiency over linear regulators and high input voltage tolerances. The MCU uses the most power at the 3.3V voltage level on the XEM circuitry so an efficient power supply was necessary. Due to the digital nature of the MCU circuitry the noise levels of switching power supplies is adequate for this purpose. Linear regulators do not have noise which is very good for analog signals but the efficiency rating is very low compared to switching regulators.

To help alleviate the regulation error of the switching supply, bypass capacitors are used generously across the MCU supply.

The switching regulators work, at minimum, by using comparators, MOSFETs, diodes, capacitors, and inductors. They take advantage of the properties of capacitors and inductors. Capacitors do not let voltages change immediately and inductors do not let currents change immediately. The MOSFET feeds the capacitor and inductor power from the input voltage and the MOSFET switching controlled using a comparator that monitors the output voltage across the capacitor. When the output voltage is lower than a preset value, the MOSFET is turned on which allows current to flow in to the inductor and capacitor. When voltage levels reach a certain level, the comparator switches off the MOSFET. At that moment the magnetic field stored in the inductor forces current to flow. A reverse biased diode is in place to complete the current path for the circuit when the MOSFET is switched off. Since the inductor stops current from changing and the capacitor stops voltage from changing, the output voltage maintains the regulated value. Stored power does not last forever however and the output voltage begins to sag. At this moment the comparator switches the MOSFET on again, feeding power to the inductor and capacitor. This cycle repeats itself as long as there is input power.

In the case of the R-783.3-0.5, all the switching regulator components are internal to the component. Only VIN, GND, and VOUT pins are made available to the designer. This makes integration easy and similar to the classic 3 pin linear regulators. This simple integration is shown in Figure 5-2. There is also a diode used for the VIN pin to allow for an external battery to power the MCU.

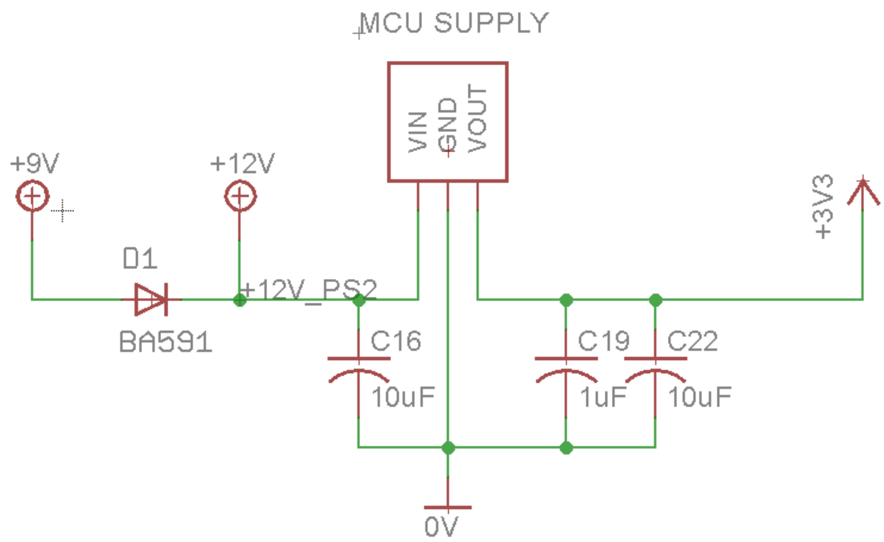

Figure 5-2: MCU Power Supply Circuit

5.1.2. HMI Power Supply

The HMI power supply was chosen to be a DC-DC buck converter made by RECOM called the R-785.0-1.0. Its max output is 5W at 5V. This is 1A at 5V. The buck converter configuration was chosen because the HMI is digital circuitry and does not require strict regulation. The HMI however is a power hog and requires a minimum of 500mA so high efficiency is required. The decision was made to use the R-785.0-1.0 instead of the classic LM7805 linear regulator was due to the efficiency differences. Figure # shows the schematic for the 5V LCD supply regulation.

To help alleviate the regulation error of the switching supply, bypass capacitors are used generously across the HMI supply. Additionally, the HMI power supply feed is controlled by the MCU. This allows for low power states when the HMI is not in use. The feed is controlled using a P-Channel MOSFET in combination with a N-Channel MOSFET to send 5V to the HMI circuitry. The P-Channel MOSFET is used as the high side switch and the N-Channel MOSFET is used to control the P-Channel gate voltage. The HMI power supply feed is shown in Figure 5-3.

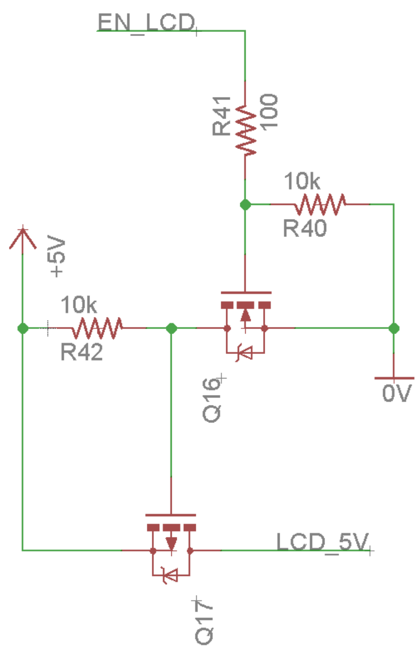

Figure 5-3: HMI Power Supply Control

When Q16 is off, EN_LCD signal is LOW, the gate, V_G, on Q17 is at 5V and the source, V_S, of Q17 is always at 5V. This makes the V_{GS} equal to 0V. This is above the turn on voltage for Q17 (turn on voltage, V_{GS}, is negative).

In the case of the R-785.0-1.0, all the switching regulator components are internal to the component. Only VIN, GND, and VOUT pins are made available to the designer. This makes integration easy and similar to the classic 3 pin linear regulators. This simple integration is shown in Figure 5-4. There is also a diode used in the VIN pin to allow for an external battery to be used to power the HMI.

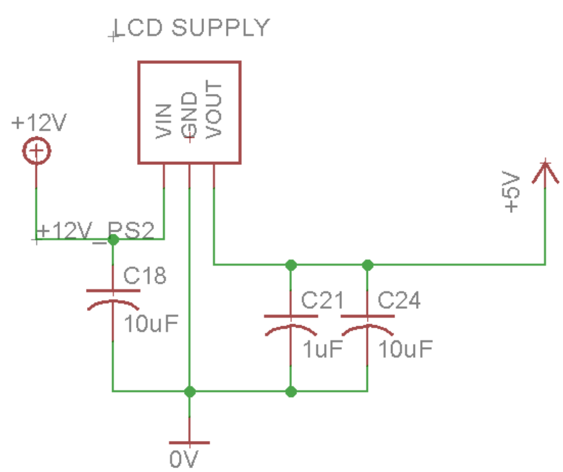

Figure 5-4: LCD Power Supply Schematic

5.1.3. Operation Amplifier 3.3V Supply

The operational amplifier 3.3V power supply was chosen to be a linear regulator made by Microchip Technology called the MCP1703AT-3302E/CB. Its max output is 825mW at 3.3V. This is 250mA at 3.3V. The linear regulator configuration was chosen because the operational amplifier is providing an analog signal which needs stability and minimal noise. This specific linear regulator by Microchip Technologies is a low-dropout regulator (LDO). This is the most efficient form of a linear regulator by 21st century standards. The operation amplifiers being supplied also do not require much power so the power losses are minimal. The important feature here is the stability. The VIN for the circuit is sourced from the 5V from the PS1 power supply to minimize power dissipation. The circuit for the 3.3V operational amplifier supply is shown in Figure 5-5. In this case, instead of burning off 9V from the 12V supply from PS2, only 1.7V is burned off over the regulator.

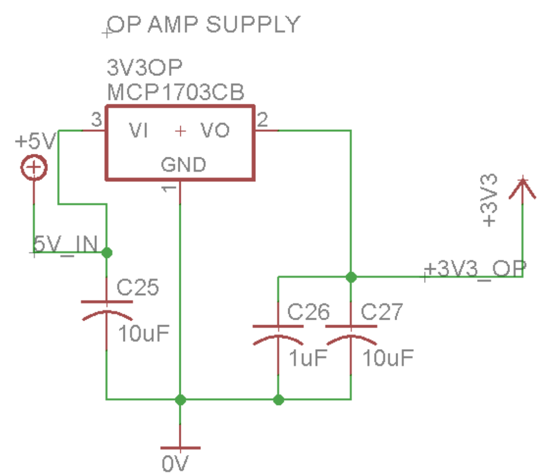

Figure 5-5: Operational Amplifier 3.3V Supply Schematic

5.2. Microcontroller Design

The LPC1769 microcontroller selected is the main brain of the XEM. All signals in the form of a hardware signal or software signal is sent to the LPC1769. In Figure 5-6, all of the connections to the LPC1769 are shown. There are multiple bypass capacitors placed next to all the power pins of the LPC1769. All the debug pins are pulled either high or low to avoid floating signals. The LPC1769 has potential to enter a bootloader mode if pins are left floating. The LPC1769 is supplied with a 12MHz clock for its main clock. The LPC1769 is powered by 3.3V. There is ample power supply decoupling capacitors to ensure there is clean power to the LPC1769. There are also bypass capacitors on the analog signals. This keeps the analog signal feedback stabilized.

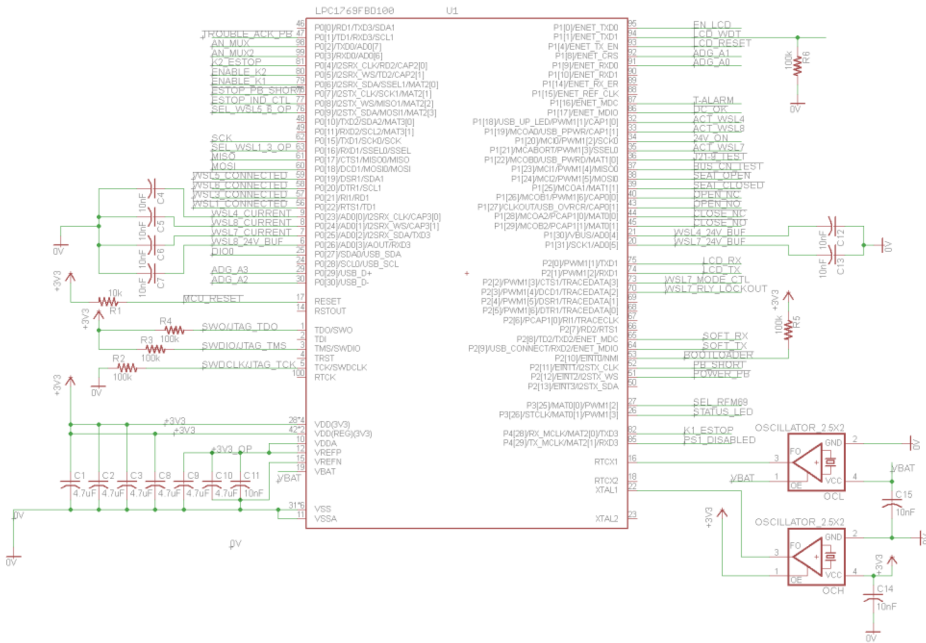

Figure 5-6: Main XEM Microcontroller Schematic

5.2.1. LPC1769 Debugger

A debug interface was incorporated to the design for debugging and programming purposes. The debug pins used are SWD and SWCLK. These are the serial wire debug pins. Figure 5-7 shows the debug connector schematic which uses the standard JTAG 10PIN setup.

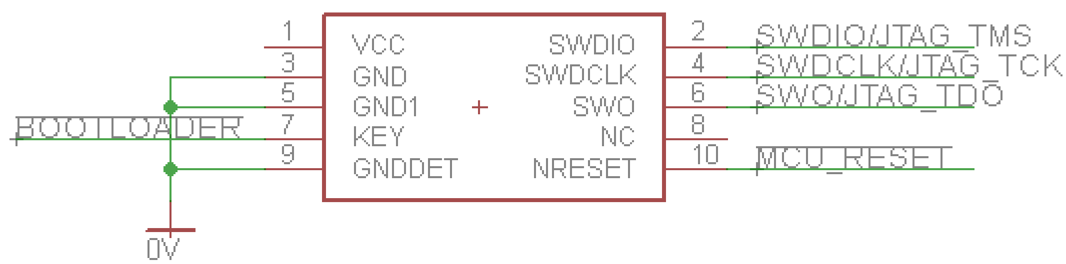

Figure 5-7: Debug Connector Schematic

5.3. Operational Amplifiers

In order to choose operational amplifiers there are a few parameters to keep in mind. The input bias of the operational amplifier and the offset.

The input bias of an operational amplifier refers to the small current that flows into the two input terminals of the operational amplifier. This small input current produces a voltage across the circuits internal resistors and if amplified along with the normal amplified voltage. The lower the input bias of an operational amplifier, the more accurate the output will be. In our applications, when an accurate reading is wanted, a precision operational amplifier will be used. The precision operational amplifier will draw less current from the circuit to give more accurate readings.

The offset of the operational amplifier refers to the voltage difference needed between the two input terminals to receive a response in the output of the operational amplifier. If the offset is very high, then changes in voltage on one terminal will not change the output of the operational amplifier and the reading will not be accurate. When accurate readings are needed, an amplifier with a low offset will be chosen.

5.4. Resistor Usage

When choosing resistors for a circuit, not only does the value of the resistor need to be calculated and the power dissipation taken into consideration, but the actual construction of the resistor as well. Resistors come in multiple varieties, such as thin film, thick film, and wirewound.

A thin film resistor is made from a uniform dense allow, such as Nichrome. The strength of this allow allows the resistor to undergo a laser trimming process to finely adjust the resistor without introducing imperfections in the resistor. This allows thin firm resistors to achieve low tolerances, low noise, low parasitic inductance, and low capacitance. These properties lend thin film resistors to applications that need a high stability, high accuracy, or a low noise factor.

A thick film resistor is the general purpose resistor used in any application. These resistors are made by applying a paste to a ceramic plate. It is then fired and comes to a glass-like finish. The glass-like finish does help in environments with high humidity. The process does not produce a resistor with comparable parameters to thin film resistors. However, thick film resistors are much cheaper, and so are used for any general purpose.

A wirewound resistor is created by wrapping a resistive material, such as copper, silver, or nickel alloys around an insulating core. The resistance of the final produce is dependent on the resistivity of the wire being used, the diameter of the core, the cross section, and the length of wire. Because each of these resistors can be accurately controlled, wirewound resistors are very highly accurate.

These resistors are essentially inductors, as they are wire wound around a core. This leads to the worst inductance of all resistor types. A precision wirewound resistor is typically used in measuring bridges and calibration equipment because the typical tolerance of these kinds of resistors is 0.1% or better. These resistors can reach even better tolerances, as manufactures may account for the decay over time of a resistor. These wire wound resistors are very finely made, reaching tolerances of 0.01%.

In our applications, thick film resistors will be used the majority of the time. When a current is needed, but not very accurately, such as supplying current to the gate of a MOSFET or limiting the current through an LED. Other resistances, such as the sense resistor on the MAX9929 needs a more accurate resistor. Ideally, the most accurate resistor would be used, however the cost increases with the accuracy, and the power dissipation across the sense resistor is also an issue when selecting a resistor, as different types of resistor have different power ratings.

5.5. ADC Operation

When using the ADC contained in the LPC1769, the most recent reading from the ADC is stored in the main ADC register, while each input has its own register that holds its most recent reading. The register will hold the reading until either a new measurement or the program says to clear the register.

Holding a measurement in its dedicated register could be useful for utilizing the value in program functions without allocating and copying to other memory. However, in our application the inputs that would be connected to the multiplexed input are already passed through a multiplexor.

Because of this, long term storage of measurements in the ADC registers is not viable, as measurements that would want to be used at the same time may be multiplexed into the same ADC input, and you therefore occupy the same storage register.

5.6. Measurement Circuits

The XEM will have the capability to measure voltage, current, and resistance over multiple sections of the load system. The XEM will utilize voltage dividers, current sense amplifiers, precision amplifiers, and Wheatstone bridges. The measurement of each of these is needed as any one of them could indicate an error in the load system or the signs of an error in the making.

For example, if a resistance measurement was shown to have an incredibly high amount of resistance then perhaps there is a disconnection somewhere in the measured circuit. The voltage measurement of the system would help determine if something is causing a larger or smaller voltage drop, either due to a short around some component or perhaps extra resistance being gained from some error.

