X-Car Electrical Maintenance Tool

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***Abstract* — The objective of this project is to design and implement a tool for use during maintenance of the Hollywood Rip Ride Rockit roller coaster ride vehicles at Universal Studios Orlando. At distribution of this document, the ride vehicles interface with a Ride Control System which performs system checks while the vehicle is in the load and unload station. However, these checks do not provide enough information to assist with troubleshooting when a discrepancy may occur. With the implementation of the X-Car Electrical Maintenance Tool (XEM), troubleshooting capabilities will improve and will prevent unnecessary part replacement, saving time and money.**

***Index Terms* — Electrical Engineering, Fault Protection, Maintenance, Measurement, Printed Circuits.**

I. Introduction

The hardware on the X-Car Vehicle Maintenance tool (XEM) 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.

The 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 is depicted in Fig. 1.

Fig. 1. The Hollywood Rip Ride Rockit ride vehicle and lap bars.

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.

II. Overview of XEM Hardware

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. The unpowered HMI is shown in Fig. 2.

Fig. 2. The HMI, showing the touch screen, open lap bar, close lap bar, trouble acknowledge, and emergency stop buttons.

A. 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.

B. 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.

C. Human Machine Interface

The Human Machine Interface (HMI) is part of the XEM which allows the end user to operate the XEM. An example screen of the HMI Is given in Fig. 3.

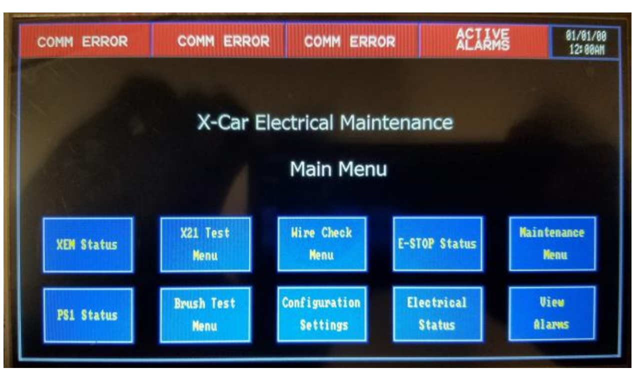

Fig. 3. The main menu of the touch screen HMI. On screen buttons lead to various sub-systems, alarms, and tests.

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. The XEM interface flowchart is depicted in Fig. 4.

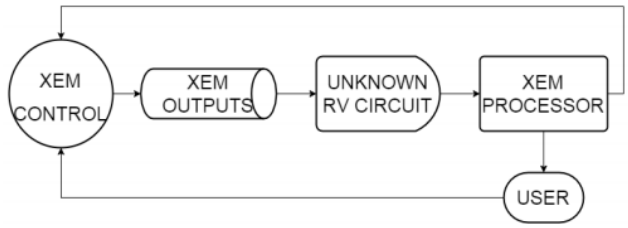

Fig. 4. The interface between the XEM control, its outputs, the unknown ride vehicle system, the input from inputs to the XEM, and the user.

D. Microcontroller

The RCS simulator consists of a Microcontroller which provides all logic and post hardware processing. A microcontroller with a large number of GPIO and analog inputs will be used to achieve the design. The Arm cortex-M3 is a microcontroller that has high level integration and low power consumption. The CPU uses a three stage; pipeline and Harvard architecture. 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. The I and D buses are relatively faster than the system bus. 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) this helps prevent some interrupt delays and assists in processing any late arriving interrupts [1].

The LPC 1769 features a 12-bit Analog to Digital Converter (ADC). The ADC is one of the most essential parts of the XEM, as accurate voltage readings are absolutely necessary to ensure useful feedback to the user.

E. Power

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.

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. A user-friendly connector type would also be a plus. For these reasons, the RSP-2000-24 was used.

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.

For the 12V supply section, the 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. The 5V power supply is used to power the LCD HMI. It is necessary for the power supply to supply at least 500mA at 5V with an input voltage of 12V. With the decent current consumption 12 on the 5V, the efficiency is of highest concern. Therefore, the RECOM's R-785.0-1.0 regulator was selected for the 5V supply.

