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Rapid Battery Exchange Safety and Sensing

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Abstract

The Rapid Battery Exchange system (RBX) swaps batteries in an electric van, allowing almost continuous operation of the vehicle. The RBX system is designed and built by The Cal Poly Electric Vehicle Engineering Club (EVEC). The system includes the exchange ramp, two battery packs, and the electric "G-Van." While the vehicle drives using one of the battery packs, the other pack charges in the exchange ramp. When the van's battery depletes, it drives onto the ramp and swaps the dead battery for the charged one, and the process repeats.

The RBX battery pack safety and sensing project divides into two main parts – voltage isolation and voltage sensing. Voltage isolation disconnects the battery pack voltage (216 VDC) from the outside of the pack when the pack is not charging or powering the van. This ensures operator, technician, and rider safety. The project also senses and records battery voltages over time, allowing technicians and engineers to find dead batteries in the pack and monitor the pack performance over time.

Introduction

Background

The two primary concerns Dr. MacCarley and EVEC expressed are the lack of battery health data, and the need to isolate the battery pack voltage from the outside of the case. Isolating the battery pack when not in use prevents accidental shorting of the battery pack across tools and people. It is requisite that the system use XBee radios because the other two elements of the system (the ramp and van) use them already.

Voltage measurements are used to tell what batteries need balancing and for battery pack diagnostics. Data is stored for one week, allowing users to analyze pack performance. The overall contribution to the RBX system is a safer battery pack, and a means to diagnose and monitor batteries in the pack.

These requirements were used to make the marketing and engineering specifications in Table 1.

Customer needs

The customers for the first part of this project are electric vehicle/machine owners and mechanics that use a battery pack to run. Customers need to stay safe from the full voltage and current of the battery packs. Additional strategies to identify customer needs can be to look for safety hazards in home and maintenance garages that may make things dangerous.

The customers for the second part are battery pack maintenance mechanics. Proper sensing of each battery is required to not overcharge batteries and extend battery lifetimes.

Requirements and Specifications

Table 1: Rapid Battery Exchange Safety and Sensing Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1	Contactor is disengaged when outside of the G-Van, not under a battery charger or not being charged/discharged.	Battery pack voltage is isolated from the outside of the case when not in use.
2, 6	Contactor coil powered by portion of the battery pack.	To keep the battery pack self powered and not needing external power source.
1	The default system position is disconnected. In the event of a system or power failure, the system remains disconnected, or disconnects if engaged.	In the case of a system failure or vehicle accident, or when the system is in a default state, it is important that the pack becomes safe so that the pack will not harm occupants or emergency response teams.
1,7	Includes a keyed manual turn on/shut off switch for emergency and technician usage.	The user must be able to manually lock the contactor into the desired position both for safety and troubleshooting measures.
1,7	Engages or disengages in less than 2 seconds from reception of command.	The operating window for a battery swap is about a few minutes. The battery pack must not lengthen the swap time of the system significantly.
8	Returns battery pack status in under 50ms.	Used for safety checks in the code. Not output to user.
5	Log at least 1 week of data including each battery's voltage and the corresponding battery. Measurements are taken every 30 seconds per battery with 10mV resolution at +/-5mV accuracy.	One week of data at 30 second intervals is sufficient to estimate battery health. The resolution is that of a handheld multimeter, which sufficiently determines battery state.
1	Four XBee modules; Van, Ramp, Pack 1 and Pack 2, communicates accurately with one another.	Multiple communication modules increases the possibility of erroneous data reception so the multiple XBee cannot interrupt the operation by operating correctly.
2, 6	Contact system must not consume more than 0.5% of the battery's charge when running and ~0% when not in operation.	To keep the batteries in the battery pack from imbalancing, the power consumption must be kept relatively low compared to the battery's total charge.
4	Layout of the Battery Management System chip must allow for connection to Lithium Ion batteries also in case the lead acid batteries are replaced with a more reliable source.	Interchangeability will allow for easier transition to more efficient and better energy sources.
3	Implement five battery management chips for each battery pack.	To have the capability of sensing each lead acid battery. Each BMS chip can read up to 4 lead acid batteries each so we need a total of 10 BMS chips for two battery packs.

Marketing Requirements
1. The battery pack is dead when not in use 2. Minimal interference with current RBX setup 3. Sensing system for each battery in battery pack 4. Flexibility in sensing system for different types of batteries 5. Status for each battery stored as data 6. Uses power from battery pack to run sensing and safety system efficiently 7. A technician can work on the pack in or out of the vehicle and ramp 8. Reliability and effectiveness of system

The requirements and specifications table format derives from [1], Chapter 3.

Table 2: Rapid Battery Exchange Safety and Sensing Deliverables

Delivery Date	Deliverable Description
Feb 2014	Design Review
March 2014	EE 463 report
May 2014	EE 464 report
May 2014	EE 464 demo device(s)
May 2014	ABET Senior Project Analysis
May 2014	Senior Project Expo

[1] R. Ford and C. Coulston, *Design for Electrical and Computer Engineers*, McGraw-Hill, 2007, p. 37
[2] *IEEE Std 1233, 1998 Edition*, p. 4 (10/36), DOI: 10.1109/IEEESTD.1998.88826

Functional Decomposition

Level Zero Block Diagram

Figure 1: Level 0 Block Diagram for RBX Safety and Sensing System

Level One Block Diagram

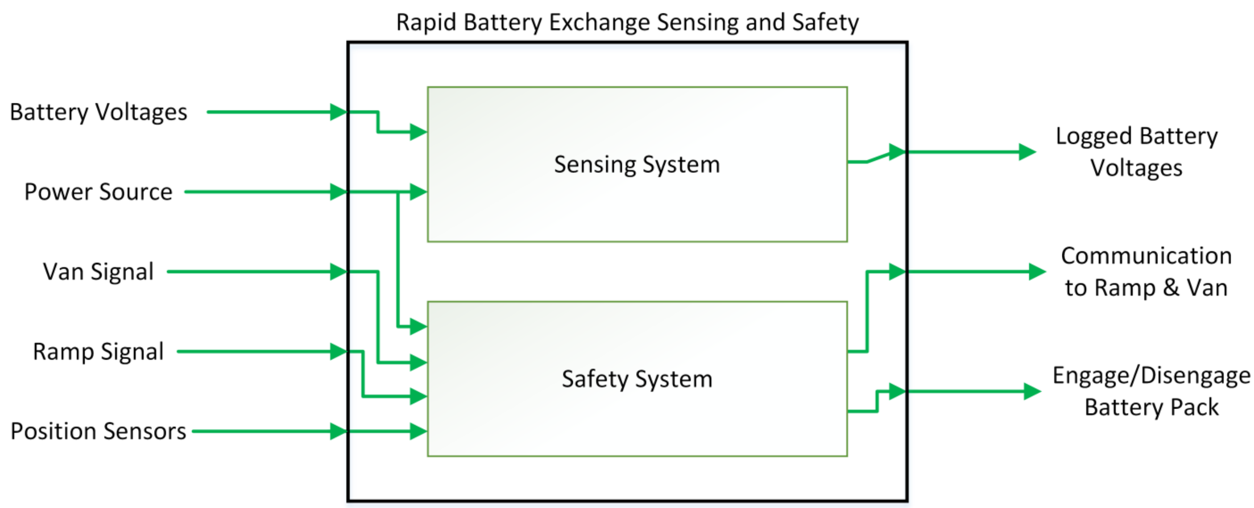


Figure 2: Level 1 Block Diagram for RBX Safety and Sensing System

Table 3: Block Diagram Inputs/Outputs and Functionality

Module	RBX Battery Safety and Sensing
Inputs	- Battery Voltages - Power Source - Van Signal - Ramp Signal - Position Sensors
Outputs	- Logged Battery Voltages - Communication to Ramp & Van - Engage/Disengage Battery Pack
Functionality	- The Power Source provides the power to both the Safety and Sensing system. - Battery Voltages are sensed with the BMS chip and stored onto an SD card. - Van Signal, Ramp Signal and Position Sensors are used for the safety system for the engaging and disengaging of the contactor.

Development Process

Special Thanks to our Sponsors

- Justin Ayscough of Kilovac for the donation of two LEV200A6NAA DC Power Relays (Contactors).
- Glen Fabian and Dave Green of Linear Technology for the donation of LTC6803 demo board and 9 LTC6803-3 chips for the battery sensing.
- Brett Ligrani of Advanced Circuits for the generous discount on the battery sensing printed circuit boards.
- Professor Art MacCarley and the Electric Vehicle Engineering Club for funding the project.
- Professor John Dunning for advice and support on battery sensing.
- Adam Morris for supporting the project during all stages.
- Woosik Yang for helping with fabrication.

Battery Safety Design

The Battery Safety system makes use of DC contactors to break the circuit when not in use. Each battery pack contains a contactor controlled by ATMega32U microcontrollers. The battery packs communicate with the G-Van and Ramp with XBee communication modules.