All of these circuits are important for the safety of the load system and are made using precision amplifiers and high quality parts where necessary. The purpose of the XEM is to lessen maintenance times and to provide better troubleshooting on the load system to ensure the highest safety while also saving time and money, therefore the precision and accuracy of these circuits is of high priority.

5.7. Voltage Measurement

The LPC1769 microcontroller in the XEM has a built-in analog to digital converter (ADC). The ADC is twelve bits, and can measure a maximum of 3.3 volts. By taking a minimum of zero volts and a maximum of 3.3 volts, the ADC has a step width of 0.8 millivolts. The voltage sent from the XEM through the system is much too large to be used by the microcontroller. The proposed voltage measurement circuit is presented in Figure 5-8.

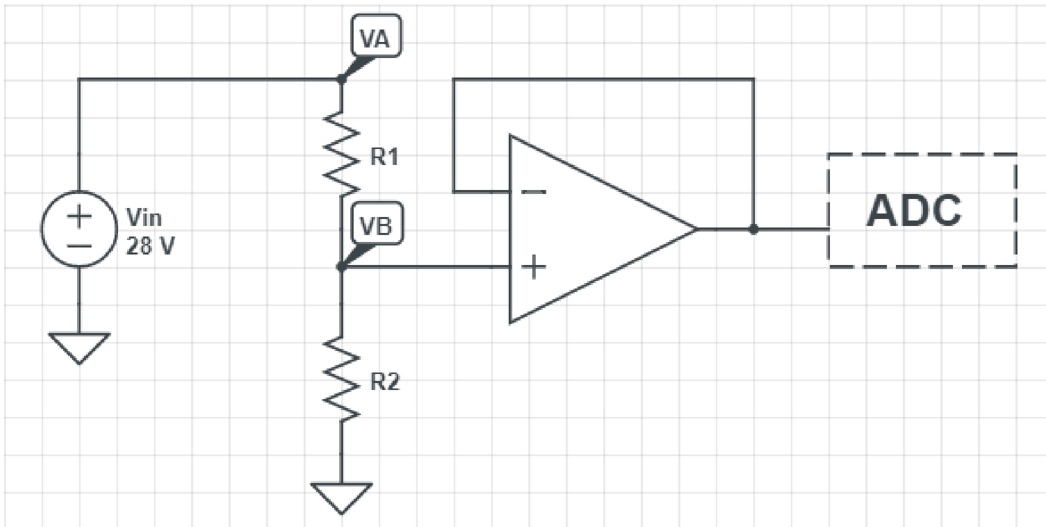

Figure 5-8: Voltage Measurement Circuit

A voltage divider is utilized to bring the voltage down to a usable level. The maximum voltage seen from the XEM will be 28 volts. The voltage at position VA is the node that connects the output of the XEM to the load system. The voltage at position VB is what the ADC is going to measure. To bring the 28 volts down to usable level, resistor two needs to have a value equal to approximately one ninth of on the combination of resistor one and resistor two. For this voltage divider, R1 was selected to have a value to be 180k ohm, and R2 to be 20k ohm. This divider drives VB to one tenth the voltage provided by the source. This will bring the total voltage down to the maximum of 3.3 volts to be usable by the microcontroller ADC. The proportional, usable voltage is fed into a buffer. The typical schematic for this analog voltage measuring circuit is shown in Figure 5-9.

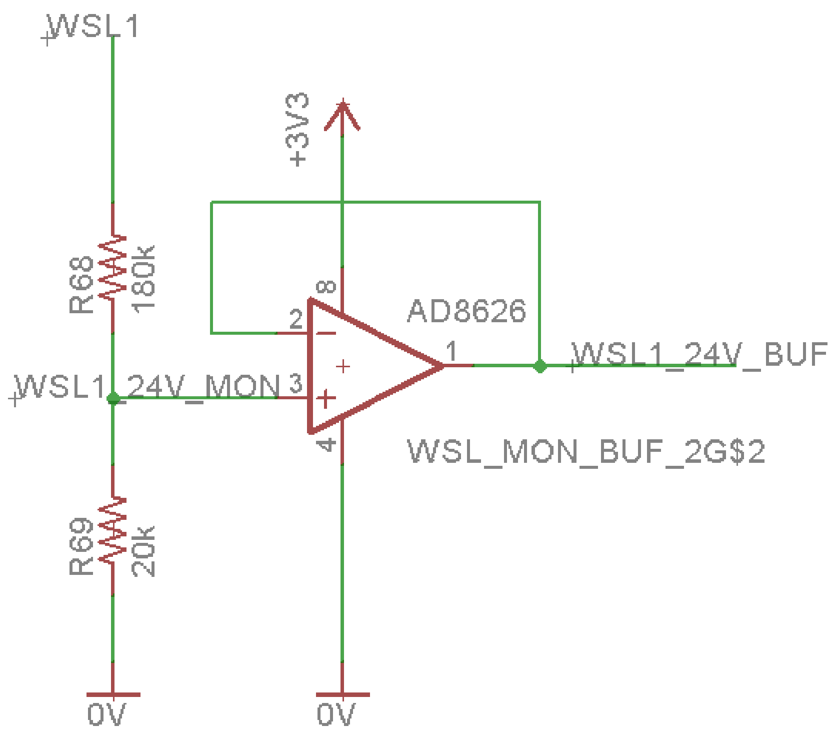

Figure 5-9: Typical Voltage Measurement Schematic

A precision operational amplifier acts as a buffer to protect the microcontroller from the main system, and to hold the voltage at a stable position. The configuration of the operational amplifier is in a non-inverting configuration. The gain of the amplifier is one. Therefore, the operational amplifier forces the output to be equal to the input, in this case the voltage at position VB. The precision operational amplifier can very accurately read the difference in voltage between its two input pins, giving the best possible output.

The buffer is made using an AD8626 precision operational amplifier. This amplifier has a very low offset voltage of only 500 microvolt maximum. The offset voltage is the difference in the voltage between the two inputs to the operational amplifier that is needed to produce an output of zero volts. Having a low offset voltage means that very small differences in the two input voltages will not be read as the same voltage and will instead output a non-zero voltage. A different operational amplifier, such as the common TL084 amplifier, has a typical offset voltage of three millivolts, six times higher than the maximum offset voltage of the AD8626. Because this application needs a higher degree of precision, this operational amplifier is used to ensure no voltage difference is lost due to error from offset voltages.

When the program passes a request to the ADC for a reading, the ADC compares the voltage at the output of the buffer to the internal reference voltage. The ADC will read the input voltage to the nearest step, which have a spacing of 0.8 millivolts. The initial division of the input can then be undone in the program by multiplying by the converted voltage. Given that the input voltage has been divided by nine, and a step spacing of 0.8 millivolts, the step scaled voltage step will be seven millivolts. The proposed accuracy in voltage reading is within 100 millivolts, so this error is well within parameters. This is good because the current and resistance measurement circuits are based on the voltage readings taken in different configurations with the load system and known resistances.

5.8. MAX9929 Current Measurement

The MAX9929 is a high voltage current-sense amplifier. The high voltage side is used because problems can arise when attempting to use the low voltage side while a common supply powers multiple load systems.

By using the high side voltage between the source and load, this problem is removed. The MAX9929 was selected due to its maximum input voltage of 28 volts to match the maximum voltage output of the XEM. The current sense amplifier also has an input common mode range independent of the supply voltage, meaning that the current sensing voltages can be far above the supply voltage to the amplifier.

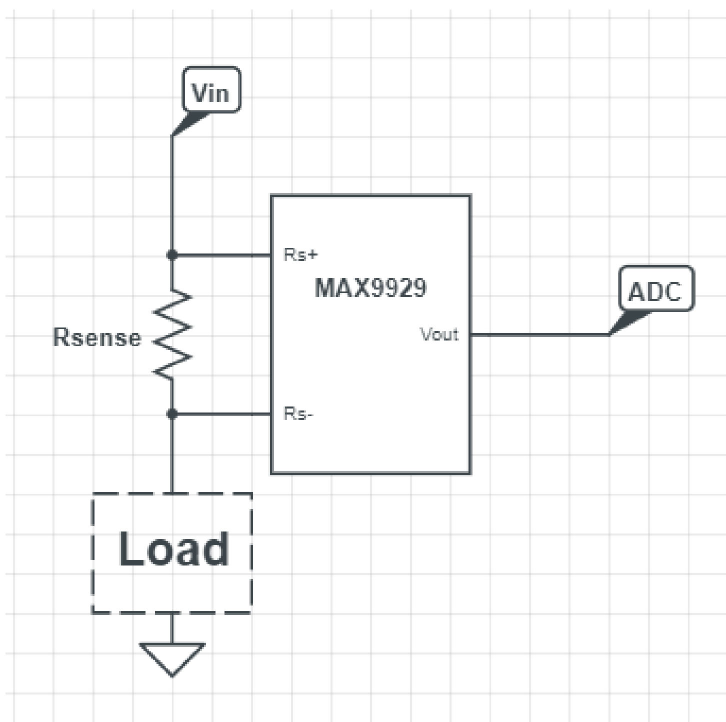

Figure 5-10: Current Sense Circuit Utilizing the MAX9929

The operation of a current sense amplifier is depicted in Figure 5-10. The current sense amplifier works by using a sense resistor which generates a voltage cross the resistor, V_{sense}, when current passes through. The voltage across the sense resistor is read by a comparator to determine the direction the current is moving, and changing a switch position on the amplifier for positive and negative detection. The output of the internal amplifier drives the base of a transistor which enables a current mirror to generate a voltage over an internal resistor. This is the output voltage of the MAX9929.

The output voltage will be measured by the microcontrollers ADC. The output voltage is based on R_{sense}, the current through the load, and the defined voltage gain of the MAX9929. Using these known and measured values the current through the load can be found. The gain of the MAX9929 is 50V/V. The MAX9929 current sense amplifier is much more accurate than using a voltage divider based circuit.

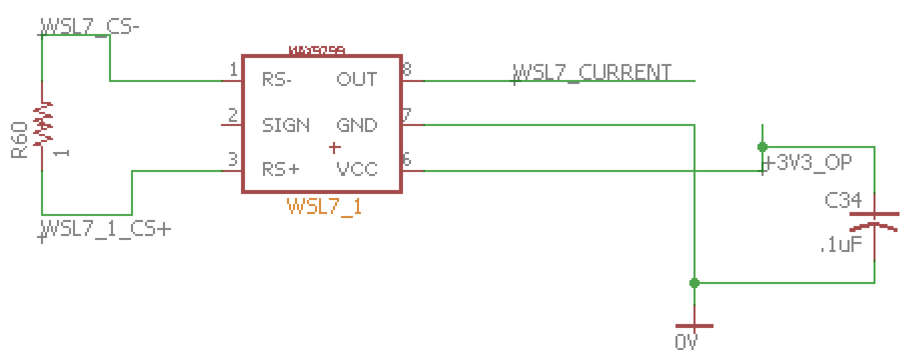

Figure 5-11: MAX9929 Current Amplifier Schematic

5.9. Current and Resistance Measurement

A current measurement circuit is depicted in Figure 5-12. The current measurement circuit has three main components, and three main measurement positions. The XEM, a known resistor, and the load system. The known resistor and the load system together are in series and therefore have the same current through them.

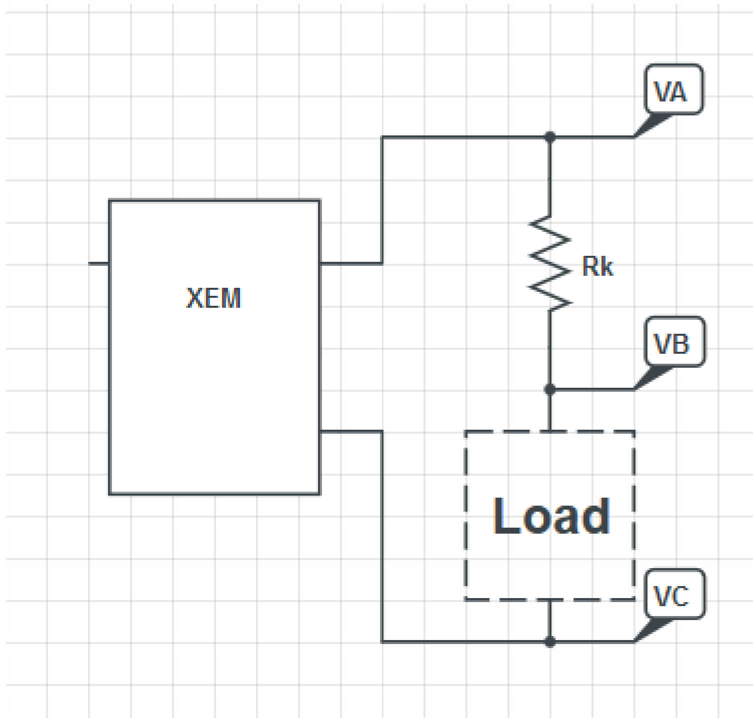

Figure 5-12: Measurement Points through Series Load

To find the current through the load system, the voltage across known resistor Rk is needed. The voltages at the different positions can be found from using the previous voltage measurement circuit. The voltage at VA should be known as it is provided from the XEM. By measuring the voltage at VB and comparing it to the voltage at VA, the voltage difference across the resistor can be found.

The measured voltages will then need to be scaled back to the larger values that are actually seen across the known resistor. The known resistance, Rk, and the newly found voltage drop across the resistor can be used to find the current through the resistor.

However, the current through the resistor has a degree of error to it. Because the voltage it being measured with the previous circuit, every voltage measurement will have its own associated error. As previously stated, the voltage error can be up to 0.8 millivolts. This voltage error will have an effect on the current calculation. The error that the voltage causes will be proportional to the value of the resistor, and the total voltage drop on the resistor.

Taking a voltage measurement on VA will also introduce the same type of error, which will compound with the error on VB. This error can be avoided by applying a specific voltage to the system. However, this has its own problems. By assuming that the applied voltage is the same as the voltage in the system, there can be an error from having a different voltage on VA than assumed.

Position VC is on the low side of the load and connected back to the XEM. If the low side is connected to ground then the voltage will not need to be measured and can be assumed in the calculations. The voltage can also be measured at this position and used in the calculations, but more error will be incorporated by using the voltage dividing measurement circuit connected to the ADC.

The resistance of the load system can be measured by taking a voltage reading on both sides of the load system. The current through the system is found using a current measurement circuit then dividing the measured voltage through the system by the measured current. The two different current measurement circuits have their own degrees of error. The resistance measurement is subject to the same error due to the ADC stepping.

This resistance measurement is not very accurate compared to a Wheatstone bridge based differential amplifier measurement circuit. This resistance measurement could still be used as a sweeping test where a low accuracy is acceptable, such as checking to see if resistance falls within a large range, before determining if a more accurate measurement should be taken using the Wheatstone bridge measurement circuit.

A short around the load system would put a large amount of current through the resistor. The over current of this system would drive the voltage drop across the resistor high leading to an over voltage of the voltage measuring circuit. The over current of the system would also dissipate a large amount of power over the resistor, possibly leading to damaging the circuit on top of the buffer to the ADC.

5.10. Wheatstone Bridge Resistance

The circuit in Figure 5-13 was used to find the resistance in brush five and brush six. The circuit utilizes a Wheatstone bridge connected to the device under test, DUT. The four resistor values of the circuit are meant to be equal. The right side of the circuit is also connected in series to the DUT. Both sides are connected between the resistors to an operational amplifier, acting as a difference amplifier.