The 3.3V supply was spec'd out to power the main microcontroller and all other 3.3V digital circuitry. For this supply, high regulation accuracy, noise immunity, and package is of highest concern. 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.

III. Measurement Circuits

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, an emergency stop can be performed.

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.

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.

The XEM was designed to meet specifications of voltage, current, and resistance limits and ranges, as shown in Table I.

TABLE I
Voltage, Current, and Resistance Measurement Specifications

Voltage Maximum	28 Volts
Current Maximum	50 Ampere
Voltage Accuracy	Within 0.1 Volt
Resistance Accuracy	Within 0.1 Ohm

A. Voltage

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. To bring the 28 volts down to usable level, resistor two needs to have a value equal to approximately one ninth, or less, of on the combination of resistor one and resistor two. For this voltage divider, the first resistor in the series was selected to have a value to be 180k ohm, and the second resistor in the series was selected to have a value of 20k ohm. This divider causes the voltage between the two resistors to be 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 which disconnects the ADC from directly interfacing with the voltages and also provides a more reliable current to the ADC from the operational amplifier. The microcontroller then uses the voltage to perform its diagnostics.

B. Current

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 some 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.

The current sense amplifier works by using a sense resistor which generates a voltage cross the resistor, Vsense, 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 which can then work backwards using known values and parameters to find the current through the sense resistor.

C. Resistance

Resistance measurement can be done it two ways. One is by using a known resistance in series with the device under test (DUT). By taking voltage measurements before, between, and after the known resistance and the DUT the microcontroller can find the voltage drop across the known resistance, leading to the current through the DUT, and the voltage drop across the DUT, leading to the resistance o the DUT. However, this method has multiple sources of error. Taking multiple voltage measurements with the ADC will propagate the error in the ADC measurements more often than only using one ADC measurement.

The resistance of the DUT can also be measured by utilizing a Wheatstone bridge. Using four equal resistors and the DUT as an extra resistance on one branch of the Wheatstone bridge, a differential amplifier will read the voltage difference caused by the addition of the DUT. A representation of the Wheatstone bridge circuit is depicted in Fig. 5.

While not in use, the terminals of the differential amplifier are grounded via mechanical switches. This protects the differential amplifier and the ADC by disconnecting it from any voltage that may come through when not in use and allows for the ADC to take a measurement when the differential amplifier should have no input voltage on either terminal. A measurement can be taken in this state to calibrate the Wheatstone bridge circuit, taking into account any offset that may be present in the differential amplifier.

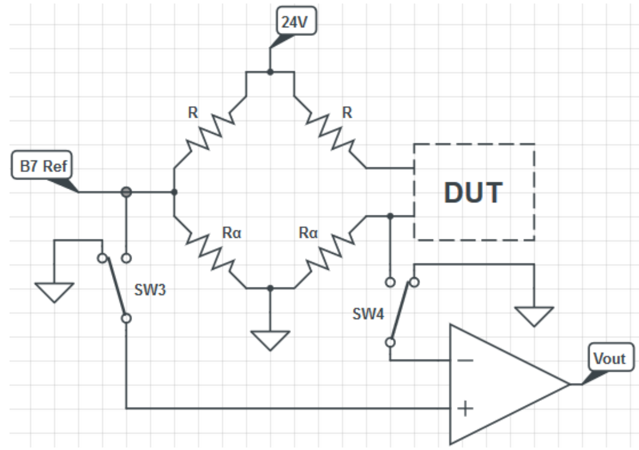

Fig. 5. The Wheatstone bridge design. SW3 and SW4 represent mechanical relays.

IV. Wireless Control Module

The Wireless Control Module (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.

A. RFM69HCW

In order to perform wireless communication with the XEM, the ATmega328P interfaces with a RFM69HCW. The RFM69HCW communicates with the ATMega328P through a four-wire Synchronous Peripheral Interface plus an interrupt line [2].

The RFM69HCW operates at 915 MHz, which is the Industry Scientific and Medical (ISM) band [2]. Using a standard antenna, the range of the RFM69HCW can extend for hundreds of meters outside in unobstructed space. Indoors, the range could extend for over 50 meters through walls [2]. These ranges are acceptable for the purposes of the WCM.