The Safety system is programmed to engage or disengage depending on the position of the battery packs. A situation can arise where the ramp, and van, and both battery packs are within range of each other. Under this circumstance, an engage command from the ramp must not engage the battery pack in the van and vice versa. Position sensing allows the battery pack to respond to commands from the ramp or van appropriately. The flow chart for the battery pack code is shown in Figure 3 and Figure 4 below.

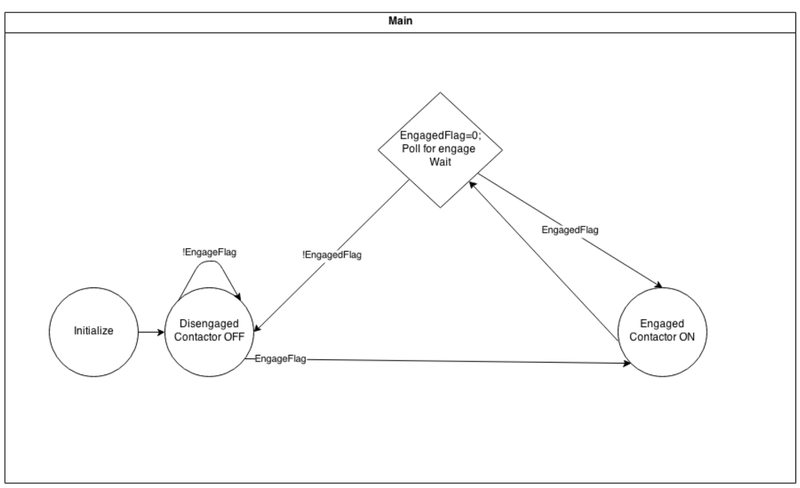


Figure 3: Battery Pack Main Function Flow Chart

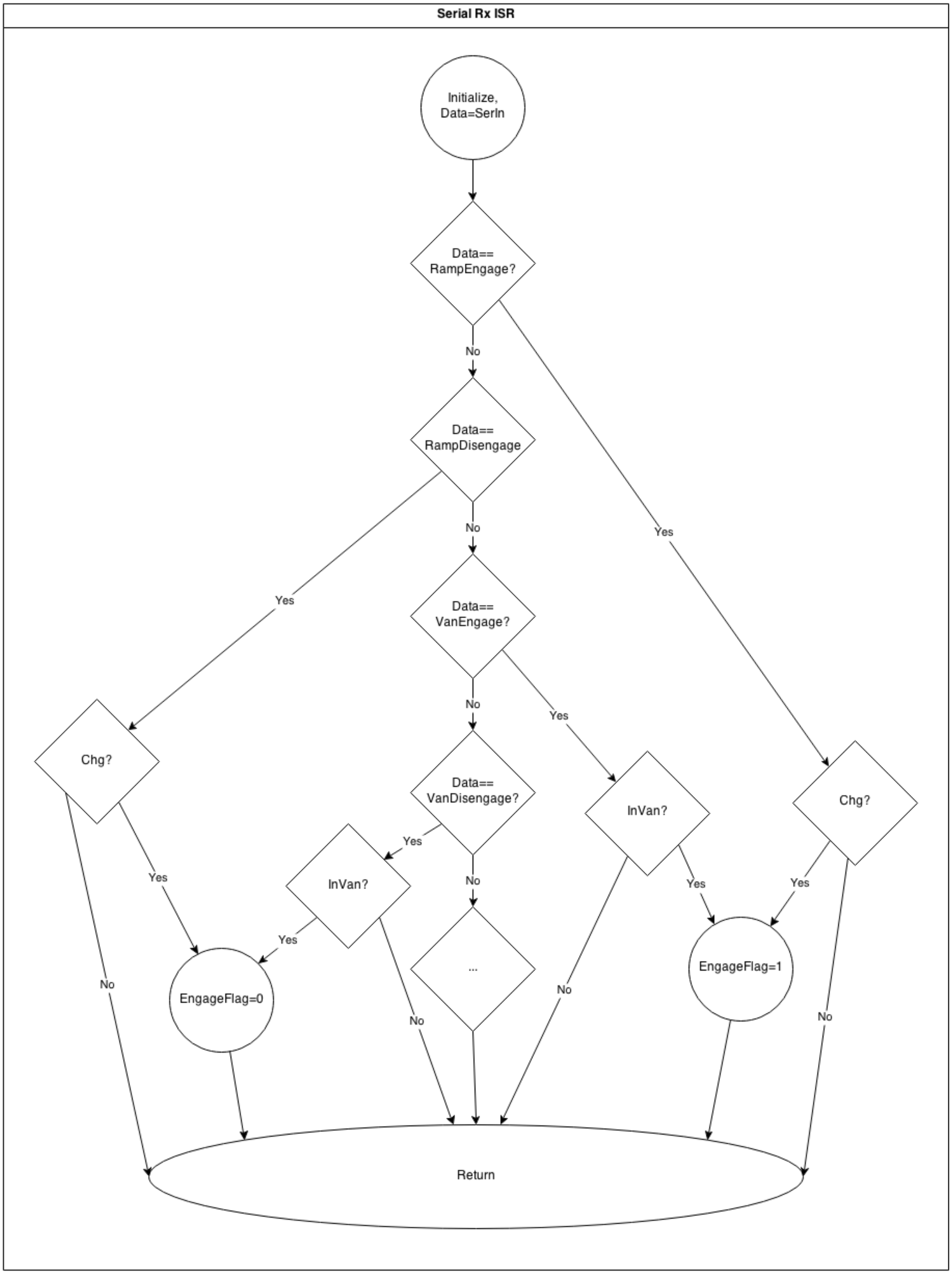


Figure 4: Battery Pack ISR Code Flow Chart

The position is determined by reed switches on the battery pack, one for sensing charger position and another for van position. See Figure 5 for the planned sensor location diagram. The charger ("Chg") sensor mounted to the side of the pack will only be activated when the pack is under a charger, preventing the pack from engaging the contactor unless it is about to be charged. The sensor for the van ("InVan") is located on the top of the pack and will only engage when the pack is in the van.

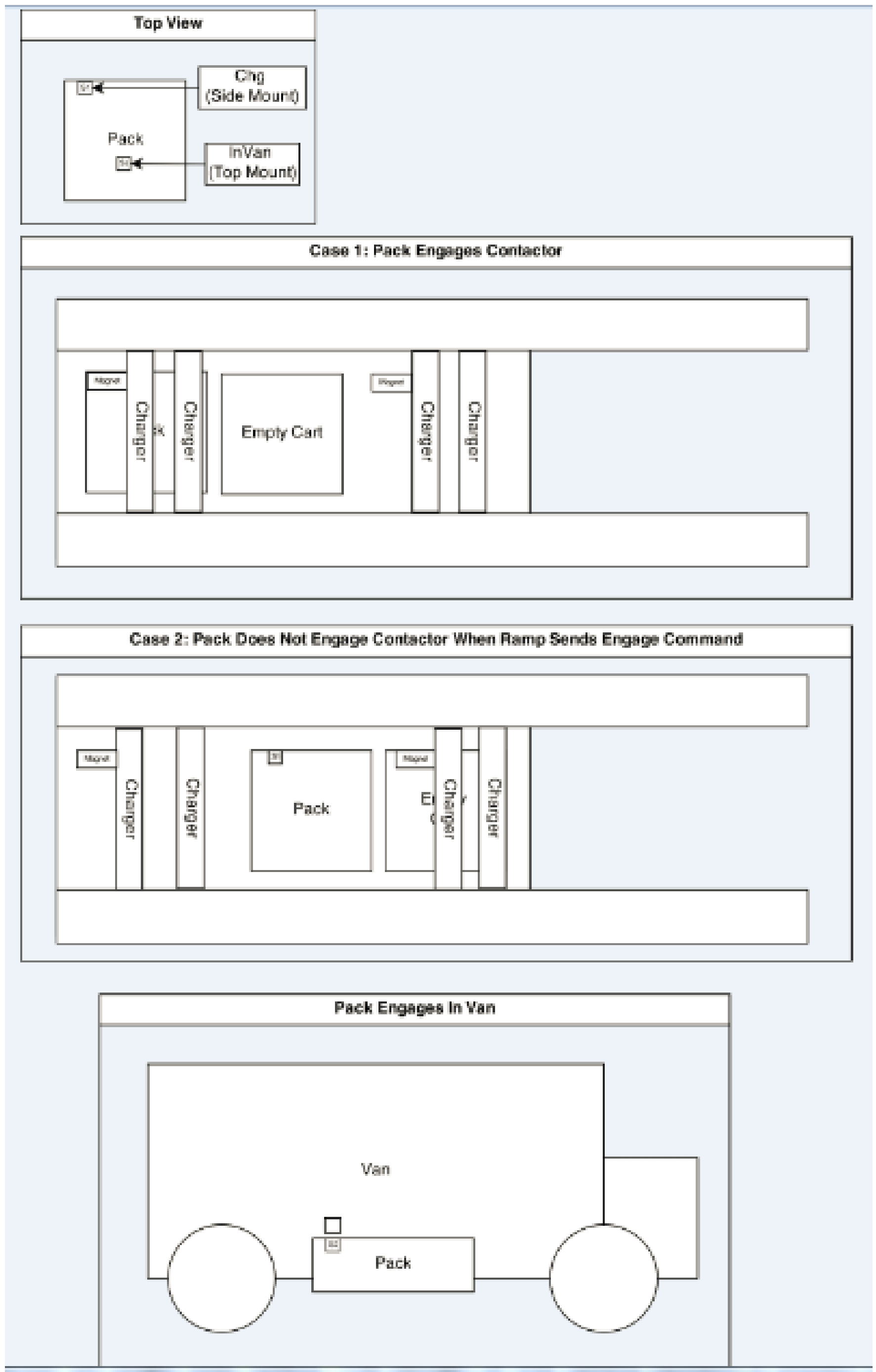


Figure 5: Battery Pack Sensor Locations

The safety system uses a $48V_{coil}$ contactor rated for 500A+ and 12-900V_{dc}. The coil is powered by the bottom four lead acid batteries and controlled by an N-channel power MOSFET. The gate of the MOSFET is controlled by the logic output of the microcontroller. The Zener diode protects the microcontroller. The 1kΩ resistor and the microcontroller sense input are used to check the state of the contactor in case of failure. A mechanical, keyed, 3 pole switch allows manual shutoff and engagement. The default position is auto (microcontroller logic), second position is contactor engaged (logic high, 5V), and the last position is contactor off (logic low, GND). The design of the safety system is shown in Figure 6 below.