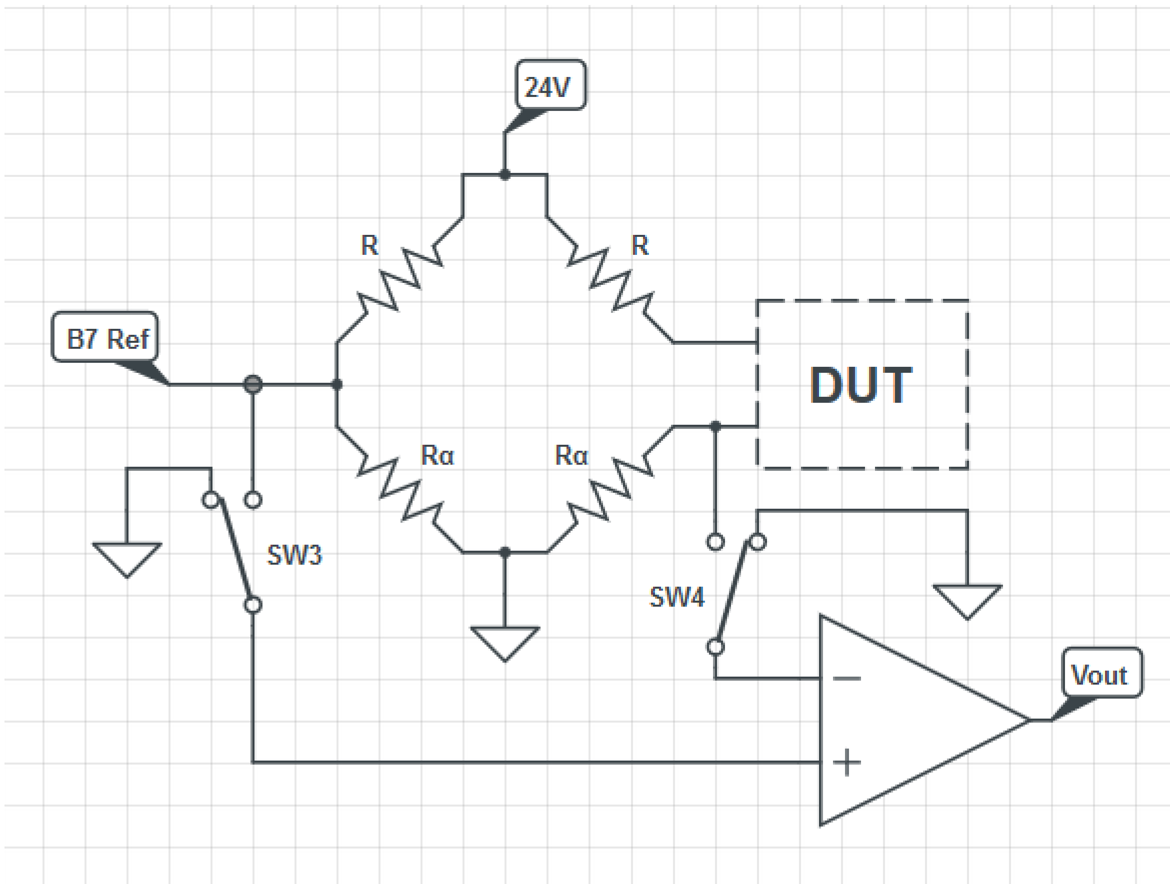

Figure 5-13: Wheatstone Bridge Combined w/ Differential Amplifier

The two input terminals on the operational amplifier are attached to switches to ground. The switches are normally grounded as a safety measure for the operational amplifier and for the attached circuits. The left side of the Wheatstone bridge is also used as a reference voltage on brush seven.

Under ideal circumstances, the output voltage would be zero volts because the voltage drop across both sides of the resistors would be equal, assuming the DUT has zero resistance. Of course, the DUT will not have zero resistance. The change in voltage on one side of the of the bridge will change the output voltage of the differential amplifier, which will be fed into the ADC and converted to a usable value and then stored.

The previous voltage division circuit is not needed in this case. The previous voltage measurement circuit first divides the voltage to a reasonable level or use by the ADC. This circuit takes the small differences between the two sides of the Wheatstone bridge, which can be manipulated to be small enough for use by the ADC.

This voltage can be measured by the ADC and the program can use the voltage reading to find the resistance imposed by the DUT. Because the voltage difference would be zero if there was no resistance from the DUT, the Vout would be zero volts.

When implementing an uneven resistance between the two sides of the Wheatstone bridge, using a known voltage source, and known resistance values the resistance of the DUT can be calculated. The calculation comes from looking at the difference in voltage drops between the last two resistors, Rα, on either side between the nodes to the amplifier and ground.

The accuracy of the voltage source is also important in this kind of circuit, as the difference between the voltage on each side of the bridge is based around a nominal value assuming a certain voltage input. If the input does not match the value used by the program to calculate the resistance of the DUT, then the calculations will be inaccurate.

This can be remedied by either having a very precise and accurate voltage source, or by measuring the input to the Wheatstone bridge input. Measuring the input propagates error through the voltage measurement circuit using the ADC and a voltage divider. This circuit already utilizes the ADC, so it would be prudent to minimize the error propagation from taking too many reading on the ADC for use in calculations.

However, assuming the voltage source is always accurate can be dangerous. If the voltage source is not accurate to the assumed value, then all calculations will be incorrect and would lead to erroneous repairs or replacements in the DUT. The voltage source should be checked before use to ensure the output of the voltage source is accurate to the value used in the programs calculations.

Equation 1: Solve for Resistance of DUT

$$V_{out} = V_{in} * \left[\frac{R_\alpha}{R_\alpha + R} - \frac{R_\alpha}{R_\alpha + R + R_{DUT}}\right] \rightarrow R_{DUT} = -\frac{V_{out}(R_\alpha + R)^2}{R_\alpha(V_{out} - V_{in}) + RV_{out}}$$

Although Equation 1: Solve for Resistance of DUT gives a negative value for the resistance of the DUT, the equation will not return a negative value for the resistance. Due to each resistance value being a positive value and the Rα being near the R value, the numerator will be a positive number, while the denominator will be a negative value. The denominator will be always be negative due to the output voltage minus the input voltage will always be negative as it is impossible to have a larger voltage difference than the supplied voltage with this circuit, and it is impossible for the voltage drop across the DUT side of the bridge to be less than the voltage drop across the left side of the bridge after introducing more resistance from the DUT. The calculations will be done by the programming. All resistance values, except for the value under test, are known and set during production, and the voltage values are either set by the voltage source or will be measured using a voltage measurement circuit.

The Wheatstone bridge resistance measurement circuit is a more accurate measurement circuit than the voltage divider based circuit. The voltage divider based circuit makes more assumptions about the systems connected to the XEM and takes more reading on the ADC, up to three separate readings. Each of these reading as error and will propagate to the final resistance value calculated.

The accuracy of the Wheatstone bridge circuit is unparalleled in this application. The subtle changes of resistance by implementing the DUT will always cause a voltage change that can be measured by the differential amplifier, so long as the resistances on both sides are balanced when there is no DUT connected to the circuit. The operational amplifier used for this application will need a very low offset voltage.

The Wheatstone bridge circuit only uses the ADC one time when determining the resistance through the DUT. This makes the Wheatstone bridge circuit much more accurate by comparison to the voltage divider based circuit.

The wheatstone bridge circuit used in the XEM is shown in Figure 5-14. Since brush system has dual purposes, a MOSFET is used as a switch to bypass the wheatstone bridge circuit. There are also MOSFET's used as a switch to enable the wheatstone bridge circuit. This protects the precision resistors.

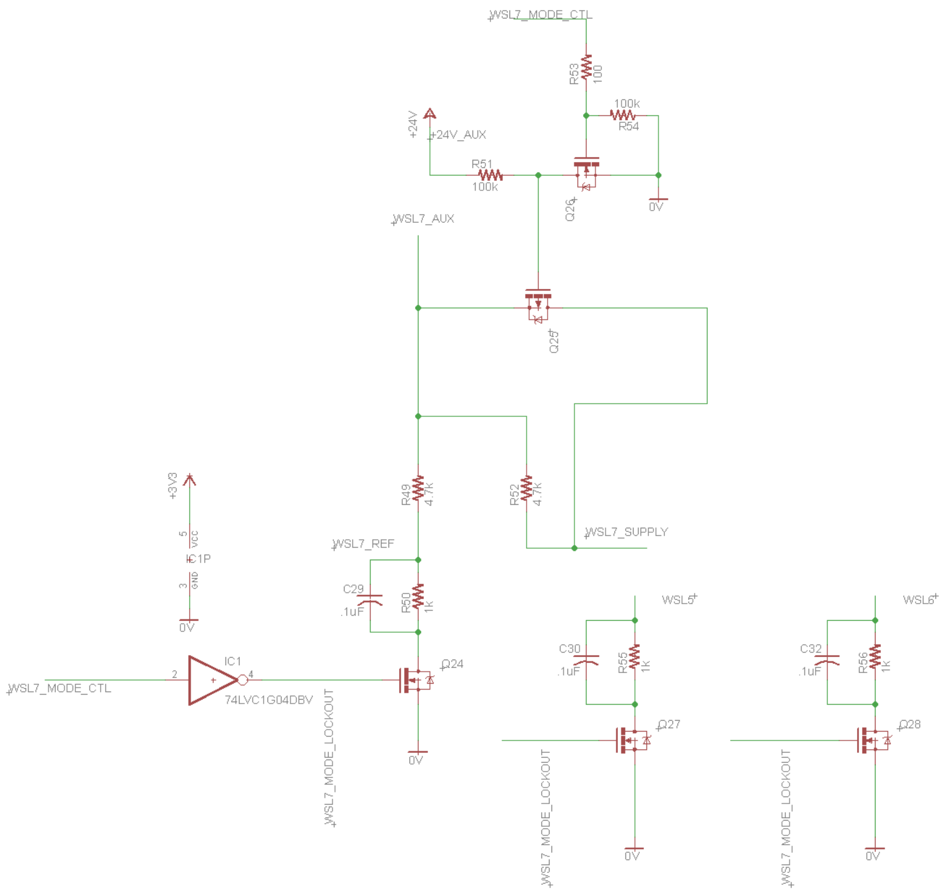

Figure 5-14: Wheatstone Bridge Schematic

5.11. Time Domain Reflectometer

The general design of a TDR has three basic components: pulse generator, characteristic line impedance, and a data capture. The general format is shown in Figure 5-15.

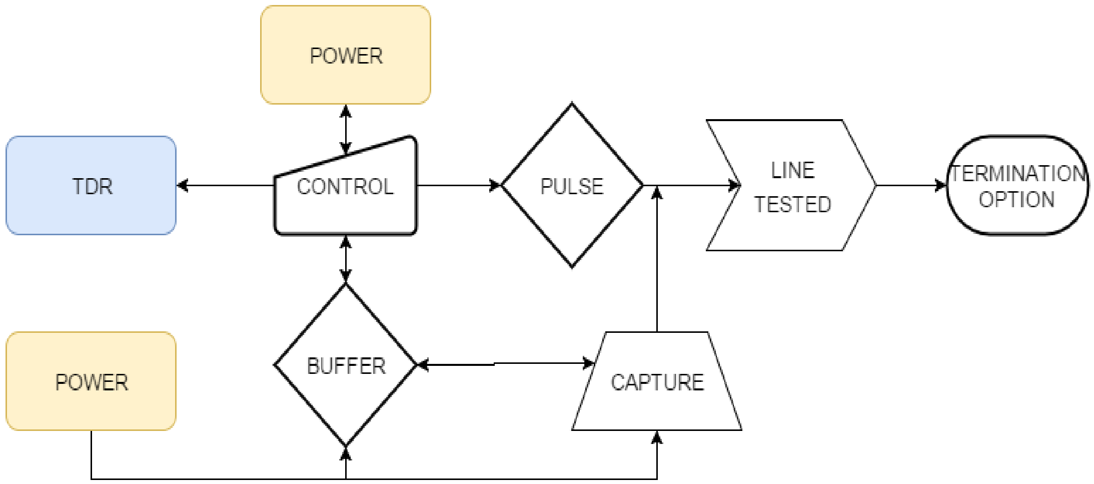

Figure 5-15: Time Domain Reflectometry Circuit Subsystem

5.11.1. Limitations

Due to the speed of charges moving through a transmission line, it is necessary to capture data at very high resolution. When dealing with high resolution data capture, the design must take in to consideration many imperfections that can normally be ignored in low speed circuitry.

- Parasitic capacitance. Capacitance resists a change in voltage. When designing a high speed circuit, any resistance to the rate at which a parameter can change will negatively impact the circuit. The routing and placement of wires or PCB traces will influence the parasitic capacitance in a circuit. At very high resolutions, these small parasitic capacitances are enough to significantly affect a circuit.
- Trace/wire inductance. Inductance resists a change in current. The length and width of a trace or wire will influence the parasitic inductance in a circuit.
- Wire/Trace routing. Rapid turns, bends, or loops in a trace or wire introduce stray capacitance and inductance in a circuit.
- Components. Typically, fully integrated circuits are for low speed designs. When reaching resolutions in the nanosecond range and below, circuits must be built using discrete components interfacing with integrated circuits. This adds complexity and also stray capacitance and inductance to a circuit depending on layout design.
- Noise. High speed circuitry is very sensitive to noise. As an analogy, if one were to zoom in very closely to a computer screen, one would see that the images on screen have rigidness to them because of the individual pixels that make up the image. When capturing a high

speed signal, the noise that would otherwise be overpowered by the rest of the signal, as a whole, is now amplified.

5.11.2. Component Selection

For the high speed pulse generator, a resistor capacitor network, NOT gate, and an AND gate will be used. These gates will be LVC (low voltage CMOS) type. The LVC gates provide the best transition and propagation speeds. The pulse generator is necessary to have a very high frequency due to the expected short transmission line length of the DUT. This is because when a pulse is generated, it must be fully "pushed out" before the charges have a chance to reach back. The moment at which this "push out" phenomenon and the reflective wave reach back is called a "blind spot". This is because it is impossible to distinguish where the transmission ends and where the pulse ends. A MUX will be used to select different pulse speeds. Figure 5-16 shows the general circuit for the pulse generator. Here the output impedance is set to 50Ω.

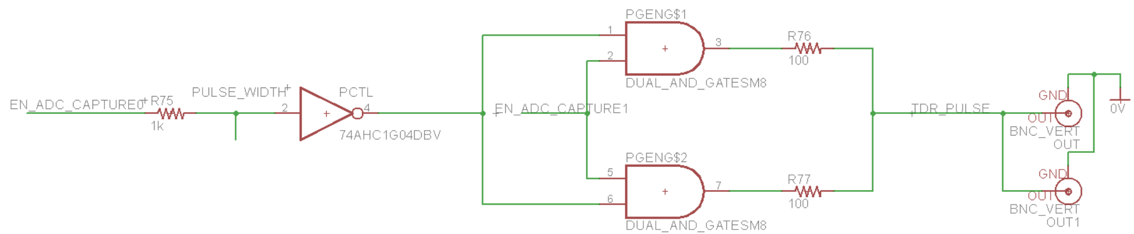

Figure 5-16: Pulse Generator Circuit

For the characteristic impedance, foil resistors were chosen due to their low inductance characteristics. This reduces any unwanted inductance on the output signal resulting in a cleaner pulse generated.

For the high speed data capture, the ADC chosen to capture data is Texas Instruments ADC08B3000 chip. This IC is low power 3GSPS ADC with a 4K data capture buffer. With the integrated data buffer, a simple MCU can handle the data processing. Very few high speed ADCs have a data capture buffer. Without the data capture buffer, other high speed circuitry must be designed to capture the analog data such as an FPGA. This adds considerable time and research in to the design. The use of an FPGA was avoided due to the integrated capture buffer of the ADC08B3000. The way the ADC08B3000 achieves such high data capture rates is through two interleaved ADCs running at 1.5GSPS. One ADC captures on the rising edge of a clock and the other ADC captures on the falling edge resulting in a net capture rate of 3GSPS.

Due to the noise limitation of high speed circuitry, the ADC08B3000 requires differential inputs and outputs. A differential input/out takes the difference between the positive and the negative of signal. The opposite values of noise riding on the signal get eradicated in this way leaving only the actual waveform data to be interpreted. In other words, the common mode noise that would be introduced in a common referenced signal is eliminated from the signal.

For the differential inputs and outputs, a positive and negative voltage supply is necessary to drive the circuitry. The positive and negative supply is generated from a LM7805 and LM7905 pair. These are positive and negative 5V supplies respectively. The schematic for the ADC for the TDR is shown in Figure 5-17.