B. Operation

The WCM executes basic functions of the XEM at range. The goal of the WCM is to be able to open and close lab bars on the ride vehicle as well as perform an emergency stop. These functions are the same functions performed by the XEM main system, as the WCM simply sends a signal to the XEM which then performs the requested function. Three push buttons are wired to terminal blocks on the WCM which trigger the WCM to send a command to the XEM.

The WCM is typically disabled and input to the WCM has no effect as the system is inert. The XEM can enable the WCM, allowing it to send and receive signals to and from the XEM main system.

C. Power

Being a wireless system, the WCM utilizes an 18650 rechargeable battery. The battery is charged using an external charging circuit. This type of battery was chosen because of its availability, ease of use, and capability to provide the requires current and voltage to the WCM. system. The ATmega328P and RFM69HCW will both operate at 3.3 volts. This type of battery will be able to provide the required voltage for the system.

D. Programming Ports and Communication

In the WCM, the ATMega328P and RFM69HCW communicate with each other through Serial Peripheral Interface (SPI), using the ATMega328P as the Master and the RFM69HCW as the slave.

TABLE II
BRUSH LABELS AND PURPOSE

Label	Brush #	Use
WSL1	1	RFID tagged
WSL2	2	Ground
WSL3	3	RFID tagged
WSL4	4	Open Lap Bar
WSL5	5	Lap Bar Status
WSL6	6	Sector Occupied
WSL8	8	Close Lap Bar

There are two ports available to program the WCM. First, the WCM can be programmed via SPI using a computer as the master sending data to the WCM as the slave. The second programming method is via Universal Synchronous/Asynchronous Receiver-Transmitter (USART).

V. OPERATION AND IMPLEMENTATION

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.

A. PCB

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.

B. Lab Bar Open/Close & Emergency Stop

The XEM will operate the lap bar mechanism on the ride vehicle. The power output of the XEM can operate all six lap bars on the train at once. The XEM also has the capability to operate single lap bars at a time. In order for the XEM to operate the lap bars, it must be in either standard mode, maintenance mode, or X21 mode.

As shown previously, the XEM has hardware buttons with which the lap bar operations can be performed. These buttons are Allen Bradley 22.5mm Push Buttons. The buttons only functions when a mode that allows for lap bar operation is enabled. The buttons are mutually exclusive, in that only one can be active at once. 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.

While in BBC mode, the hardware buttons can only be activated for a limited time due to the high-power output. The output is limited to 20 seconds with 5 second intervals between operation.

The only hardware button that also has a circuit hardware tie in is the Emergency stop push button. This button is a maintained state button, meaning that it when pressed it stays pressed. The hardware ties in the hardware emergency stop circuit. 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.

VI. 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. Software design will be executed using the C programing language due to the chosen ARM microcontroller. 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 final hardware input 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 labeling, brush number, and use of each brush is given in Table II.

The XEM will check the voltage for the power source, open lap bar, and closed lap bar and send 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. The function flowchart is shown in Fig. 6. The formulas used to get these voltages are shown in (1) and (2).

$$voltage\ divider * \frac{33}{4095} = v \quad (1)$$

$$v * 1000 = Voltage \quad (2)$$

The XEM will check the current for the power source, open lap bar, and closed lap bar and send 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. The function flowchart is shown in Fig. 7. The formulas used to get these currents are shown in (3), (4), and (5).

$$\left({}^{ADC\ value}/_{4095}\right) * 33 = amplified\ voltage\ across\ sense\ resistor \quad (3)$$

$$amplified\ voltage * 1000 = current\ amps \quad (4)$$

$$\frac{(current\ amps * 1000)}{500} = current\ amps\ with\ 3\ decimal\ point\ precison \quad (5)$$

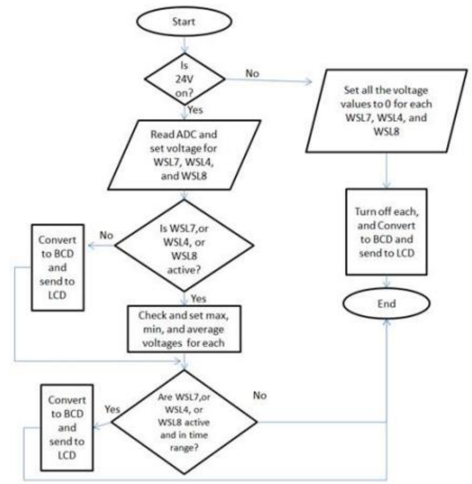

Fig. 6. The voltage flowchart shows the checks and operation of each step during the function.