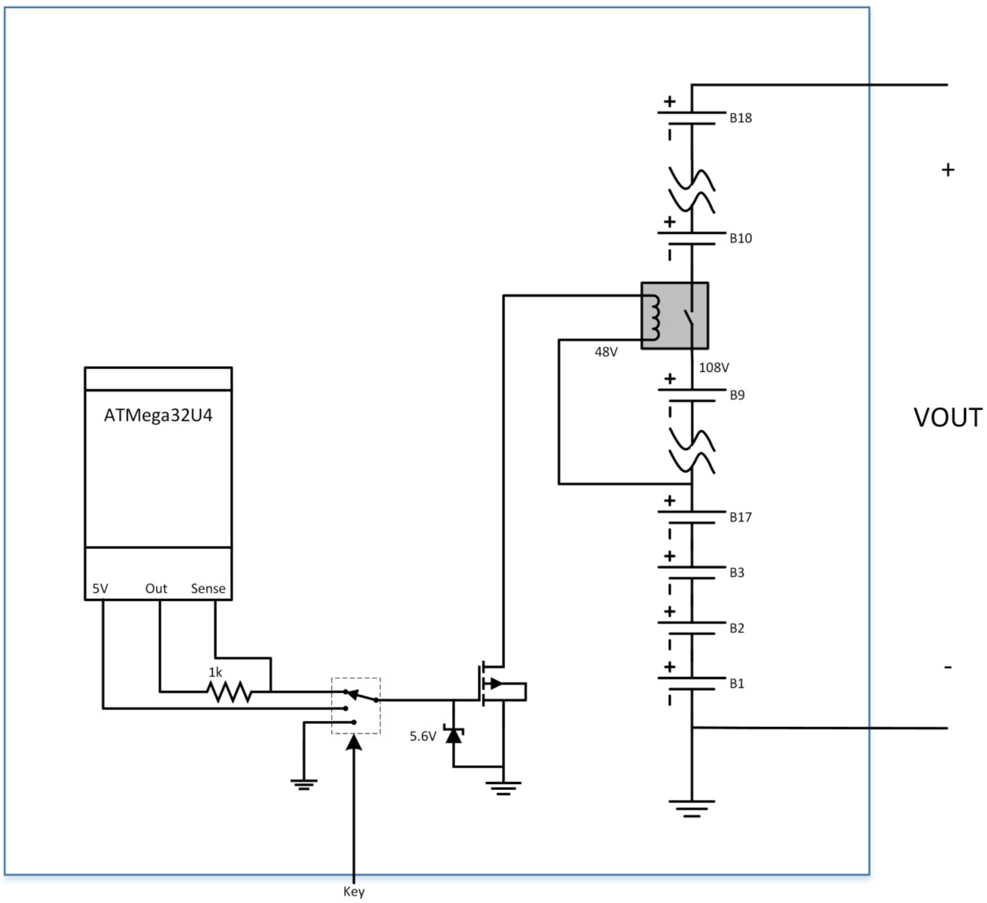


Figure 6: First Contactor Circuit Design Schematic

During the design for the implementation of the contactor, it was determined that the remaining space within the battery pack is insufficient. It is necessary to cut open a piece of the battery pack top cover to make enough space. Figure 7 below shows the implementation design of the contactor. In Figure 8, the contactor is mounted to a wooden board. The BMS breakout board and the contactor prototyping board are contained in enclosures and secured in other places in the battery pack. As shown in Figure 9, a contactor plate cover seals and protects the contactor.

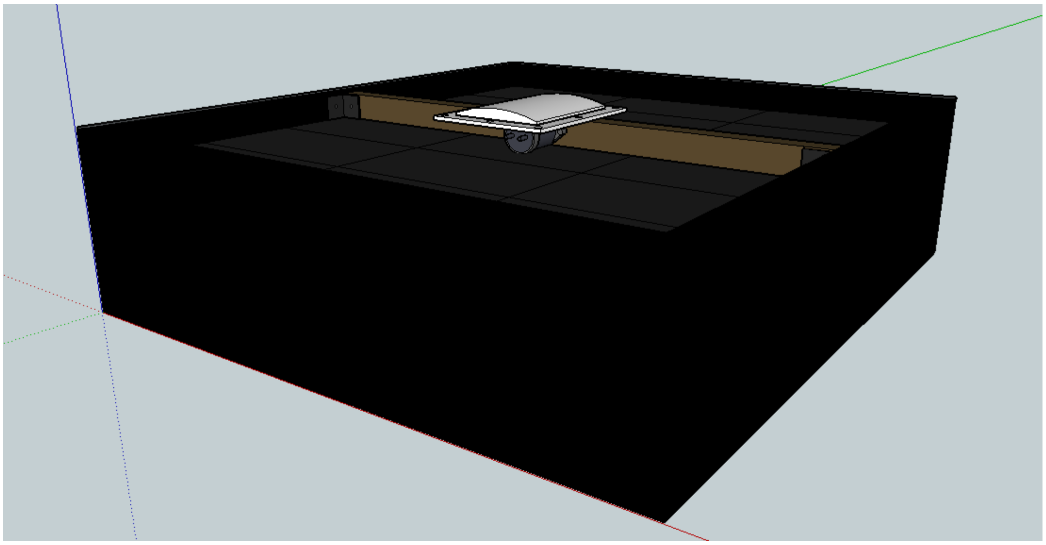


Figure 7: Contactor Implementation: Full Battery Pack

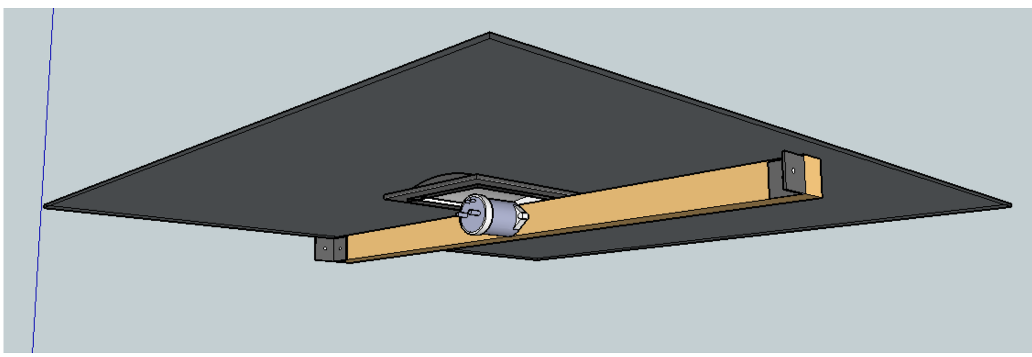


Figure 8: Contactor Implementation: Contactor Mounted to PVC Board

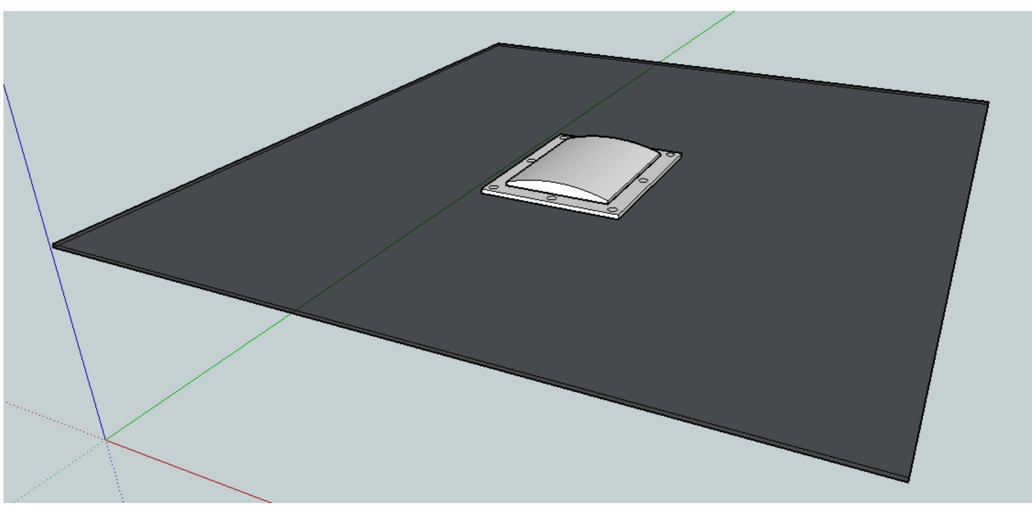


Figure 9: Contactor Implementation: Top Cover with Contactor Plate

Battery Sensing Design

The first design of the sensing system was a resistor network feeding into an analog multiplexor which would then select which battery to sense. The output of the multiplexor would then feed into an analog to digital converter which would feed the data into a microcontroller. The data would be stored on an SD card. After getting advice from Professor Dunning, this design was essentially scrapped because there are ICs that will handle the voltage readings internally that will be more efficient than our design.