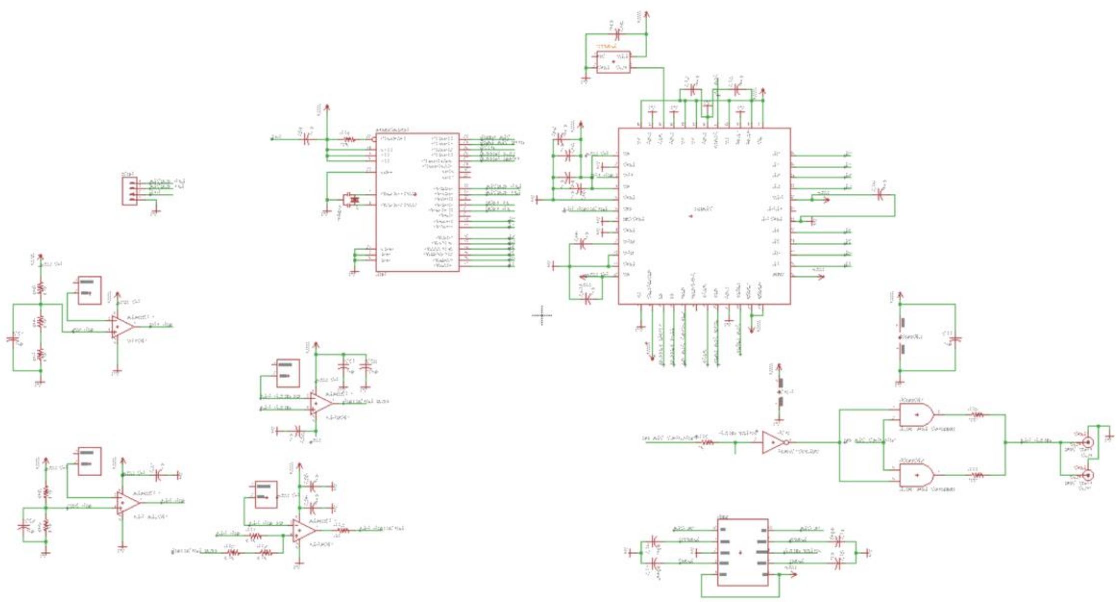

Figure 5-17: TDR Circuit Schematic

5.12. Wireless Control Module

The WCM design utilizes an ATMega328P and RFM69HCW to perform wireless communication. The RFM69HCW is a wireless transceiver controlled by the ATMega328P that sends and receives instructions to and from the XEM when the WCM is enabled.

5.12.1. Operation

The XEM system can also execute basic functions at range using the Wireless Communication Module. The WCM is typically disabled and input is rendered inert. The XEM can send a signal to the WCM to enable wireless control. The wireless control has three signals it is able to send to the XEM. The first signal is the Open Lap Bars signal, the second is the Close Lap Bars signal, and the final is the Emergency Stop signal. These three signals can be seen as the buttons in

Figure 5-18. If the signal from the WCM is valid and able to be executed by the XEM when received, the XEM will carry out the function. The results of these functions are the same as if they were executed from the XEM itself.

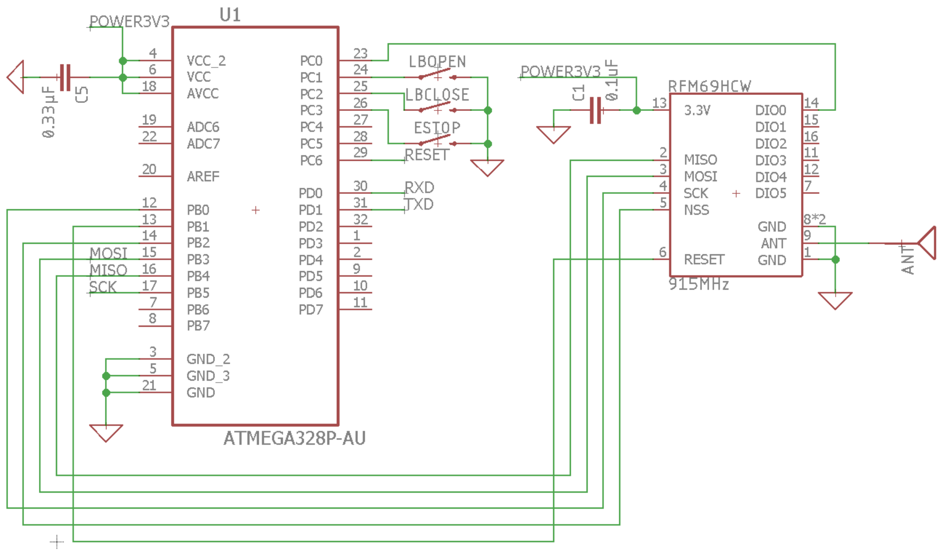

Figure 5-18: ATMega328p and RFM69HCW Schematic

5.12.2. Power

Because the WCM is a wireless system, it is required to have an internal power source, in this case a lithium polymer battery. The battery is charged through an off-board charger. The internal battery does, however, have an under-voltage circuit to prevent the battery from being drained too low, which could cause damage to the battery and lower its lifetime.

The standard voltage of a lithium polymer battery is 3.7 volts and can charge to 4.2 volts. The RFM69HCW is a 3.3 volt system, therefore a lithium polymer battery will be acceptable. The ATMega328P can operate from a range of 1.8 volts to 5.5 volts. Coupling capacitors are used on both the ATMega328p and the RFM69HCW to help alleviate change in supply voltage. The battery voltage needs to be regulated to 3.3 volts for use by the system. Figure 5-19 shows a voltage regulator circuit that has an output of 3.3 volts.

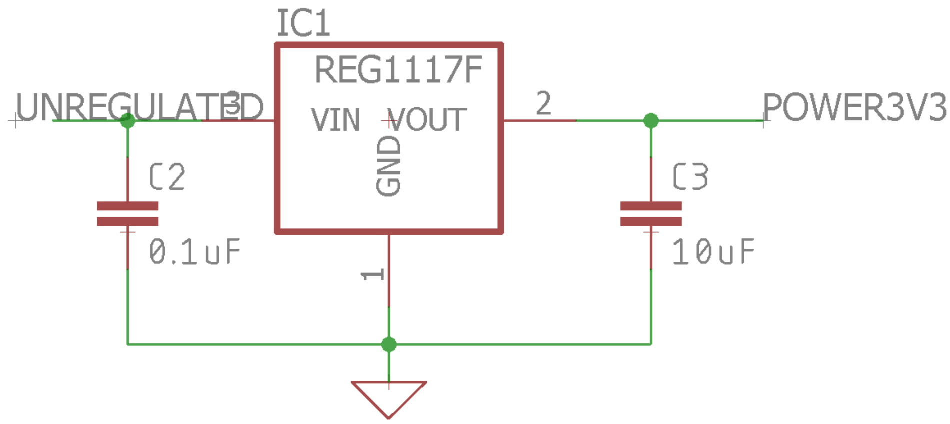

Figure 5-19: Voltage Regulation Circuit - WCM

Using a single lithium polymer battery could be used to operate the ATMega328P, but using a lower voltage rating may limit the options for clock rate. An external clock needs a higher voltage in order to be used by the ATMega328P. By using a lower voltage, it allows the ATMega328P to interface directly with the RFM69HCW without needing to use a logic level converter and without losing too much operation potential. Using only one battery would also give the WCM a shorter lifetime, as the operation is best above the 3.3 volts needed by the RFM69HCW. When the supply voltage drops below the receiver/transmitter voltage the system will become more unreliable, which is unacceptable in this application as an emergency stop signal could be lost.

A battery level indicator circuit is also included in the WCM to give the operator the ability to determine low battery levels at a glance, as depicted in Figure 5-20. The battery level indicator utilizes the zener voltage of a zener diode to give different paths for the current, powering different LEDs. When the supply voltage is above the zener voltage, current will flow through to the transistor, which will ground the green LED branch, not giving current to the second transistor in the red LED branch. When the voltage drops below the required amount to overcome the zener diode, the transistor in the first branch will no longer receive current. Because of this, the transistor in the red LED branch will receive current, activating the red LED branch.

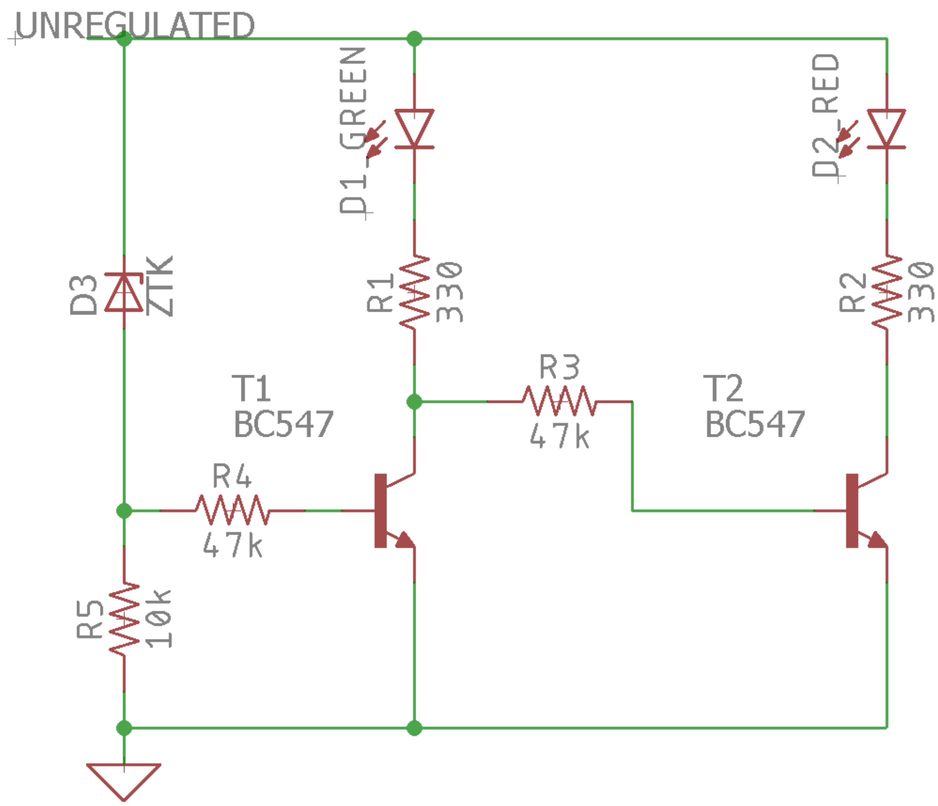

Figure 5-20: LED Battery Indicator Circuit

The under-voltage circuit is depicted in Figure 5-21. This circuit is designed for use with a battery and disconnects the load from the battery when the voltage on the battery drops to a threshold voltage. In this circuit the voltage threshold is set as 3 volts. This circuit combined with the low voltage indicator circuit gives the user ample indication when the voltage is nearing a level below the minimum used for WCM operation, and shuts the system down after the voltage drops too far below the operational level. This under voltage protection circuit features a very low current draw, allowing for the battery to be connected to this circuit after dropping under the threshold voltage without risking damage for a very long time.

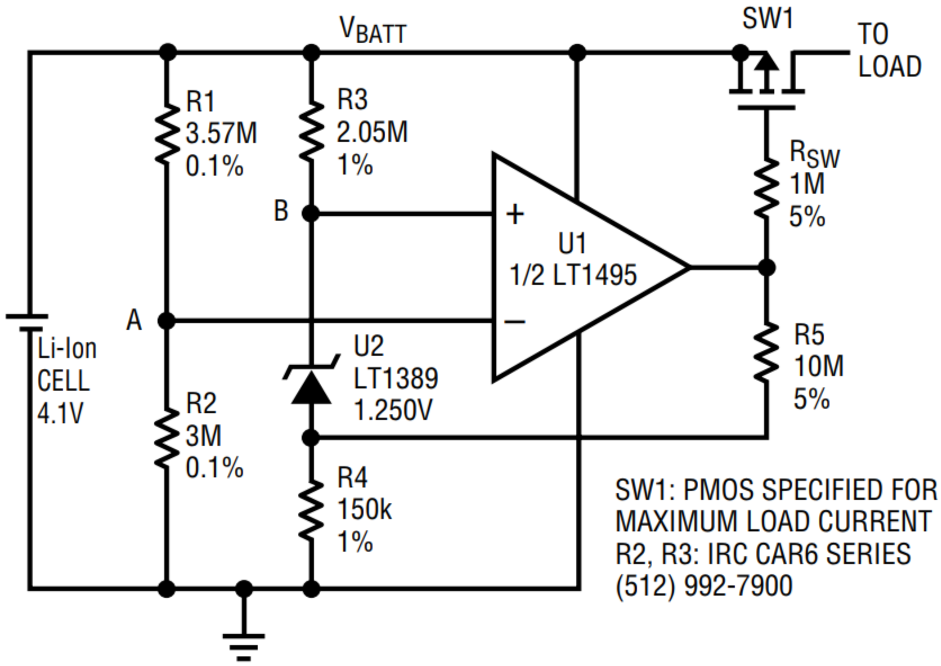

Figure 5-21: Battery Under-Voltage Protection [12]

The WCM is activated by the XEM, but the device itself has a power switch, as depicted in Figure 5-22. The power switch uses a transistor to separate the switch from the current to the load of the batteries. The switch uses a smaller amount of current from the battery to power the base of a transistor to allow current to flow into the load and power the WCM.

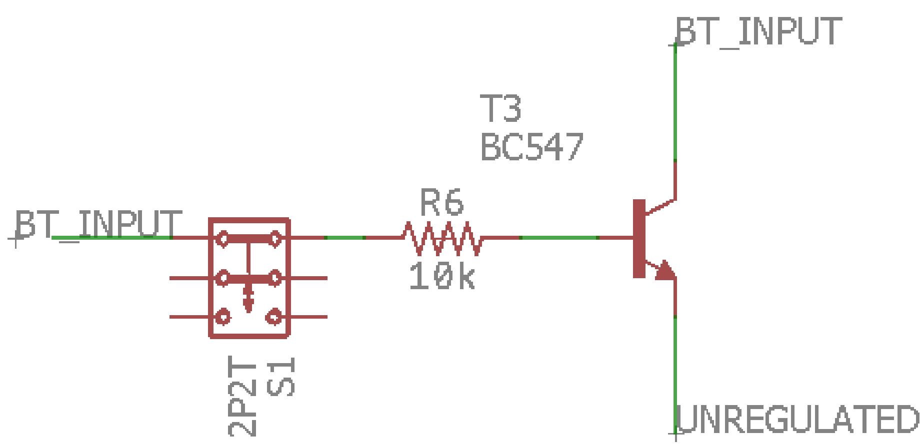

Figure 5-22: Battery Switch

5.12.3. Programming Ports

The ATMega328P and RFM69HCW communicate with each other through Serial Peripheral Interface, SPI. The ATMega328P takes the role of Master and the RFM69HCW the role of Slave. The RFM69HCW uses four wire SPI communication, MISO, MOSI, SCK, and one data line to signal the ATMega328P when data is ready.

In order to program the system, two ports are available. Programming via SPI is available, treating the ATMega328P as the slave and programming it using another system, such as a computer. The Universal Synchronous/Asynchronous Receiver-Transmitter, USART, is also available for programming the ATMega328P.

The three operations of the XEM are triggered using push buttons. Each of the buttons are connected to different pins on port C of the ATMega328P, which have internal pull up resistors. When a button is pushed that pin is grounded, which will be used by the programming to execute the operations.

6. Technical Data –Operation and Implementation

This chapter describes the operation of the X-Car Electrical Maintenance tool, the hardware implementation, and the software implementation. This chapter is provided to the technical user for operation procedures and fault descriptions. The hardware implementation is also explained in this chapter. The hardware implementation covers their function and how they are tested. The software implementation is also explained in this chapter. The software implementation covers its function and how the software was tested.

6.1. Operate Lap Bars

The XEM will operate the lap bar mechanism. It has enough output power to fully operate all lap bars on a train at once (six). The XEM can also operate single lap bars at a time. There are three modes that allow operation of the PS1 high power output and the operation of the lap bars. The XEM must have standard mode enabled, maintenance mode enabled, or X21 mode enabled. The lap bars cannot be enabled in TDR mode.

To operate the lap bars the E-Stop safety circuit must be verified ok. The safety circuit is verified ok when the E-Stop bus is active. Next one of the following modes must be selected: standard, maintenance, or X21 mode. Next the mode must be enabled. In order to enable standard mode, the X21 or BBC must be connected to the XEM. The X21 and BBC cannot be connected at the same time in standard mode. In order to enable maintenance mode, the X21 or the BBC must be connected unless the XEM is in maintenance bypass. The X21 and BBC cannot be connected and used at the same time. In maintenance mode, the lap bars made be operated through the HMI. Figure 6-1 shows the HMI software buttons that allow for lap bar operation.