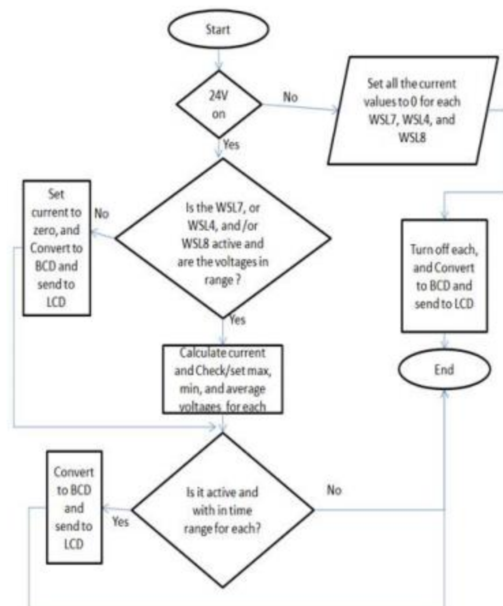

Fig. 7. The current flowchart shows the checks and operation of each step during the function.

The XEM will check the ohms for open lap bar, and closed lap bar and send 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. The function flowchart is shown in Fig. 8.

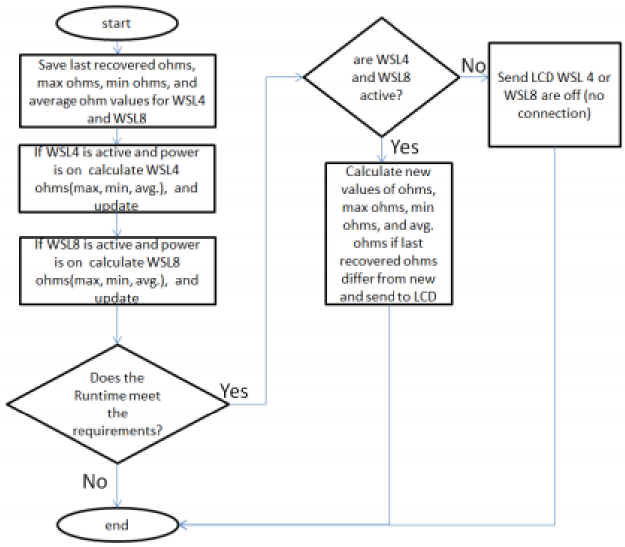

Fig. 8. The resistance flowchart shows the checks and operation of each step during the function.

The main function for the HMI ties in all these functions and more in order to achieve a working interface that allows the user to achieve the requirements specified earlier. The most important aspect of main will be the continuous loop, this loop will check times, but most importantly execute the above functions. functions.

VII. 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.

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.

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 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. Through circuitry the vote of one input will influence the others to remove their vote as well. 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.

The XEM tool will use different standardized communication protocols in order to collect, distribute and display information. The XEM 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. The main XEM 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.

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.

VIII. Conclusion

The progression of this project overall was very challenging and labor intensive. Along the way there were many failures and successes. 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. 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 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.

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 Engineers

Matthew Hunt is a 23-year old graduating Electrical Engineering student. Matthew plans to pursue a career in the electrical engineering field with an interest in electronics design and automation. Matthew also hopes to continue studying programming languages and methods as well as foreign language.

Alexander Washington is a 28-year old graduating Electrical Engineering student. Alexander presently works at Universal Orlando as an Associate Project Manager. Alex's interests are electronics, embedded systems, circuit board design, controls engineering, electric vehicles, automation, and mobile applications. Alexander hopes to become a larger role in the development of theme park attractions.

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