The second design includes a LTC6803, which is a Battery Management System chip. These samples along with a demonstration board was donated by Linear Technology's Sales Engineer, Glen Fabian. The new design is shown in Figure 10 and Figure 11 below.

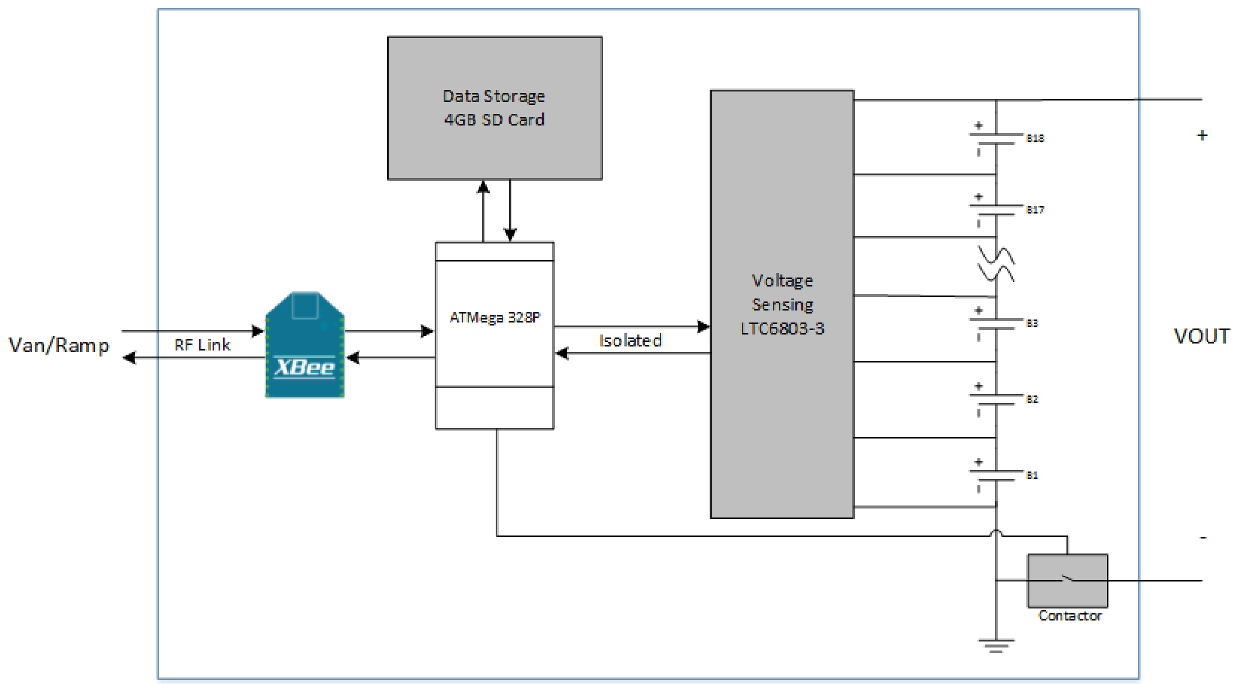


Figure 10: Detailed Block Diagram of the Battery Pack Safety and Sensing System

This battery voltage sensing system is implemented on a printed circuit board. We based the design on a Linear Technology application note by Jon Munson [25]. Linear Technology provided us with a demo board to test the LTC6803-3 chip. We had to make our own PCB because the demo board topology is significantly different from what is necessary for your battery pack system.

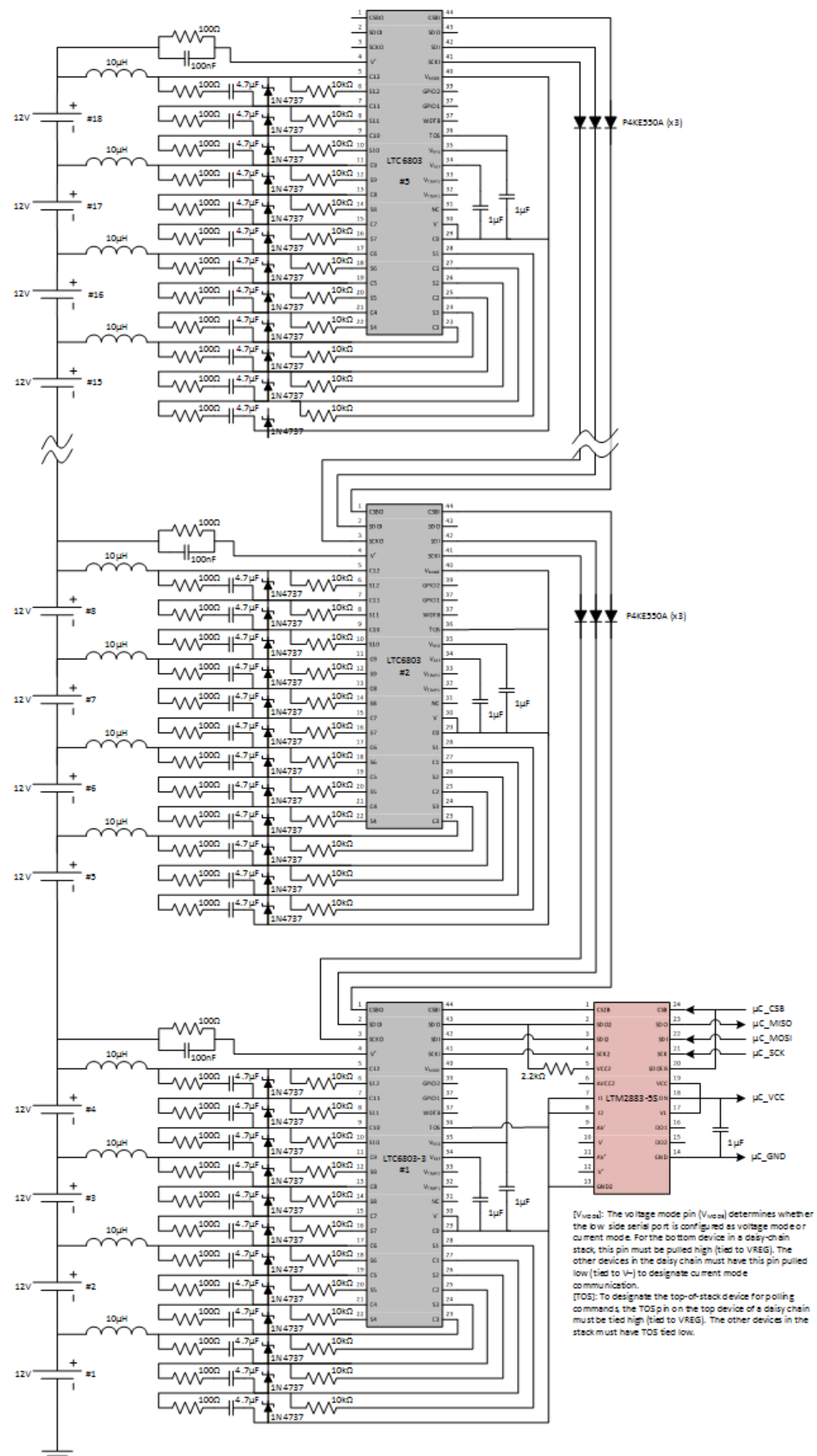


Figure 11: Detailed Schematic of LTC6803-3 layout.

Battery Sensing and Safety Circuit and Code Testing

The code testing setup includes a suitcase which was outfitted with LEDs, potentiometers, buttons, and switches for any testing application which we set up for our RBX system. Figure 12 shows the set up with four different microcontrollers connected to XBee modules, which are set up to communicate with one another. The four microcontrollers are programmed code for the van (bottom left), ramp (top left), battery pack 1 (top right), and battery pack 2 (bottom right).

Figure 12: Test Setup

Many of the code's bugs and errors were found and fixed using this test system. With this system, we were able to test smooth operation of the exchange, robustness of the code, communication between the XBee modules, and hardware operation. We ran the system for three hours continuously with six exchanges with no errors.