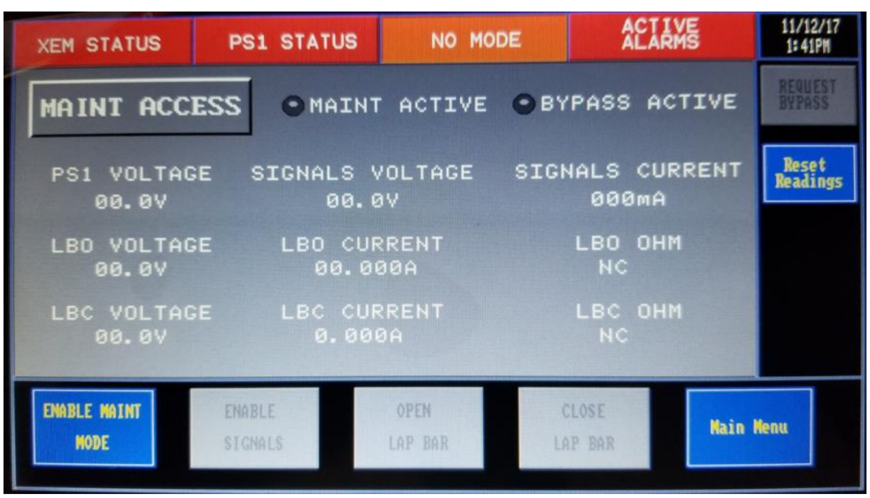

Figure 6-1: Operate Lap Bar Software Buttons

In order to enable the X21 mode the X21 connector must be connected and the BBC not connected. In the X21 mode only the hardware push buttons control the lap bar operation.

Once the mode is enabled, the PS1 24V output is enabled. To operate the lap bars opening or closing, the activation must be enabled using one of the following: Standard screen on HMI, Maintenance screen on HMI, hardware push buttons, or the wireless module. Maintenance mode must be enabled for the screen soft buttons to activate the lap bar mechanism.

6.1.1. Hardware Buttons

On the front of the XEM exist the hardware buttons which can command the lap bar operation as shown in Figure 6-2. These buttons are Allen Bradley 22.5mm Push Buttons. These buttons only function when a mode that allows for lap bar operation is enabled and the PS1 24V output is on. The buttons must be fully pressed to send activate their command. Only open lap bar or close lap bar can be active at once. Due to the safety factor, these buttons must see a full press or else the XEM will generate a fault. The fault is to ensure only verified presses are confirmed for activating the lap bar mechanism.

The hardware buttons can only activate for a limited time in BBC mode. This is due to the high power output in this mode. Output is limited to 20 seconds with 5 second intervals in between operation.

The hardware buttons are only software inputs so in actuality the software handles all safety for the user and hardware. When faults are generated that fault the button such as pressed too long (stuck) or single input failure or dual input failure or an emergency stop condition, the buttons have no function. Even while emergency stopped the XEM will generate push button faults such as button stuck or single input failure or dual input failure.

The only hardware button with also a circuit hardware tie in is the Emergency stop push button. This button is a maintained state button. This means when the button is pressed it stays pressed. The hardware ties in the hardware emergency stop circuitry. When this button is pressed, the XEM high power outputs are indefinitely disabled. If a wire is left disconnected or tied to the wrong signal, a hardware emergency stop will occur.

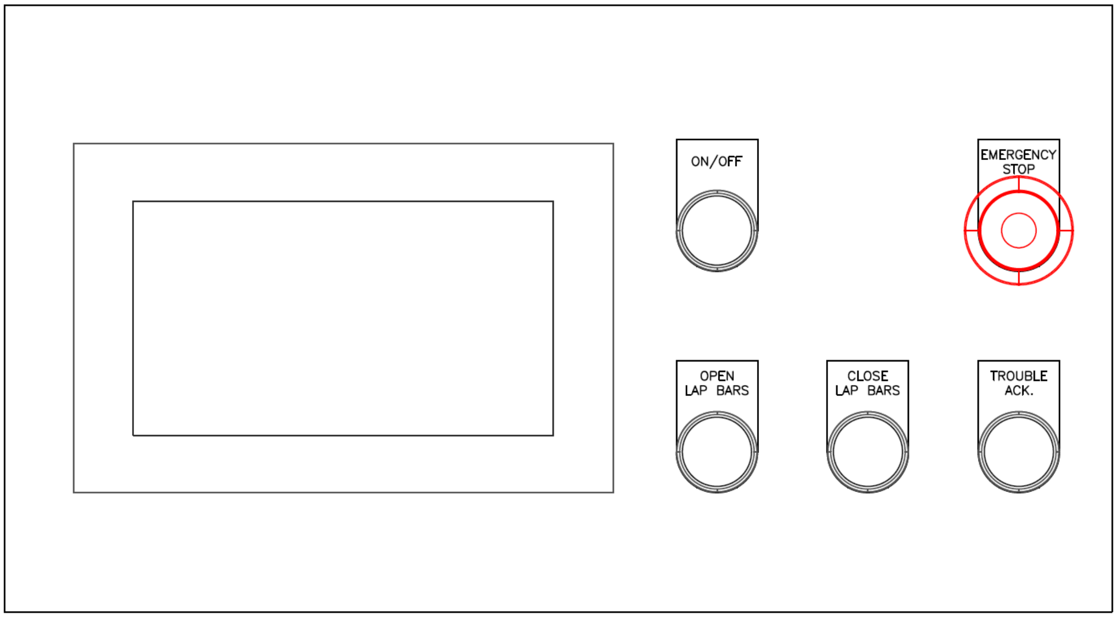

Figure 6-2: XEM Lap Bar Hardware Buttons

6.2. XEM Main Circuit

The XEM Main circuit is the main brain of the XEM tool. It contains all connections to all the subsystems including the HMI. The XEM main circuit is what handles all controls. The PCB design for the XEM main circuit is shown in Figure 6-3 and Figure 6-4. The PCB was designed using EagleCad. The board is a four-layer circuit board. It uses 1-Oz copper and FR4 dielectric insulation material. The board is a four-layer design because it has over 200 components and components with 0.1mm pitch pads. The top layer, layer one, of the board is the signal layer. Most of all signal traces are on this layer. The top-middle layer, layer two, is the power layer. The power layer has several different voltages laid out throughout the layer. The voltages are either 12V, external battery, 5V switching supply, 3.3V switching supply, 5V linear supply or 3.3V linear supply. The bottom-middle layer, layer three, is the ground layer. Essentially this entire layer is the ground plane. This entire layer was made to be the ground plane so that current paths were handled properly. There are bypass capacitors at nearly every component to give a low impedance path to this ubiquitous ground layer. The bottom layer, layer 4, was the secondary signal trace layer. The secondary signal trace layer was used to components that were placed on the bottom layer or to get around signals being blocked on the top layer. Much care and concern was taken to signals that had high frequency or were power signals. High frequency signals were kept as short and straight as possible to reduce stray capacitance and reflections. Power signals were kept as wide and short as possible to reduce trace inductance.

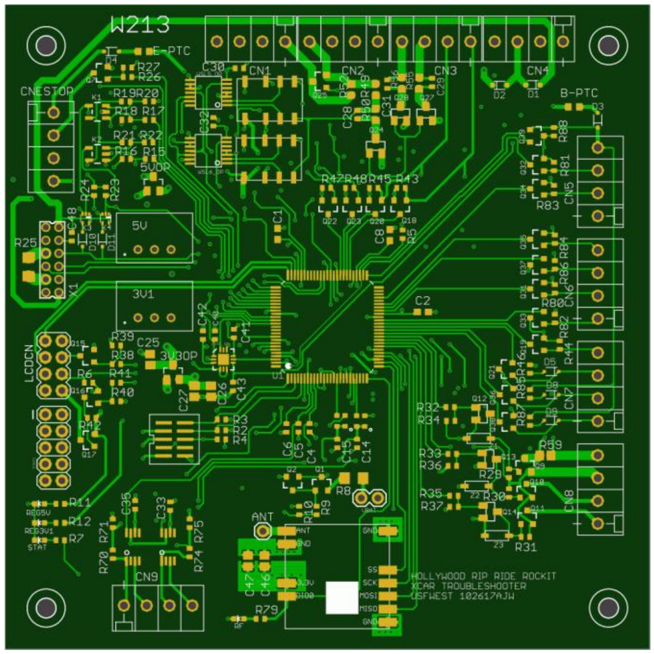

Figure 6-3: XEM Main Circuit - TOP

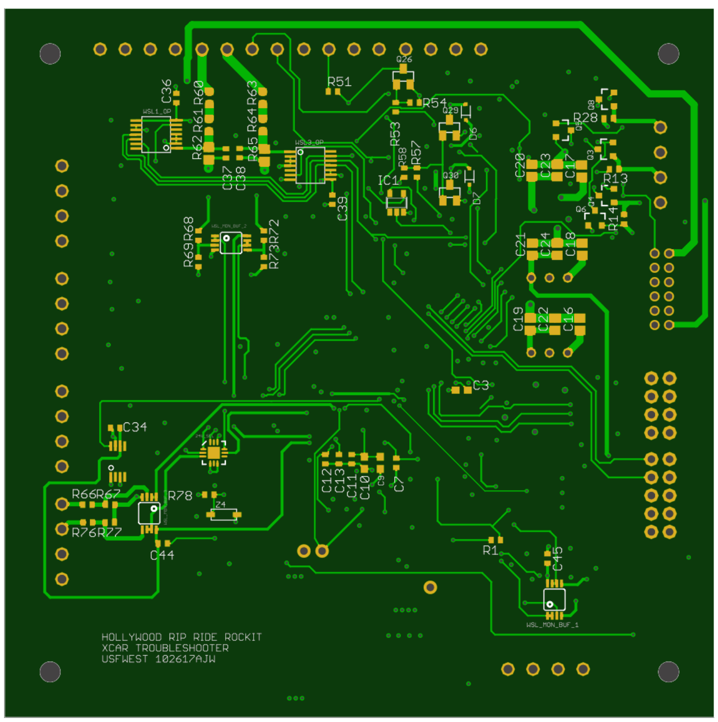

Figure 6-4: XEM Main Circuit - BOTTOM

6.3. Time Domain Reflectometer (TDR)

The TDR is designed to capture transmission line waveforms. By analyzing the transmission line waveform, open circuits, short circuits and bad connections can be detected. By further analyzing, the location of these issues within the ride vehicle onboard circuitry can be determined.

The TDR can only operate when the X21 and the BBC are not connected to the XEM. Furthermore, the PS1 must be off when using the TDR. Failure to do so will result in damage to test equipment. Software will prevent the aforementioned from occurring but any stray voltages on the DUT can cause component failure or false readings.

The TDR operates using two coaxial cables with matched impedance. The DUT MUST have no power, voltage, or current on it. One end is connected to the generating coaxial cable with set impedance and the other end of the DUT is connected to the terminating coaxial cable with set impedance. Then using the HMI, the frequency of the generator is chosen and the pulse trigger is enabled. Once triggered the HMI will automatically display the waveform of the transmission line. It will be up to the end user to decide which frequency to use but the best resolution is with higher frequencies on a clean transmission line.

6.4. MCU Software

The microcontroller software will play a role in operating the hardware to the HMI circuit where it can then use the LCD and buttons as inputs and outputs designed to relay key points of information to the user. This section refers to the XEM main circuit board software.

6.4.1. Project software Design Details Summary

Software design will be executed using the C programing language due to the chosen ARM microcontroller Cortex M3 LPC 1764 FBD 100, 551. The main goal of the software is to provide a HMI. The HMI will be responsible for the user interaction with the XEM. The XEM will consist of a touch screen, 7 inch LCD where inputs can be taken by the user and outputs can be displayed in order to signal valuable information to the user.

6.4.2. Software Functionality

In regard to the touch screen LCD, the user will be able to use the touch screen to navigate between different windows that appear. These windows will have information conveying which actions (inputs) to give the system and then show the (outputs) as requested. Some windows will also have the ability to take in numerical inputs if wanted by the users.

The first screen will be the loading screen displaying the rides title this screen will appear when the XEM is turned on. The next screen to appear once the XEM is powered will be the home screen which will contain ten touch screen buttons on the bottom of the screen as shown in figure 6-5.

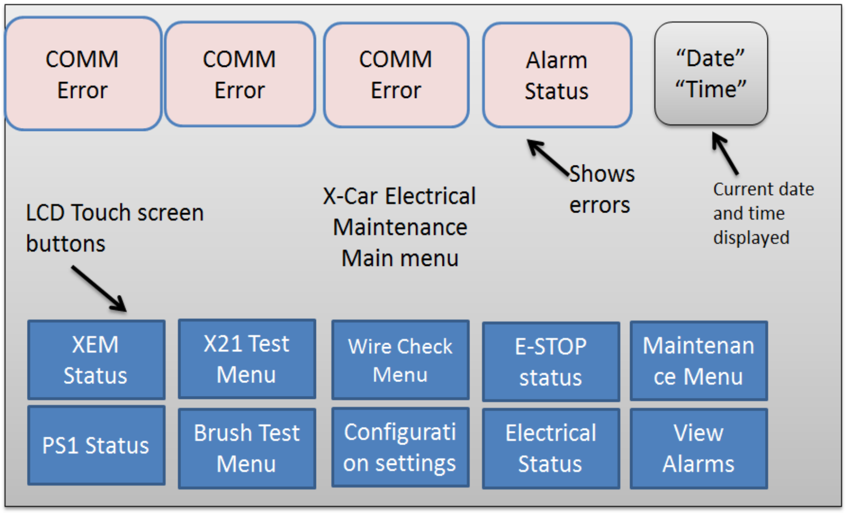

Figure 6-5: X-car main menu interface

On the top of the screen will appear 5 status windows. These status windows will display any current error happening with the microcontroller, the last window will only indicate date and time. All these windows with the exception of the date and time are color coded to alert the user when something is at fault. Red indicating E-Stop activation is present along with problems pertaining to the microcontroller, green showing that everything is alright. The ten bottom buttons are used to help the user distinguish the problems more in depth. The XEM status will show the XEM primary circuit and how it is running as shown in figure 6-6.

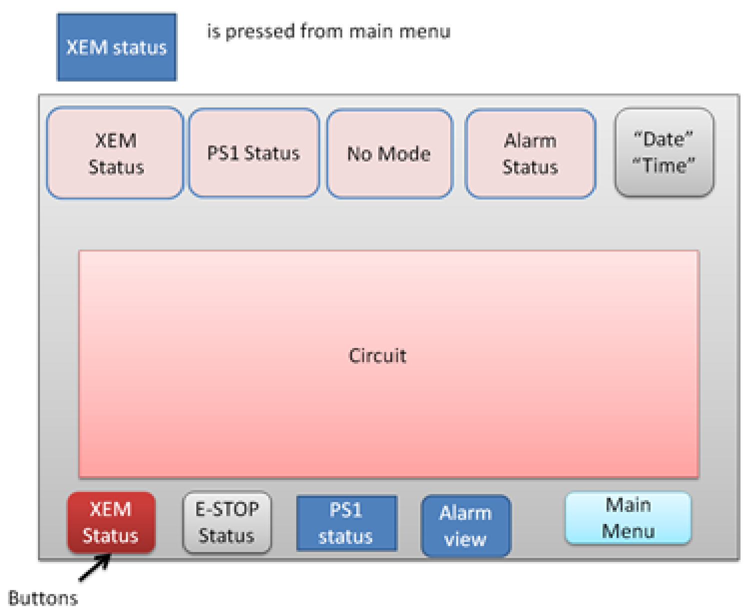

Figure 6-6: X-car XEM status menu interface

The alarms button will show (figure 6-7) a list of alarms either that have recently occurred or what has occurred along with time stamps. In the Alarm view window and like in any other screens the top windows will not change and will always show the status of the microcontroller. The bottom buttons on the alarm window will assist the user for scrolling through the alarm history as well as giving them the chance to reset alarms, and/or the Estop to get a clear picture of the errors that are happening in order to better fix the problem. Many of the navigational touch screen buttons lead the user to windows that always have a back button also known as the main menu button located at the right-hand corner side of the screen.

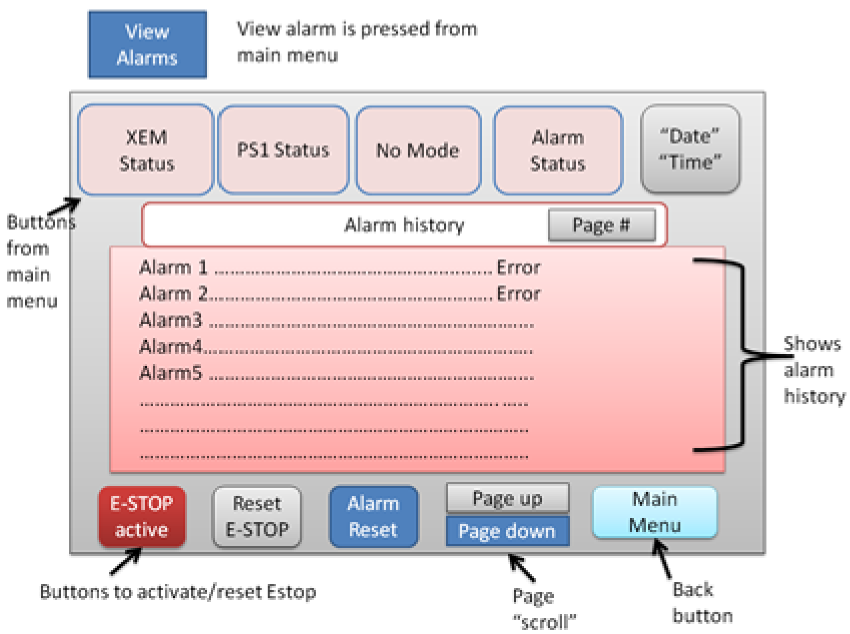

Figure 6-7: XEM alarm View interface

The Maintenance menu button leads the user to a screen that displays the voltages, currents, and ohms for the open and closed lap bar sensors (see figure 6-8). This screen will allow the user to go into maintenance mode, and have the ability to request bypass. The user will also be able to reset the readings for the voltages and currents. The next home menu button is the Estop status button that will bring the user to the window of the Estop circuit as shown in figure 6-9. The rest of the button navigations from the main menu screens are shown below.

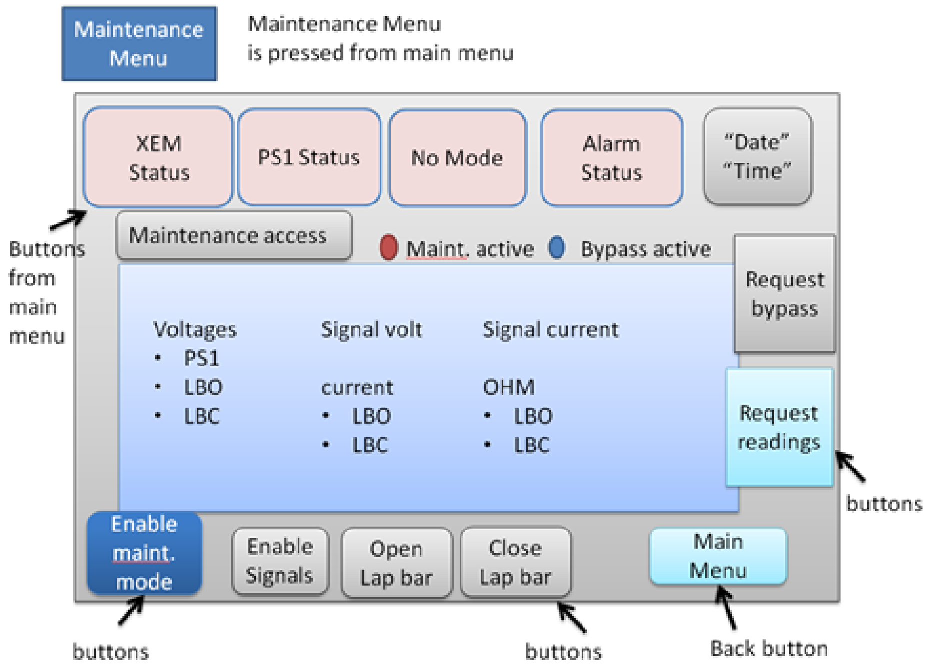

Figure 6-8: XEM Maintenance interface

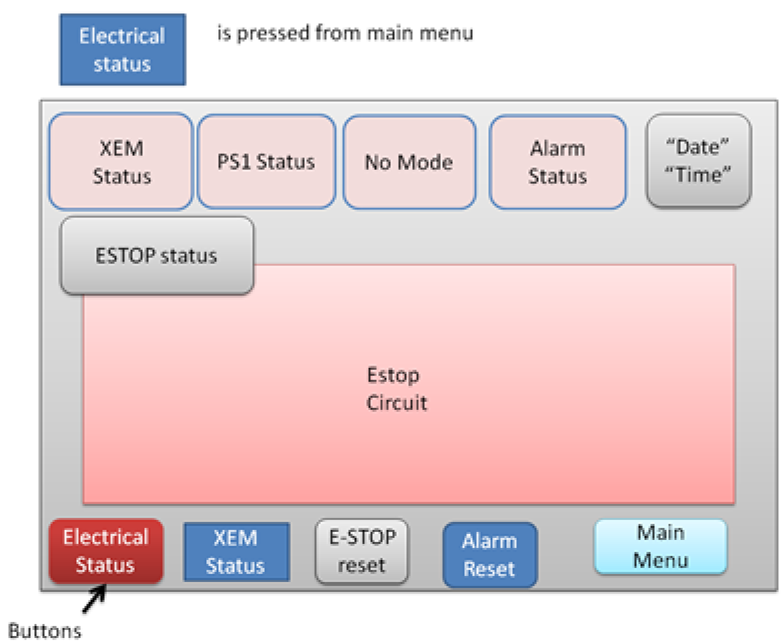

Figure 6-9: XEM E-Stop Logic

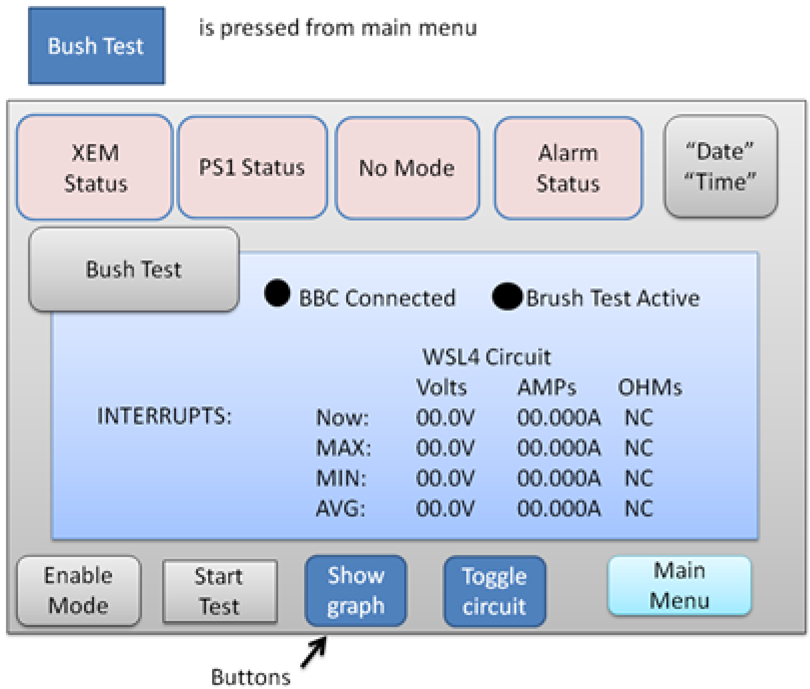

Figure 6-10: X-car Bush test interface

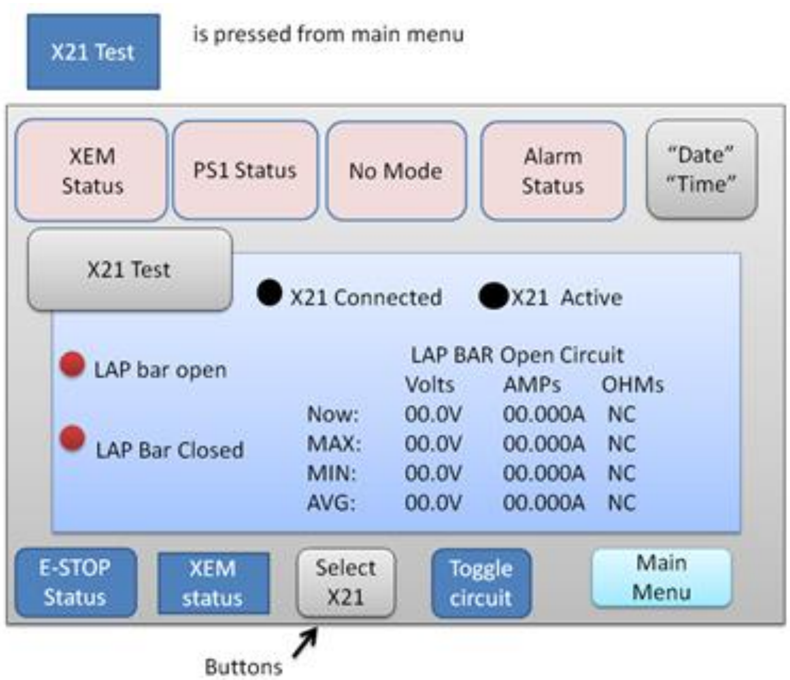

Figure 6-11: X-car X21 test interface

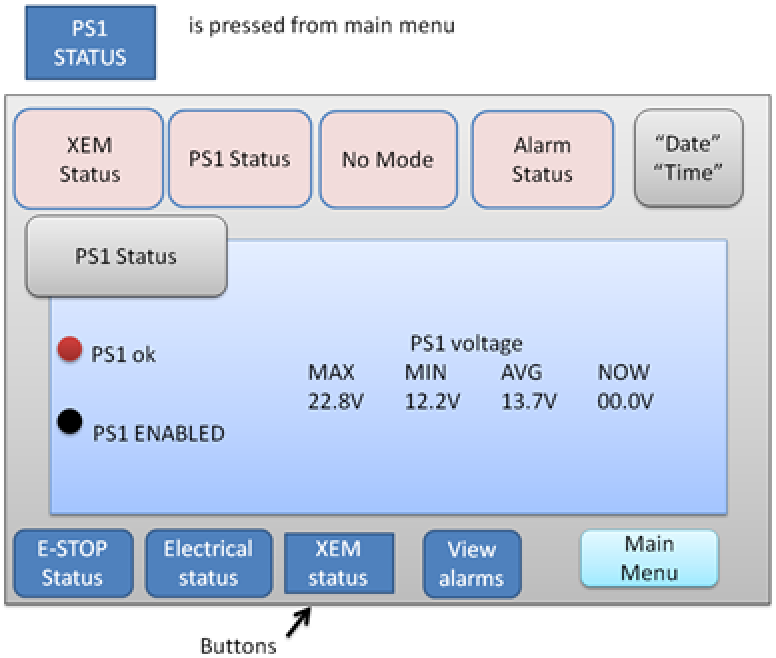

Figure 6-12: X-car PS1 STATUS interface

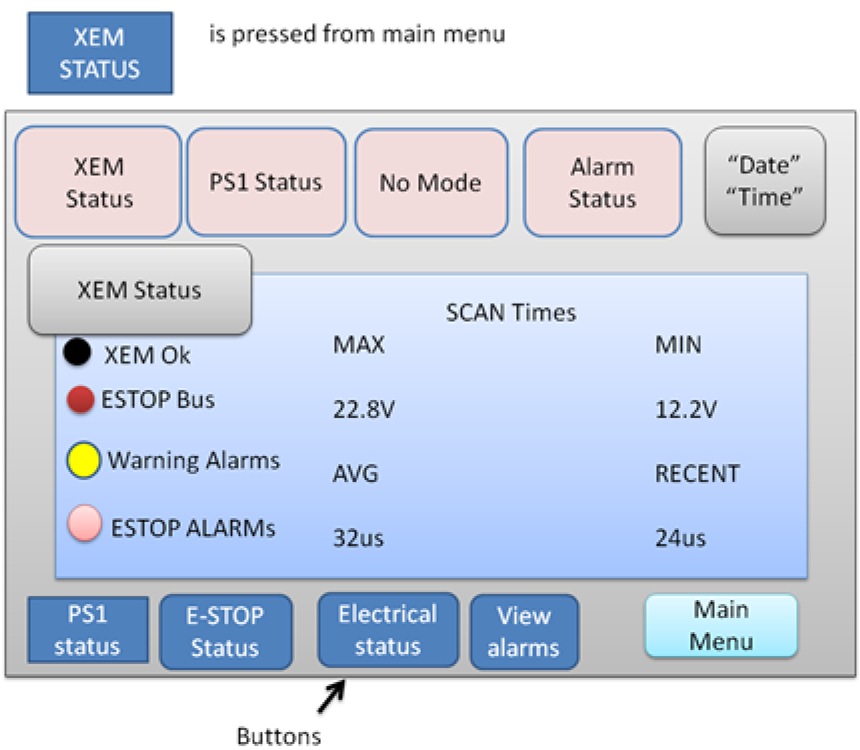

Figure 6-13 - X-car XEM STATUS interface

6.4.3. Software Inputs and outputs

There will be five physical buttons that signify set inputs that can allow the user easier control. The first will be the basic on and off switch for the XEM. The second button will be devoted to a fail-safe, off button also known as the emergency Stop Estop(red). The Estop will have a flashing LED signifier as well. Two other buttons will allow for opening and closing the lap bar. The final button will be a trouble acknowledgment, which will allow the access of a certain fault to be bypassed. Connections will consist of a bus bar connector that will connect the Vehicle brushes with the XEM. The primary use for this bus bar is to test the whole vehicle of the ride. The X21 connector is able to test the individual seats, and its primary checks will be the WSL4 and WSL8. The TDR connector modifies time-domain reflectometer; it tests wiring connections through signal propagation. There will be other on-screen touch buttons, as mentioned above, that allow the user to navigate to other windows displaying more information.

6.4.4. Software Referencing tools and Goal

The referencing tools that will be used in achieving these ideals will be mainly from the UM10360 LPC176x/5x User manual [8]. The ultimate goal here is to summarize the code structure, and the different coding techniques that will be utilized in achieving the desired functionality just described; which will be used to gain a smooth and easy connection/communication from user, and XEM. There will be different c Files and header files in order to organize, utilize, and achieve the requirements for this system.

Note the Brushes on the cart are labeled as such and will be referenced by these names throughout the rest of the software.

- WSL1, brush one; RFID tagged
- WSL2, brush two; ground
- WSL3, brush three; RFID tagged
- WSL4, brush four; open lap bar
- WSL5, brush five; lap bar status
- WSL6, brush six; sector occupied
- WSL8, brush eight; close lap bar

6.4.5. Support Files

There are several source and header C files that were created to organize and develop the main XEM circuit software. Each file and their purpose and function will be described in this section. The files include the function only of the main XEM circuit. The HMI, TDR, and WCM all have their own respective files. However, some of these files are reused on the other aforementioned systems because of the necessity for these systems to communicate with each other.

6.4.5.1. BitManip Files

The BitManip files, which include a header and a source file, deal with any manipulation of bit fields. There are several manipulations of bit fields that are necessary for the XEM system to perform properly. Due to the large amount of data needed to be passed across from system to system, many of the messages between systems are bit fields of a large word. These bits must be checked for the current status. The BitManip file has functions to check these specific bits. There is one function, called checkBit, which takes in two unsigned integers (unsigned 32bit). The first unsigned integer is the word holding the current status of the bits. The second unsigned integer is the word with the bit fields to test. If the bit fields tested are one or zero the function returns true or false respectively. This function is used throughout the XEM main file named HRRR_RVT.c. This function is necessary because many conditions must be verified before functions can proceed safely. Two other important functions exist in the BitManip file. The first being the checkSum function. This function takes in a message to be delivered between the systems and returns the checksum value. The checksum value is the hexadecimal 0xFFFF with the value of the message subtracted from it. The checksum function takes in a pointer and the size of the pointer and then performs the math of the values to return the checksum value. This checksum value is used in the HRRR_RVT.c file extensively. The next important function is the decodeSum function. The decodeSum function is for the receiver end of a message sequence. The message that is sent to another device in the system holds the checksum value that was sent. The receiver performs a checksum on the message received and verifies it matches the checksum that was received. This function returns true or false whether or not the checksum matches or not.

6.4.5.2. HRRR_Faults File

The HRRR_Faults file is a header file which defines references and base conditions for all the faults that can be detected on the XEM. The header file defines the system wide time limit for a disagreement between safety inputs. The disagreement time for safety inputs are 500ms. Depending on the purpose of the safety input the correct response is taken which may or may not be immediate. This however is not defined in this file. All faults are stored as bits within an array of 32 bit integers. This file defines the reference of the bit fields to the fault. This file also defines a macro, fault_bit(n), which automatically sets the fault bit in the array based on the actual fault number. The macro is defined as (1<<(n%32)). For example, if fault 34 occurs, then number 34 can be used and it will set the value to bit field position 2. All of the fault numbers are referenced using a logically sound name. For example, the fault for the E-Stop button being pressed, fault 0, is defined as mESPBPRESSED. The masks for fault resetting is also defined in this file. The fault mask is set based on the consequence of the fault. All faults which do not cause an emergency stop condition are set to one mask. All faults which do cause an emergency stop condition are set to another mask. There are two levels of fault recovery. The first level only clears the low level warning faults. The next level clears the emergency stop high level alarms if the fault condition is clear.