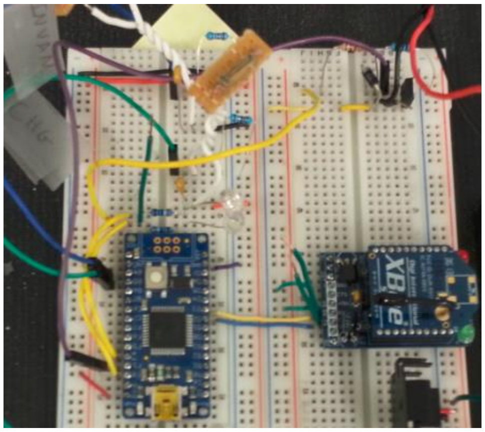


Figure 13: Contactor Circuit Testing

The reed switch position sensors were tested using a multimeter and a magnet array to ensure adequate range and reliability. The sensors were also tested with the microcontrollers to ensure compatibility.

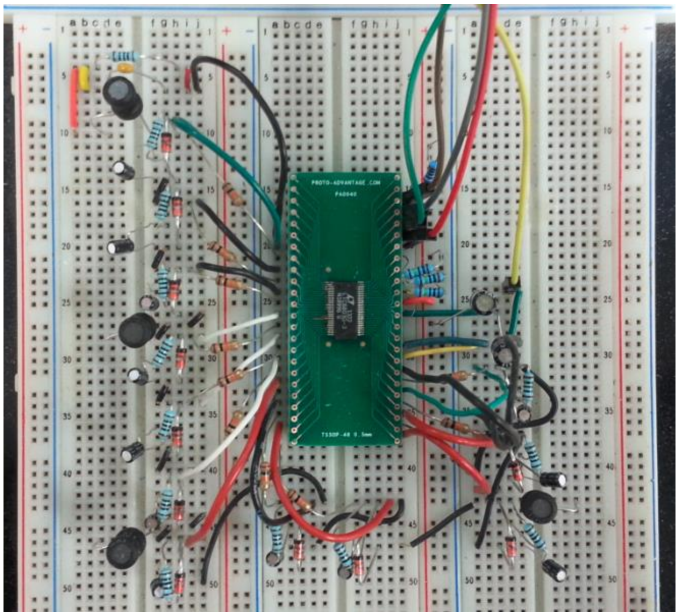


Figure 14: Battery Monitoring Test Circuit

Figure 15: Testing Monitoring Circuit

The Battery Management circuit has been implemented on the breadboard as shown in Figure 14. The battery management code was also tested on the circuit using an ATMega328P, as in Figure 15. Once the circuit was found to be working, it was put laid out on a PCB using PCB Artist supplied by Advanced Circuits.

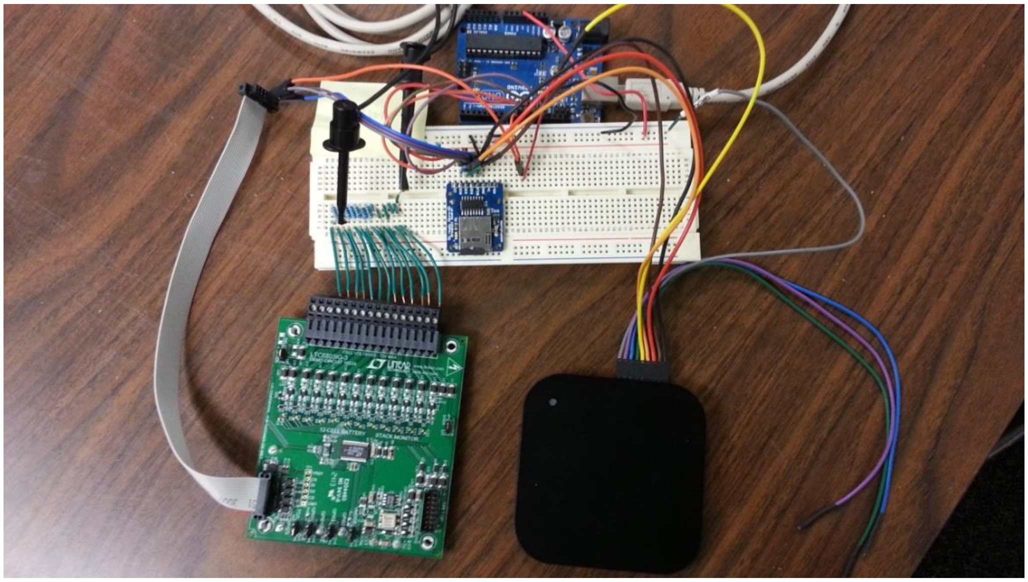


Figure 16: LTC6803 Battery Management chip tested with data logging code onto SD card

The data logging code was tested using the LTC6803 Demo board, shown in Figure 16 above, which reads the voltage levels. The system then stores voltages on the SD card, which can be read by a computer. Voltage levels are set by a resistor string connected to a power supply. Each pin of the LTC6803 sees a voltage that can be changed using the power supply. The system was tested by altering the power supply voltage and ensuring that the correct battery voltages were being written to the SD card.

Battery Safety Circuit Implementation

The contactor circuit was tested on breadboard and built on prototyping board, as shown in Figure 17. The circuit has breakout connections via DB9 connectors for easy connecting and disconnecting of the circuit board.

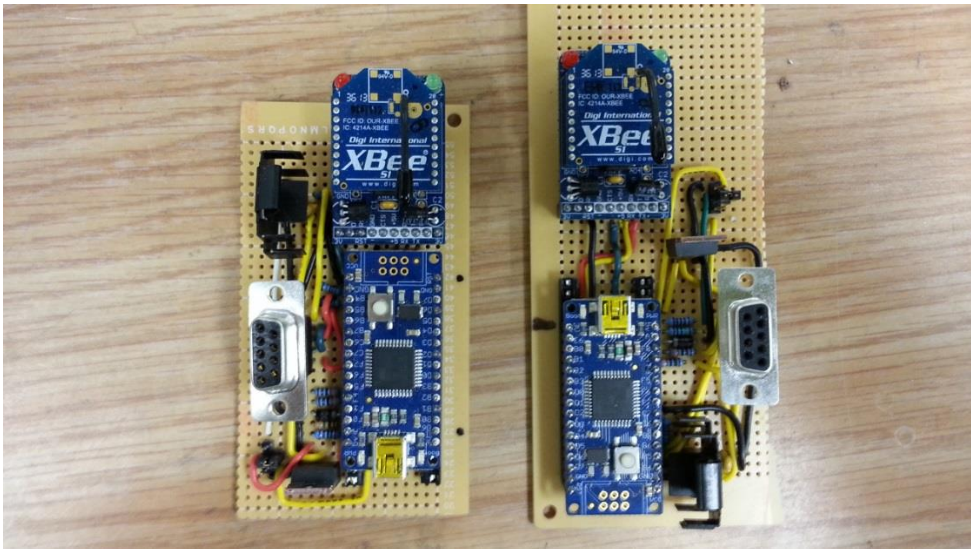


Figure 17: First Safety System Prototype

The circuit connects to the contactor and the battery pack. The pack powers the circuit and the contactor.

The contactor circuitry is placed in an enclosure to protect the circuitry and placed in the battery pack with Velcro for easy removal. The system is screwed in with spacers to prevent shorting and provide mechanical stability.

This circuit bench tested very well, but when installed on the battery pack, it was unreliable. The microcontroller would reset when the charger was connected to the battery pack. This was likely due to the floating ground on the battery pack connecting to the charger ground. As the grounds connected, noise caused the voltage rail, GPIO, and Reset pins to go low on the order of 10's to 100's of nanoseconds.

Because time was limited, the circuit was simplified as shown in Figure 18. The design functionality of this system is summarized in Table 4. The ATMega32U4 microcontroller, voltage regulator, and XBee communication module have been removed. The ON and OFF functions of the key switch remain the same. The auto position now controls the contactor using the reed switches already implemented in the previous design. This ensures that the normally open contactor engages only when the battery pack is under the van or under a charger. In all other cases, when no magnets are present to engage the reed switches, the contactor will remain open and no voltage will be seen across the positive and negative terminals of the battery pack, ensuring the safety of anyone near the packs.

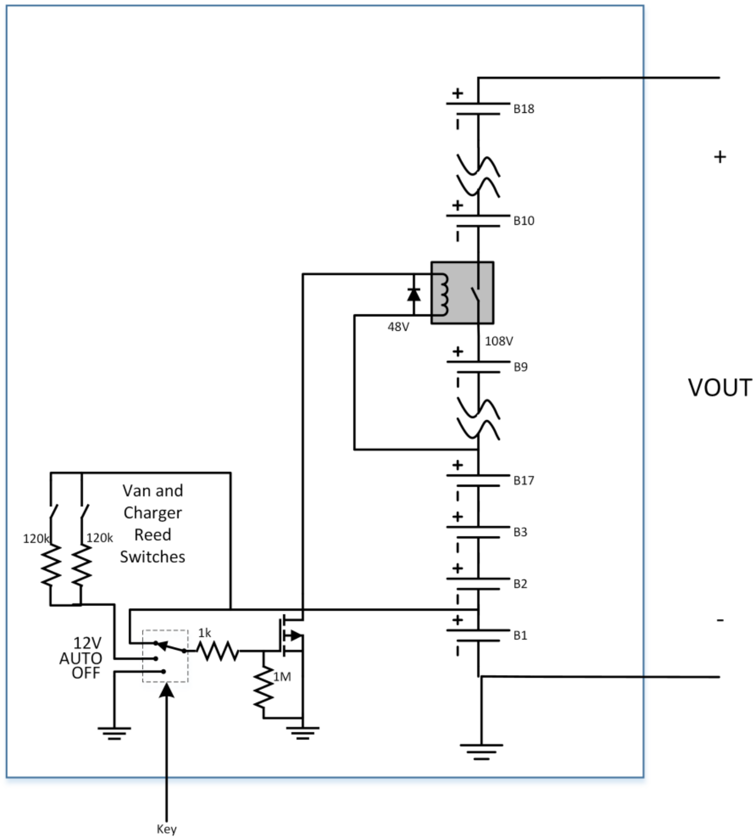


Figure 18: Simplified contactor circuit schematic with protection (freewheeling) diode

A protection diode was added across the coil of the contactor to provide a discharge path for the winding. The diode is sized by calculating the maximum reverse peak voltage across it.

Table 4: Summary of functionality changes due to simplification

Functionality	**Microcontroller Design**	**Simplified Design**
Automatically Engages under charging station and van	Yes	Yes
Keyed Control: • ON • AUTO • OFF	 • Yes • Yes • Yes	 • Yes • Yes • Yes
AUTO Mode Functionality: • When out of van and ramp • When van powered off • When ramp powered off	 • Yes • No • No	 • Yes • Yes • Yes
Contactor Engaged LED	Yes	Yes

The simplified contactor circuit shown in Figure 19 has decreased considerably in size and is more robust than the previous design.

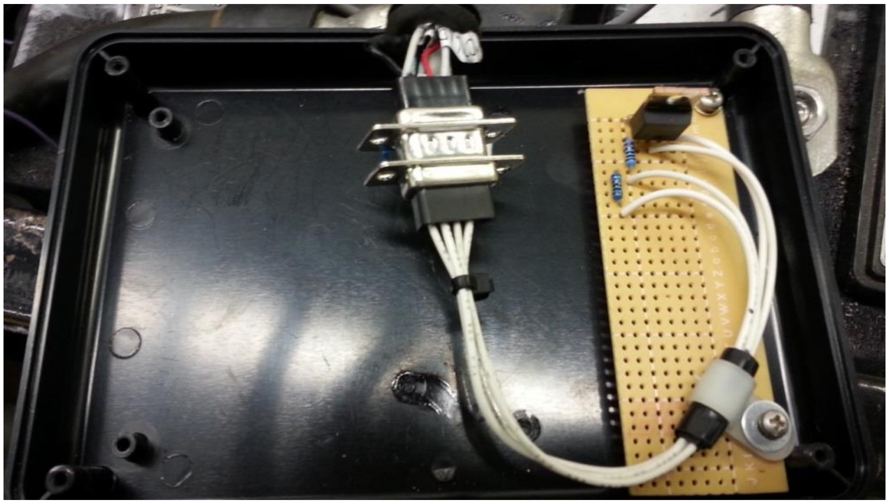


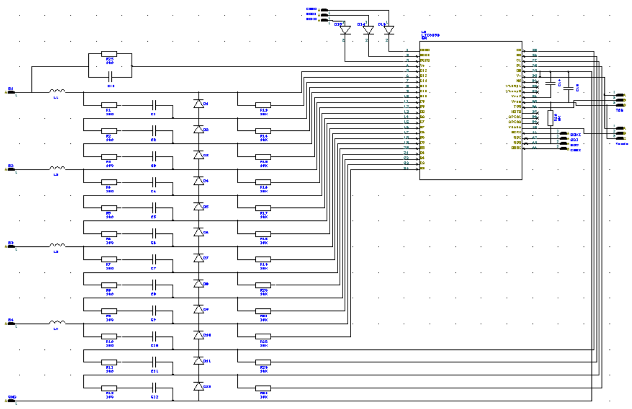
Figure 19: Simplified contactor circuit implemented

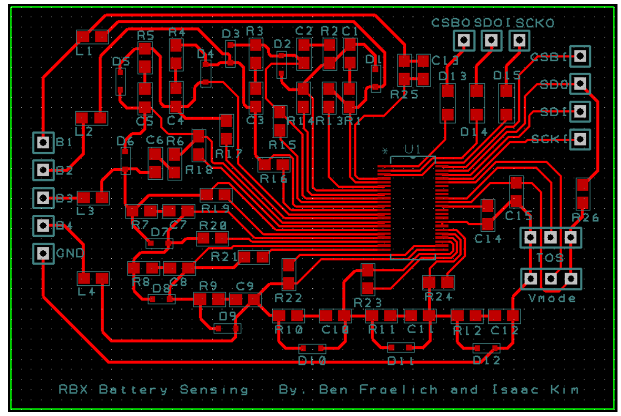
Battery Management Circuit Implementation

The LTC6803 demo board shown in Figure 20 allowed us to get our code working properly, but does not work with our RBX system, which currently uses lead acid batteries instead of batteries with individual cells, such as lithium ion or NiMH.

Figure 20: LTC6803-3 Demo Board (DC1653A)

Since our system uses lead-acid batteries, we had to use different circuitry mentioned in the Battery Sensing Design section.





The battery monitoring circuit was design on a printed circuit board by inputting the desired circuit in schematic form and then using the software to set up the layout as desired. We were able to place all the traces on one side of a two layer board and set up the holes for input/output terminal blocks. All components are surface mount and have been soldered onto the printed circuit board as seen in Figure 21.

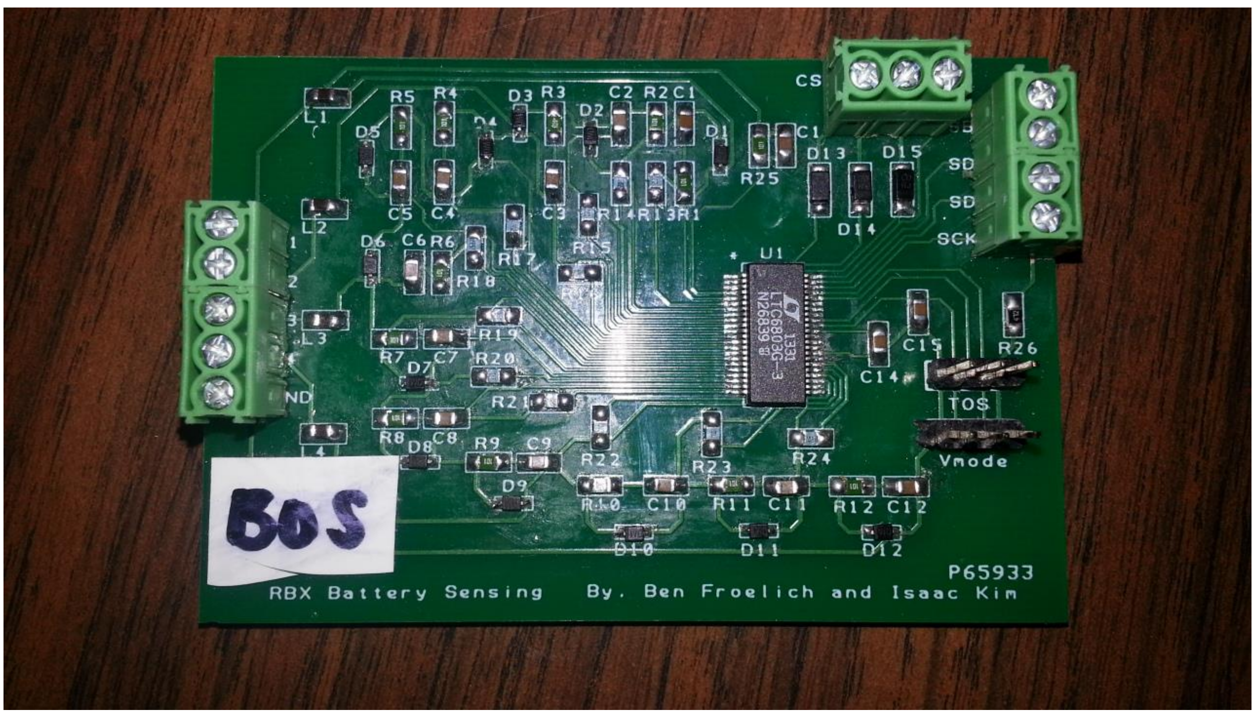


Figure 21: Battery Sensing Circuit with all components, output terminal blocks and jumper leads to set mode.

Most of the components on the circuit board are for IC protection. The output terminal blocks connect the boards to batteries and data lines. Header pins on the TOS and Vmode pins configure the LTC6803 as bottom of stack, top of stack, or middle of stack. This configuration is necessary for SPI communication between several LTC6803's and the microcontroller. Board configurations for each position in the stack are summarized in Table 5.