The HRRR_Faults file also handles the alarm data structure. The alarm data structure includes the alarm message, date and time, active/not active and priority levels. To handle the alarm message list, a linked list was defined using structs. A struct called alarm_data was defined. An alarm_data pointer was also defined as a typedef. This allows for the linked list to be built. Within the alarm_data struct, a reference to the next and previous alarm is stored. Along with the previous and next alarm reference, the message, priority, active level, date, time, position in the list, and the reported status is stored in the struct. A reference, only for convenience, to the alarm list is also contained in this file. It lists the messages for each alarm that is defined. Lastly, it contains one function definition. The function relates to the alarm and fault monitoring. The function is called countActiveAlarms. This functions purpose is to count the alarms which are still active in the alarm arrays. The function does not count the total number of alarms active in the linked list. This allows the XEM to see which alarms of the sixty-one alarms are still active even though the alarm list may be up to one hundred.

6.4.5.3. HRRR_PinManip File

The HRRR_PinManip file is a header file which defines all ports used on the LPC1769 microcontroller. This file uses the include of the HRRR_PinNames header file. The defines give a human readable name to the ports used. The defines are all macros. This grants the quickest code execution. The human readable name also gives a description of the macros function. The macros are in reference to one of three things: input pull-up port, input port, output port. The input pull-up ports macro all have the not operator in front of their macro. The input ports macro do not have a not operator in front of their macro. The output macros are used in two ways: status and control. The status macros check the state of the output port. The macro returns a one or a zero. These are used extensively in the HRRR_RVT.c file to check and verify statuses.

6.4.5.4. HRRR_PinNames File

The HRRR_PinNames file is a header file which defines pin names to relevant descriptions. All of the defines in this file are macros. The macros ensure the most rapid code execution. The defines in this header file all represent bit positions. The bit positions are in reference to the port. For example, the watch dog input from the LCD is port 1 bit 1 and is defined as bit 1 (decimal value of 2). This file also makes a reference for the analog to digital converter multiplexer. There are eight analog to digital converter inputs. They are all connected to a multiplexer. This file defines a relevant name for each select line for the multiplexer.

6.4.5.5. HRRR_PinSetup File

The HRRR_PinSetup file is a header file which defines the initial pin setup. On the LPC1769 the general purpose input/output pins can be set as either an output or an input. On the LPC1769 there are four different input types: input pull-up, input pull-down, repeater and standard input. Before pins are used at all in the program, the initial state must be set. This file uses define macros to assist with the initial pin setup. All input pins are set to their necessary state according to the main XEM schematic. The macros assist with making the code readable in this file. All pins are accounted for before the setup. Any input pins not used are set to input pull-down to avoid any floating pins and wasted power. The LPC1769 registers for setting up pins are called the PINMODE registers. The PINMODE registers use two bit fields per pin. There are two bit fields per pin because the input pins have four different possibilities. When the pin is set as an output the PINMODE register is ignored. There are only three input types used in the XEM: input, input pull-up and input pull-down.

In the HRRR_PinSetup file there is also a function defined for setting up all the pins on the XEM main circuit. The function is called in the setup stages in the main of HRRR_RVT.c. The function sets all output pins to outputs and all input pins to inputs. The input pins are then set to either normal input, pull-up or pull-down. The output pins are set to LOW before they are set to outputs to ensure nothing is mistakenly activated. All pins on the LPC1769 default to standard inputs before they are set up. In the setupPins function the analog to digital converter is also setup and enabled. The analog to digital converter setup is defined in the lpc_useful files.

6.4.5.6. HRRR_StatusBits File

The HRRR_StatusBits file is an upper abstraction layer of the HRRR_PinManip file. The file summarizes modes and status of the XEM by using define macros and 32-bit words with bit field definitions. There are several words that hold all of the upper abstraction layer definitions in their bit fields. The 32-bit words holding the bit field descriptions are XEMStatus, lastXEM, OutputStatus, lastOutputs, inputStatus and lastInputs. The XEMStatus holds all status information about the XEM system. Throughout the HRRR_RVT.c file the XEMStatus is used for its bit fields. The system mode, system health and critical system inputs are stored in the bit fields of XEMStatus. The file defines macros which explain and reference all the bit fields of the XEMStatus. The macros have relevant names that can infer their purpose. The Output status holds information about all of the outputs in the XEM system.

6.4.5.7. LCD_Commands File

The LCD_Commands file is a header file which defines the XEM and HMI communication settings. In HRRR_RVT.c main, the LCD and XEM main circuit communicate using the two wire serial protocol. The layer above this serial protocal, the messages are placed in a structured format. Each message between the LCD has the following structure: command header (1-byte), message (optional), checksum (2-byte) and tail end of message (2-byte). The LCD_Commands file has define macros which define a name to each command header byte. The name is logical and relative to the function of the message or command. There are four functions defined in the LCD_Commands file. The four functions are only prototyped here. The actual function definition is made in HRRR_RVT.c. The reason for this is because the actual implementation is circuit specific. This allows for the file to be reused on the TDR circuit which uses the same LPC1769 microcontroller. The message queue is also configured in the LCD_Commands file. The message queue function is, once again, defined in the HRRR_RVT.c file. The message buffers, the message buffer sizes, queue timers and other messaging timers are defined in this LCD_Commands file. There are also define macros which put a relevant description to the name of the screens for the screen number value. In addition, the file also has define macros for the resistance report messages. There are three specific scenarios that repeat themselves when reporting resistance. The three specific scenarios are a bad connection, no connection or shorted connection. The macros for these scenarios are defined here and are placed in the resistance report message when the scenario is true. There is also some message related faults that are initialized herein this file. The faults for checksum mismatches and watch dog timers are initialized in this file.

6.4.5.8. lpc_spi Files

There are source and header files for the lpc_spi. The lpc_spi files define the serial peripheral interface. The serial peripheral interface is a 4-wire serial peripheral. The initialization, setup and usage of the serial port interface are defined in these files. The lpc_spi header file defines macros for relevant registers for setting up and using the serial peripheral interface. There are two types of serial peripheral interfaces on the LPC1769. The standard communication protocol is called the serial peripheral interface. The additional peripherals on the LPC1769 that are able to perform the serial peripheral interface are called the synchronous serial port. In this case, only the serial peripheral interface is used.

The registers to use the serial peripheral interface are the PCONP register, the PCLKSEL0 register, the PINSEL0 register, the S0SPCR register, the S0SPSR register and the S0SPCCR register. The macros for the bit fields of these registers are defined in the header file. They are all given relevant names to the function of the bit fields they represent. The PCONP register is used to enable the power and clock for the serial peripheral interface in the LPC1769. There is one bit, bit 8, in the PCONP file that must be set to one in order to power the serial peripheral interface. The PCLKSEL0 register is used to select the clock source for the serial peripheral interface. There are 4 bit fields that must be set to select a clock source. In this instance, the clock source was set to the main clock and divided by two. This leaves the serial peripheral clock set to 60MHz. However, this is not the clock at which the data is clocked out on the synchronous clock. The final clock speed for the data output is set with the S0SPCCR register. This register sets the final division ratio. In this case, it was set to divide by 8. This sets the synchronous data clock to 7.5MHz. The PINSEL0/1 registers are used to set the pins for the four pins required for the serial peripheral interface. In this case, only three of the pins are set and the slave select pin is set within the HRRR_RVT.c based on the main XEM circuit.

Lastly, within the lpc_spi files the useful serial peripheral interface functions are prototyped and defined. There are four functions defined within the lpc_spi files. The functions defined are beginSPI, beginSPIMO, SPI_transfer, SPI_transfer16. The function beginSPI sets up the serial peripheral interface. The function powers on the serial peripheral interface and then defines the pins that will be used for the communication. The clock for the serial peripheral interface is also configured and then the serial peripheral interface nested vector interrupt controller (NVIC) interrupt is enabled. The spi transfer functions take data as an input and write to the serial peripheral interface. The functions also read in data as they write out. The data read in is returned at the end of the function. The interrupt handler is also defined in the lpc_spi source file. Every serial peripheral interface transfer causes an interrupt to occur. The interrupt lets the system know when the transmission is complete.

6.4.6. Functions in HRRR_RVT.c;

The following Functions are those that preform important task that allow for the HMI to function, these are vital in the communication of the microcontroller and LCD, as well as for the computations used from the ADC to achieve readings of voltage and amperage. Collectively these functions will allow for smooth communications between device and user.

Check XEM

The check XEM function will be responsible for showing any faults, and or errors occurring. This will be one of the first functions to run. The table below shows some alarms that will be tested. The goal is to check for any potential faults, these alarm triggers indicate errors, some of which activate the Estop.

Table 6-1: Alarm List

Alarms		
Number	Description	Consequence
0	E-Stop button is pressed	Estop
1	PS1 not detected	Warning
2	X21 Connector disconnected while Seat Test in progress	Warning
3	Bus Bar Connector disconnected while Bus Bar Test in progress	Estop
4	PS1 Detected 24V output <80%	Estop
5	PS1 Detected high temperature	Estop
6	24V from PS not detected	Estop
7	WSL4 over current detected	Estop
8	output or control failed	Estop
9	control or output failed to energize	Function disabled
10	24v over current detected	Function disabled
11	Software E-Stop Active	Estop
12	Low voltage from PS1 detected	Warning
13	Low voltage on WSL4 detected	Warning
14	Low voltage on WSL8 detected	Warning
15	Low voltage on 24V detected	Function disabled
16	WSL8 over current detected	Function disabled
17	Open Lap Bar command timed out	Estop
18	Close Lap Bar command timed out	Warning
19	X21 and Bus Bar Connectors are connected, cannot use both at once	Warning
20	XEM Watchdog timer failed	Warning
21	HMI Watchdog timer failed	Estop
22	Control or output failed to energize	Estop
23	XEM detected brownout on low voltage circuitry	Function disabled
24	Open Lap Bars contact disagreement	Warning
25	Close Lap Bars contact disagreement	Warning
26	E-Stop power failed OFF (Reset with E-Stop pressed)	Warning
27	E-Stop power failed ON	Estop
28	No output detected on 24V (Check connector)	Estop

29	No output detected on WSL8 (Check connector)	Warning
30	No output detected on WSL4 (Check connector)	Warning
31	Unexpected voltage drop from PS1	Warning
32	LCD Message Queue overflowed	Estop
33	XEM has generated an E-Stop condition	Warning
34	HMI to XEM checksum error	Estop
35	XEM to HMI checksum error	Warning
36	Command from HMI undefined	Warning
37	WSL4 detected while SSR201 is off	Warning
38	24V detected while XEM is off	Estop
39	WSL8 detected while SSR301 is off	Estop
40	XEM encountered non-recoverable hard fault (Power Cycle REQ)	Estop
41	Function requires E-STOP button to be pressed	Estop
42	TDR parallel buffer transfer failed to start	Estop
43	TDR parallel buffer transfer failed to complete	Warning
44	Invalid selection for requested command	Warning
45	Read from HMI failed	Warning
46	Invalid message from ADC buffer received	Warning
47	ADC_BUF TO XEM checksum error	Warning
48	TDR failed to initialize. Cycle power and contact Eng.	Warning
49	Invalid address access. Cycle power and contact Engineer	Warning
50	Data bus access or execution failure. Cycle power and contact Engineer	Estop
51	Unaligned address access. Cycle power and contact Engineer	Estop
52	ERR WSL1 calibration out of range, re-calibration mandatory	Estop
53	ERR WSL3 Calibration out of range, re-calibration mandatory	Warning
54	ERR WSL5 Calibration out of range, re-calibration mandatory	Warning
55	ERR SWC Calibration out of range, re-calibration mandatory	Warning
56	ERR OPEN CIRCUIT DETECTED IN WSL5 WIRING! Ohm test only for closed circuits	Warning
57	ERR OPEN CIRCUIT DETECTED IN SWC WIRING! Ohm test only for closed circuits	Function disabled
58	Safe alarm bypass is active. Do not read into the term \"safe\	Function disabled
59	Full alarm bypass is active. Software circuit protection removed	Warning
60	Brush Test timed out. No trigger detected within 15s	Warning

Estop button

One of the many inputs for the XEM will be the Estop button. The software will operate so that when the button is pushed, emergency stop will be turned on along with alarm 0. This process involves an estop check, this check determines if the Estop button was pressed. If the process determined that indeed the estop button was pressed then the emergency stop is activated. If this process determines that the estop button was not pressed then the emergency stop activation is skipped.

Close Lap bar

One other input for the XEM will be the close lap bar button that will allow for the user to close the lap-bar. This button will check for a pressed time limit to assure that the button was pressed intentionally.

Open Lap bar

Another input for the XEM will be the open lap bar button that will allow for the user to open the lap bar. Like the closed lap bar button this function will assure the button is pressed with a given time confirmation.

ESTOP indicator

An output that allows the user to see when the Estop is activated either by software or hardware purposes will be indicated by LED flashing.

Output state

Output state will check and update the Output state bits depending on what triggers in order to portray outputs in the system. The Output state will be used to communicate to the LCD to show the current output. The Output state function will update the output status in order to assure an up to date state. Some of these checks are the 24 V, if the lap bar is open or closed, and checking if Estop is active. This is continued on checking and updating the status for the TDR trigger and powered, the 24 V connections is appropriate, if the TDR paired with Sector occupied, bar status, RFIDs triggered are active. The only minor difference this function holds is the check for an active high being on or off, because instead of updating the output status it updates the XEM status.

Connectors state

The connector will update the XEM based on the disconnection and connections of connectors.

Read LCD

The read LCD goes through the Serial port to check for data. This takes input from the user through the LCD and sends it out in the serial port to the Microcontroller.

Read BUF

Read Buffer goes through the Buffer port to check for data. This takes input from the ADC and sends it out in the serial port to the Microcontroller. Below is a software flow chart of the Read Buffer.

LCD Message Queue

The LCD takes in messages from the Microcontroller through a message queue, this function is responsible for making sure that the message queue is checked, and used to communicate with the LCD. The LCD message queue function is vital for communication between the LCD and microcontroller. On start up the message queue is first checked to see if it is active and if the queue is not empty, if it is not active or the queue is empty this ends this function. If the initial check passes, the first message in the queue gets sent out; and the queue is updated, possibly leaving it empty.