Table 5: Battery monitoring board configurations

Board Position	Communication Diodes (D13-D15)	SDO Pull-up Resistor (R26)	Jumpers
Bottom of Stack	Yes	Yes	TOS VMODE
Middle of Stack	Yes	No	TOS VMODE
Top of Stack	Optional	No	TOS VMODE

During the testing of the sensing system with the RBX charging system, which has been implemented by Adam Morris, the contactor was set in the "OFF" setting via the contactor manual key switch. We assumed that this would prevent the chargers from engaging. However, because the voltage sensing system bypassed the contactor, the chargers turned on during the exchange and the aftermath is shown in Figure 22.

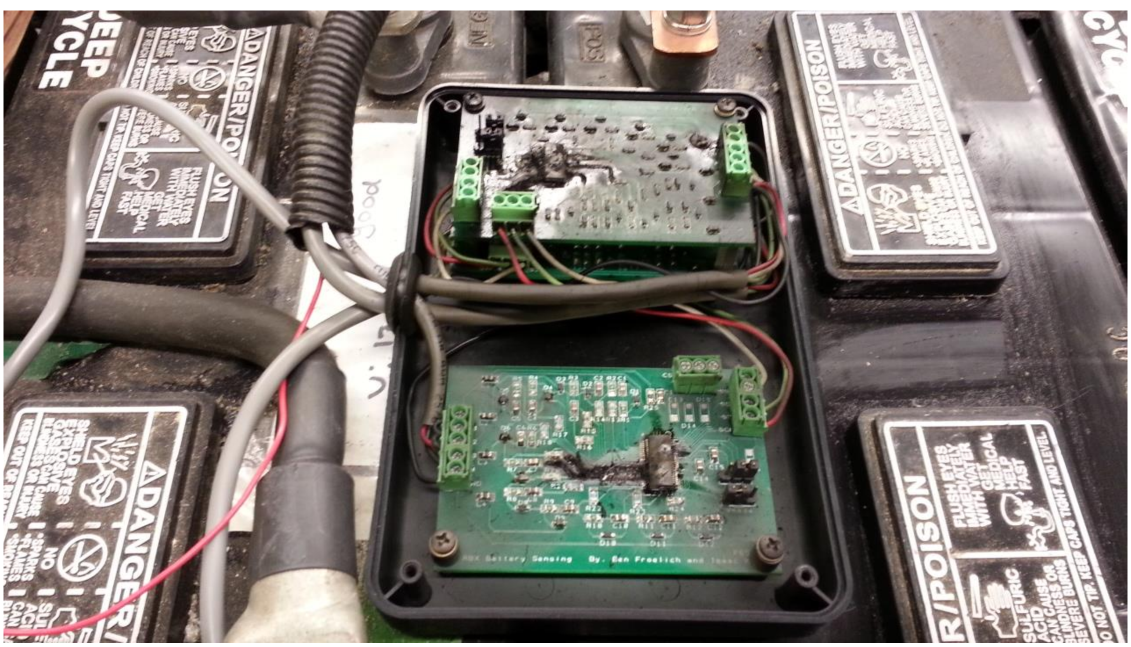


Figure 22: Aftermath of combined implementation of charger and battery sensing system

The sensing circuit created a path for the voltage to be seen at the charging terminals even with the battery pack contactor in the "OFF" state. Because the charger turns on/off depending on the voltage read across the charging terminals, it thought that the battery pack was engaged. Since the contactor was actually disengaged, the only path for the charger to take was through the sensing paths. Applying large voltages to the sensing system proved to be catastrophic. The expensive lesson learned is that even if the senior projects are separated, if working on the same system, it is necessary to have design meetings between the two teams to know the nuances of each other's systems to prevent mistakes such as this.

Luckily, two sensing systems were made for the two battery packs, so we still have one working system, shown in Figure 23 and Figure 24.

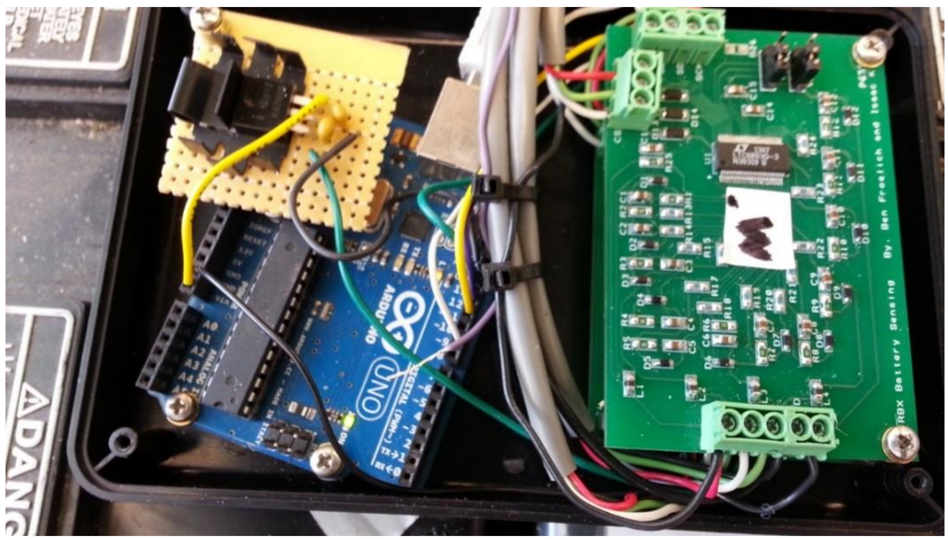


Figure 23: Arduino UNO microcontroller and two battery sensing boards reading batteries 1-8.

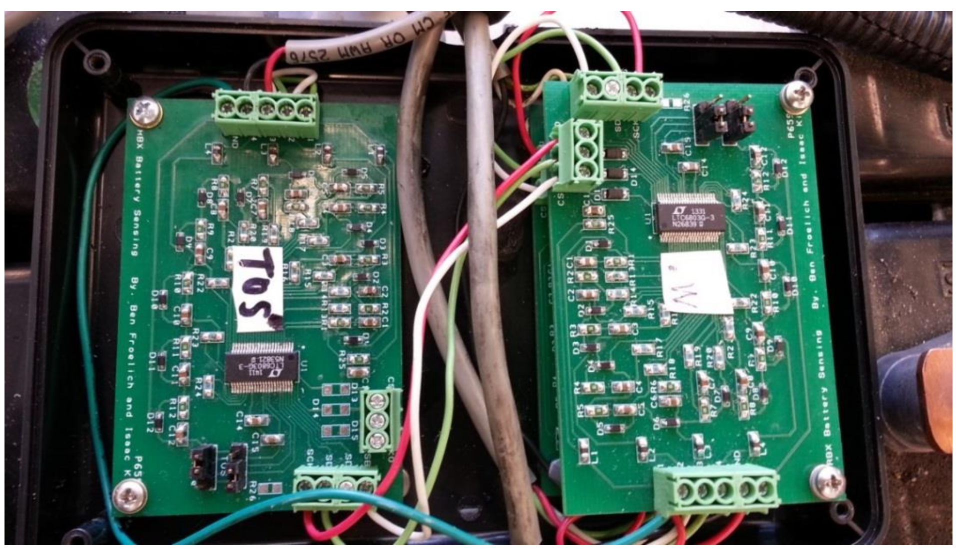


Figure 24: Three battery sensing boards reading batteries 9-18.

The leads coming out of the boards connect to either batteries or are used for SPI communication between boards. The board-to-battery connections are shown in Figure 25. The terminal interface reading from the Arduino UNO is shown in Figure 26.

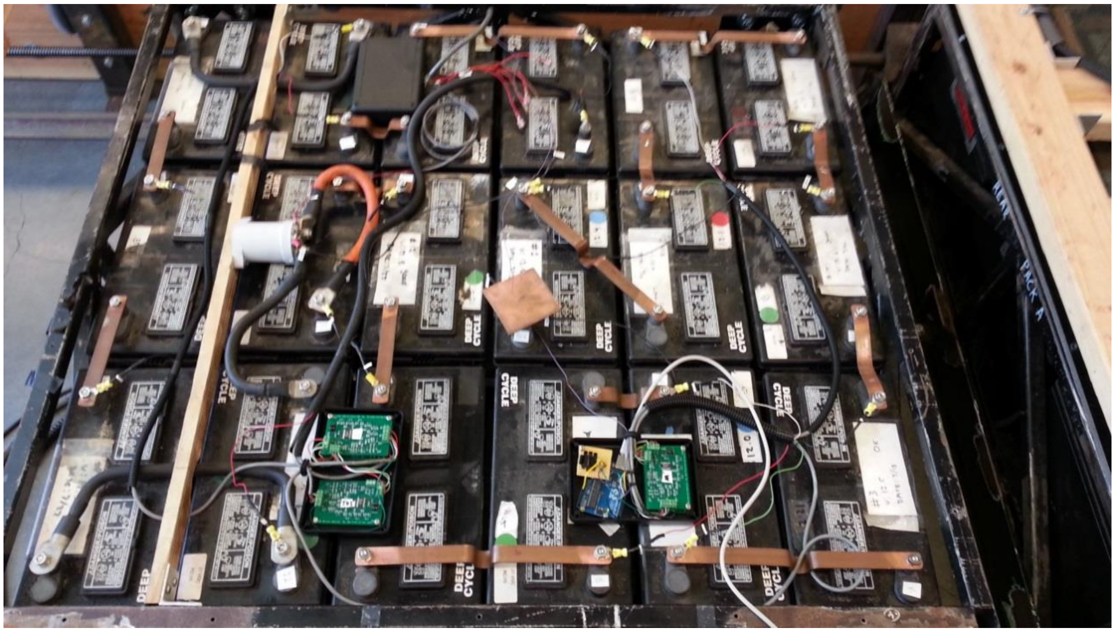


Figure 25: Battery sensing boards connected to each individual battery in the battery pack.