Voltage

Checking the voltage for the power source, open lap bar, and closed lap bar and sending the data to the LCD for the user. The ADC is used to obtain a reading of the sources and then is manipulated to gain the maximum, minimum, and average voltages (figure 6-14). The formula used to get these voltages is as follows.

$$voltage\ divider * \frac{33}{4095} = v$$

$$v * 1000 = Voltage$$

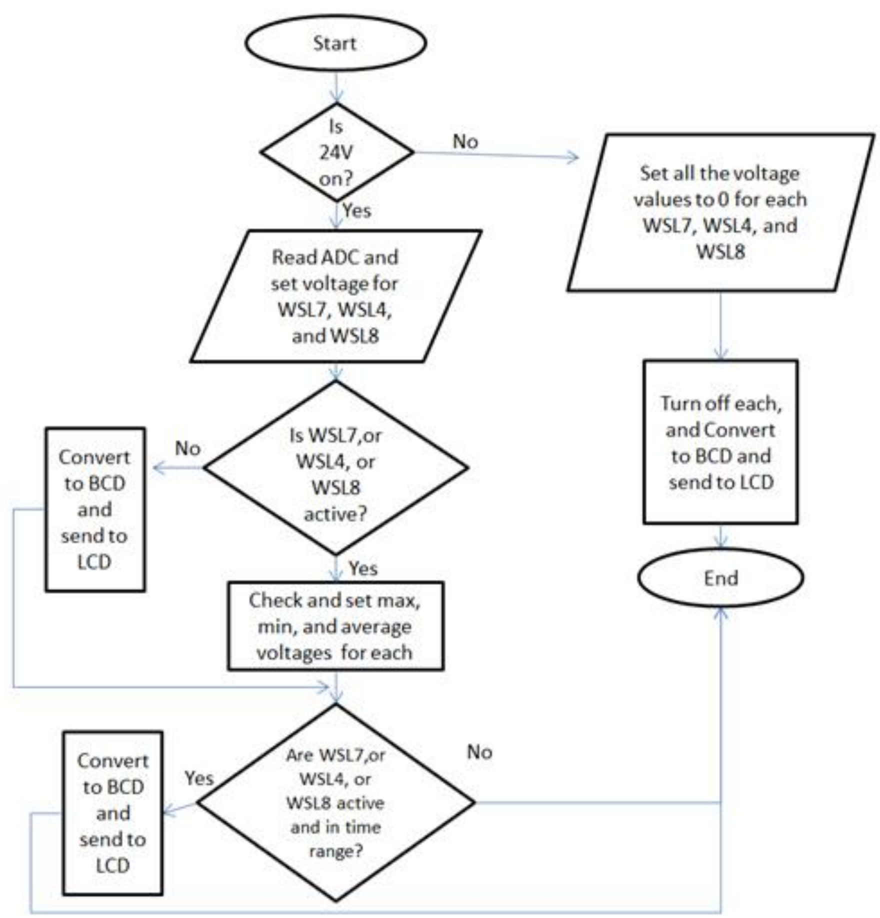

Figure 6-14: I/O code flow chart for voltage check

AMPS

Checking the current for the power source, open lap bar, and closed lap bar and sending the data to the LCD for the user. The ADC is used to obtain a reading of the sources and then is manipulated to gain the maximum, minimum, and average current (figure 6-15). Below is the formula used to get the current readings from the given ADC raw value.

$$\left({ADC\ value}/_{4095}\right) * 33 = amplified\ voltage\ across\ sense\ resistor$$

$$amplified\ voltage * 1000 = current\ amps$$

$$\frac{(current\ amps * 1000)}{500} = current\ amps\ with\ 3\ decimal\ point\ precison$$

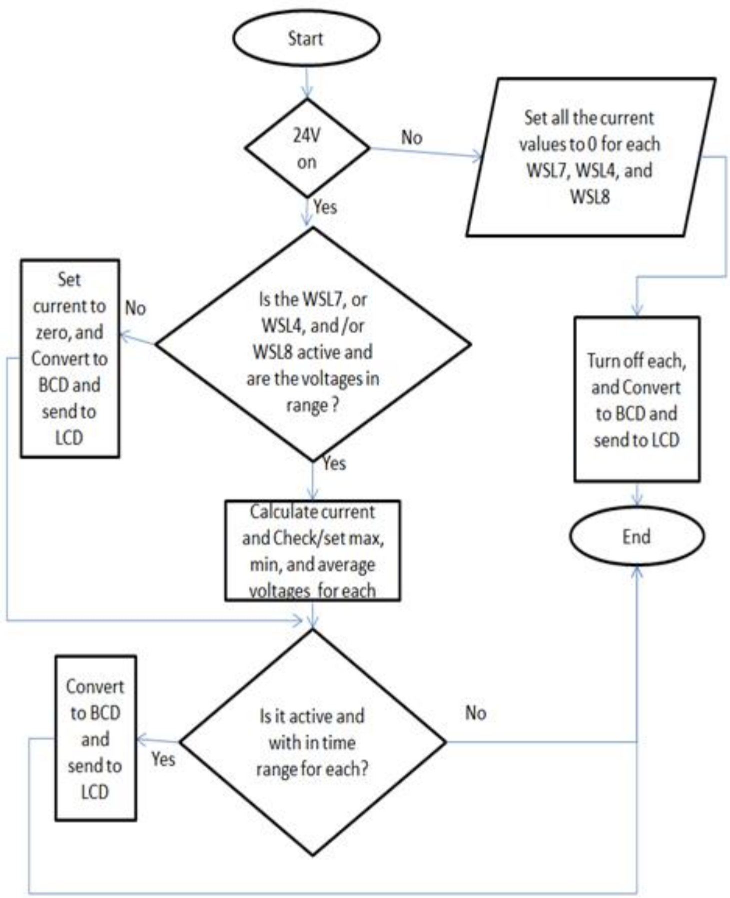

Figure 6-15: I/O code flow chart for current check

Ohms

Checking the ohms for open lap bar, and closed lap bar and sending the data to the LCD for the user. Using the voltage and current obtained from the ADC the Ohms can be calculated to gain the maximum, minimum, and average ohms of active sources as shown below.

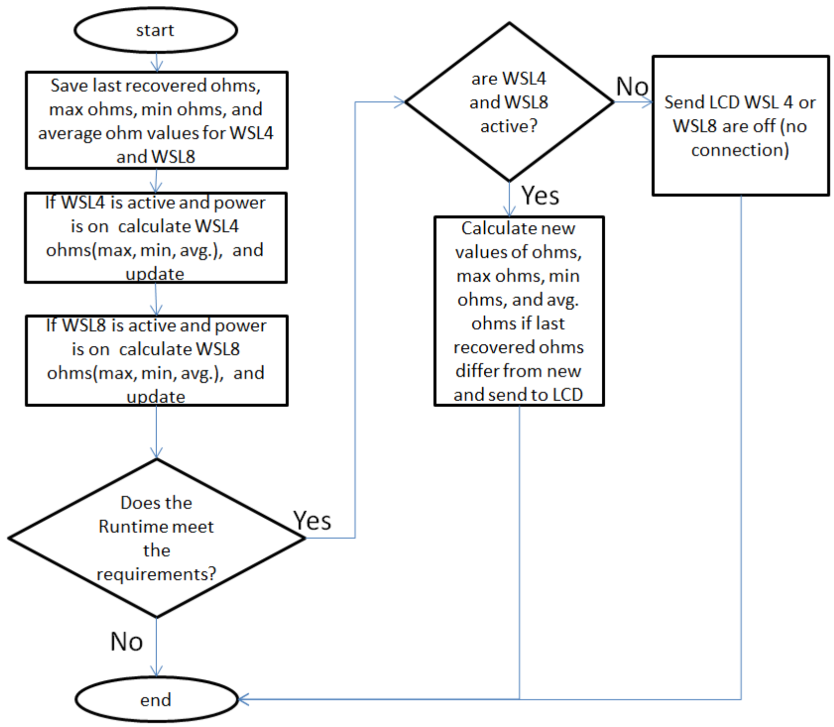

Figure 6-16: I/O code flow chart for ohm check in lap bar open and close

<u>mOhms</u>

This function calculates the low resistance values for the RFID tags, lap bar status and sector occupied form the ADC.

<u>Inputs</u>

Inputs state will set and update the input state bits depending on what triggers in order to portray inputs in the system. The input state will be used to communicate to the LCD and microcontroller. This function is important in that it extends the users' needs to the hardware. How this works is that when it runs it preforms checks to see if any new inputs are being executed and then updates the input status accordingly.

<u>BBC status</u>

The BBC Status checks progress of the BBC test.

6.4.7. Main Function

The main function for the HMI ties in all these functions in order to achieve a working interface that allows the user to achieve the requirements specified earlier. This is done by first setting up the RIT, Power control, RTC, and pins. Then the LCD and Buffer serial port gets defined. The UART gets set up and so does the SPI. The SPI will consist of a 16-bit message with a 7.5 MHZ clock. The timers will be set and the initial steps will be completed. The most important aspect of main will be the continuous loop, this loop will check times, but most importantly execute the above functions. Below in figure 6-17 is a code flow chart for the main function illustrating the basic working of the HMI.

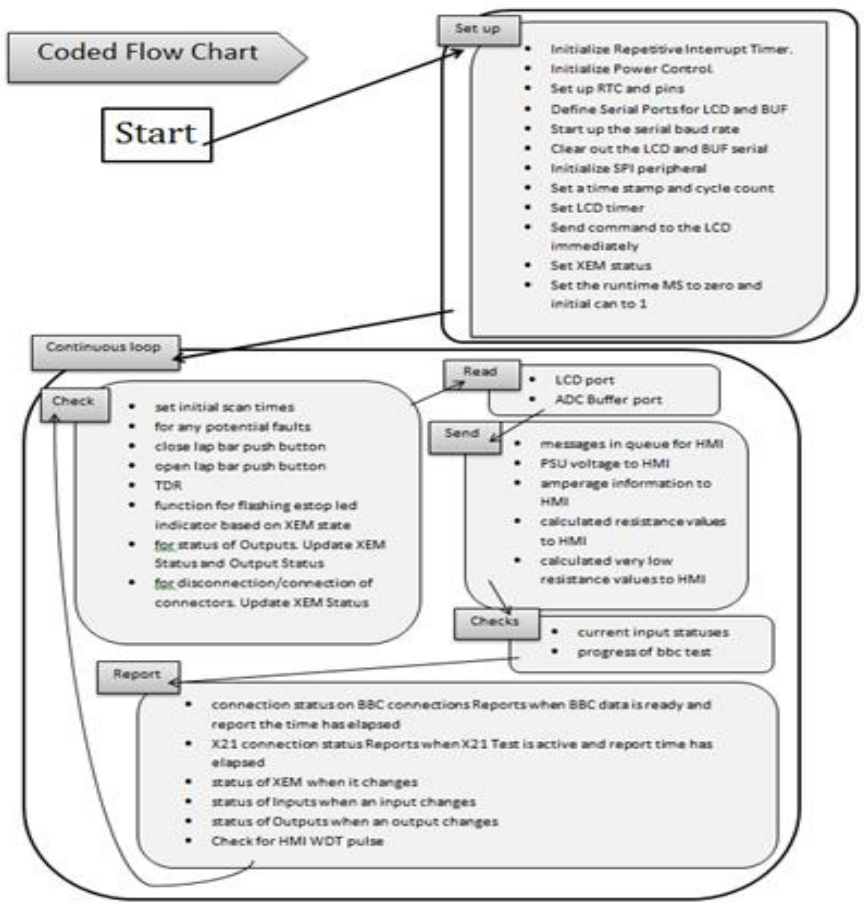

Figure 6-17: Main Code Flow Chart

7. Administration

This chapter discusses administrative information involved with the design and production of the X-Car Electrical Maintenance tool. The administrative information includes topics about project milestones and budgeting information. All project milestones are described in Table 7-1 and Table 7-2. These two tables represent milestones for Senior design 1 and Senior Design 2. The schedules for these two tables will be respected and taken seriously. It is important to respect the milestones in order to produce a product on time without waiting until the last minute to get the product completed. This also leaves time for error checking and review in order to create a well-designed and reliable product.

Table 7-1: Milestones Senior Design 1

SD1 Fall 2017				
	Week 1	Week 2	week3	week4
September	Team idea, bootcamp	Irma	DC doc 22nd	Plan and research
October	5 pages each person	5 pages each person	5 pages each person	Combine all pages and review
November	Review **60 pages due 7th (45)**	10 pages each person	Review: **100 pages due 17th (75)**	5 pages each person
December	Review: **Final paper due 4th**	Break	Break	Break

Table 7-2: Milestones Senior Design 2

SD2 Spring 2017				
	Week 1	Week 2	week3	week4
January	Break	Starts: order/make all parts	Review and get parts	Build prototype
February	Test prototype, assess	Acquire more parts, fix, review, and change	Build main project (extension of prototype)	Build main project and test
March	Build main project and test	Test, assess Acquire more parts, fix, review, and change	Build main project and test	Build main project and test *final*
April	Test, assess Acquire more parts, fix, review, and change	Test, assess fix, review, and change, (MUST work)	Test, assess fix, review, and change (MUST work)	End, final presentation

Universal Orlando has agreed to sponsor this project for the X-Car Electrical Maintenance tool in return that Universal Orlando owns the property. All hardware and software involved with this project will have full ownership by Universal Orlando. The money sponsored by Universal Orlando is detailed in Table 7-3.

Table 7-3: Sponsorship by Universal Orlando

PART	COST
XEM MAIN PCB	$800.00
XEM CHASSIS	$2,500.00
XEM TDR PCB	$800.00
XEM REMOTE PCB	$200.00
XEM REMOTE CHASSIS	$300.00
TOTAL SPONSORSHIP:	$4,600.00

8. Conclusion

The progression of this project overall was very challenging and labor intensive. Along the way there were many failures and successes. The initial challenge was to decide what project to choose as the main topic for senior design. There were many ideas tossed around but the one that took hold was the X-Car Electrical Maintenance tool. The reason for this selection was the great benefits that could be provided to Universal Orlando by making the device, the experience and knowledge gained, and the sponsorship.

The experience and knowledge that was hoped to be learned during the design and production of this project was mainly electrical hardware design and software design. Unexpectedly, some mechanical design knowledge was gained in the production of the X-Car Electrical Maintenance tool. There had to be mechanical drawings made along with dimensional constraints for a contract company to cut out and align components for the XEM chassis. There were also mechanical connectors that had to be developed and made. Aside from the mechanical design, there was much application of knowledge that was gained during the progression through upper-level classes for electrical engineering. There was also a lot of new information learned through the design of the time domain reflectometer. A lot of this circuit was learned through the research of this project. In the classes required for undergraduate electrical engineering, not much of the time domain reflectometer circuitry or theory is taught. The software developed for the XEM also was not covered very thoroughly which was also a good learning process. The microcontroller used was an ARM chip which is becoming the industry standard due to its open sourced architecture. It was a very good learning opportunity to use and develop software for the ARM core. The programming structure was also something new that was learned. The programming for a system that requires safety standards was new.

The electrical design for the printed circuit board was also a great learning experience. The main circuit board developed was a four-layer board with multiple power supplies and safety circuitry. The circuitry also had a very high component count and some chips had a very high pin count which made the layout very critical and challenging. The building, soldering and testing of the circuit board was also a very good experience. In the undergraduate program not much, if any, focus of circuit board design is covered. This should not be the case because electrical engineers will at some point in time be developing and building a circuit on a PCB.

Ultimately, the development of the X-Car Electrical Maintenance tool was a good experience. It took a lot of application of knowledge and learning ability to develop the tool. Not to mention, it also took a lot of time. The project milestones were met, accomplished and the project did not go over budget.

A1 References

[1] 4D Systems, “4Duino-2.4” Arduino Compatible Display Module,” 4D Systems 4Duino 2.4" TFT LCD IoT Display Module datasheet, August 2016 [Revision 1.2].

[2] 4D Systems, “ 7.0” DIABLO16 Intelligent Display Module,” uLCD-70D uLCD-70DT datasheet, August 2015 [Revision 1.4].

[3] 4D Systems, “Armadillo-43(T) 4.3” Linux based Display Module,” Armadillo-43(Non-Touch) Armadillo-43T(Resistive Touch) datasheet, April 2015 [Revision 1.1].

[4] A. Ndegw, "Resistor Power Rating, Derating, and Temperature Coefficient", *Digikey.com*, 2017. [Online]. Available: https://www.digikey.com/en/maker/blogs/resistor-power-rating-derating-and-temperature-coefficient/a8c993213afd48c3b08b65d2e372197c. [Accessed: 15- Nov- 2017].

[5] Atmel, “8-bit Atmel Microcontroller with 16/32/64KIB In-System Programmable Flash,” Atmel ATmega640/V-1280/V-1281/V-2560/V-2561/V datasheet, Feb.2014.

[6] Keyence America, “ISO 13849-1 Revisions: Safety Knowledge|KEYENCE America”, *Keyence.com*, online document, https://www.keyence.com/ss/products/safetyknowledge/performance/, [Accessed: Nov 14, 2017]

[7] NXP, “32-bit ARM Cortex-M3 microcontroller; up to 512 kB flash and 64 kB SRAM with Ethernet, USB 2.0 Host/Device/OTG, CAN,” LPC1769_68_67_66_65_64_63 datasheet, May 2017.

[8] NXP, “UM10360 LPC176x/5x User manual”, NXP Semiconductors, April 2014 [Revision 3.1].

[9] Texas Instruments, “Choose the right data converter for your application”, *ti.com*, 2017. [Online]. Available: https://www.ti.com/europe/downloads/Choose%20the%20right%20data%20converter%20for%20your%20application.pdf. [Accessed Nov 22, 2017]

[10] Texas Instruments, “Mixed Signal Microcontroller,” MSP430G2x53 datasheet, April 2011 [Revised May 2013]

[11] "Wirewound resistor » Resistor Guide", *Resistorguide.com*, 2017. [Online]. Available: http://www.resistorguide.com/wirewound-resistor/. [Accessed: 15- Nov- 2017].

[12] Lee, A. (1999). *4.5μA Li-Ion Battery Protection Circuit*. [online] Cds.linear.com. Available at: http://cds.linear.com/docs/en/lt-journal/LT1389_0699_Mag.pdf [Accessed 2 Dec. 2017].