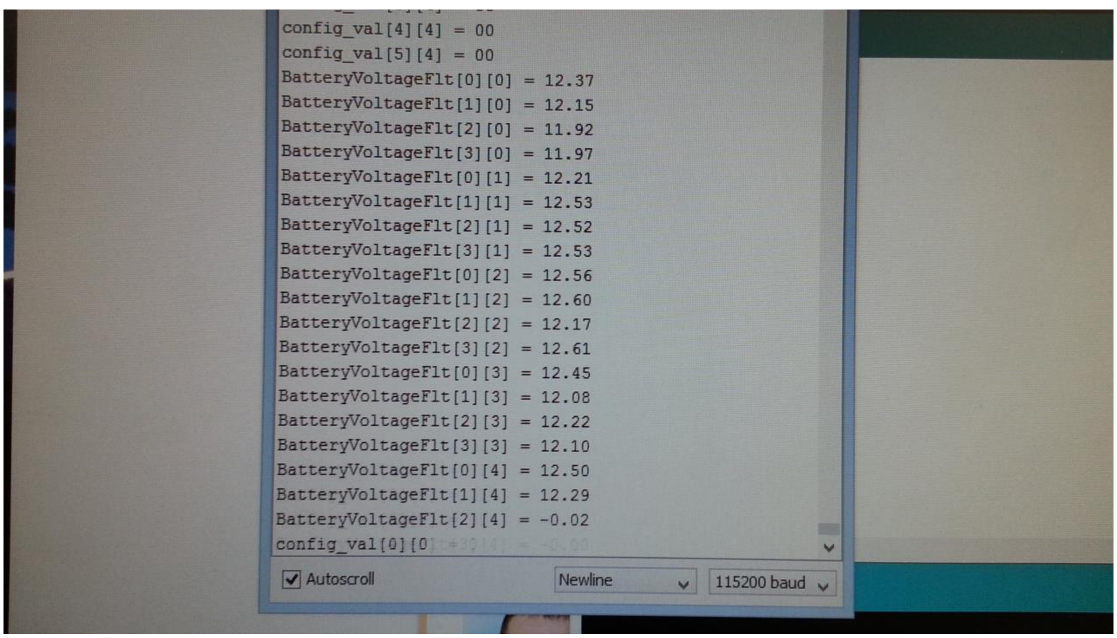


Figure 26: Voltage reading of each battery from the Arduino UNO on terminal.

The bottom two voltage readings shows 0V because they have been shorted because the top two battery sensing pins were not necessary.

Contactor Plate Implementation

The contactor plates on top of the battery packs are made from fiberglass plating which we formed over a mold shown in Figure 27 and Figure 28. These are necessary because of the size of the contactor requires extra space inside the battery pack.

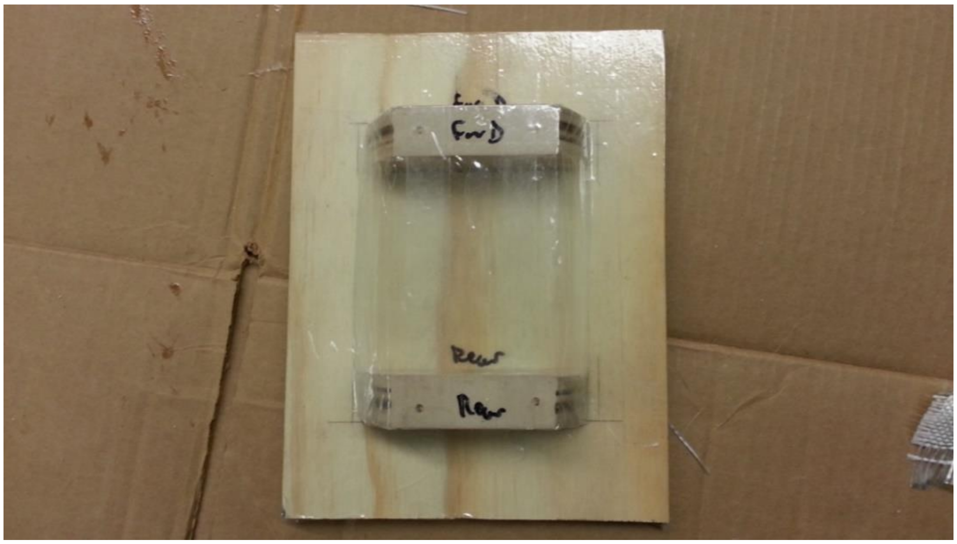


Figure 27: Contactor Plate mold

The contactor plate mold is covered in packaging tape for easy removal of the fiberglass/resin after the plate dries. The mold plate was made after measuring the amount of space needed along with how much extra room was remaining under the van. The pieces are cut from wood and screwed together.

Figure 28: Contactor Plate made with Fiberglass cloth

The mold was then covered with polyurethane resin and fiberglass cloth. Four layers were applied for thickness, strength and stability.

Figure 29: Contactor Plate sanded down and spray painted black.

As shown in Figure 29, the fiberglass was covered with a layer of body filler and sanded down until the surface is smooth. Then the plate was covered with several coats of black spray paint. The cover is shown installed in Figure 30.

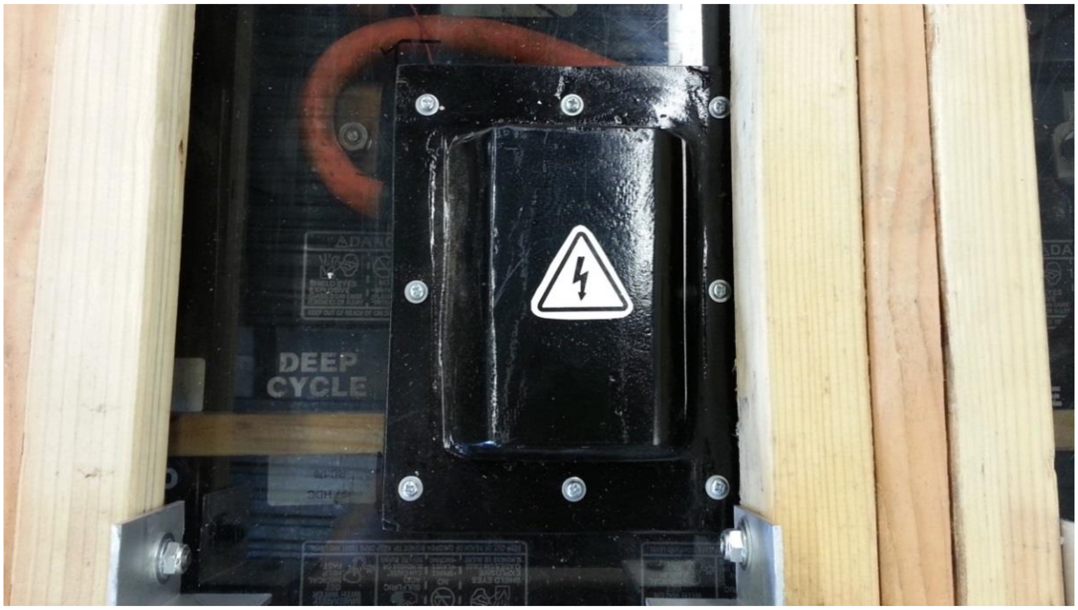


Figure 30: Completed Contactor Plate connected to the battery pack cover with high voltage symbol.

Battery Pack Status and Manual Control Plate Implementation

The battery pack status and control plate is shown in Figure 31. The panel allows manual control and status update of the contactor position and battery health. LED's indicate the contactor state and the battery pack health.

The plate mounts to the side of the battery pack, with all controls and indicators facing toward the back of the pack. This prevents the protruding components from catching on the ramp or van, and reduces the chance of debris damaging them. The housings were fabricated using galvanized steel sheet.

Figure 31: Battery pack status and manual control panel

The control panel also contains the key switch which allows for manual control of the battery pack. The three states are manual on, manual off, and auto. This allows for safer maintenance and testing.

RBX Safety and Sensing Video Links

- Rapid Battery Exchange video
- RBX Safety portion operation video
- RBX Sensing portion operation video

Next Steps

- Implement an isolated DC/DC topology instead of using a linear regulator to solve the ground noise problem. This will allow usage of a microcontroller and XBee module in the contactor circuit, as detailed in "Isolated DC/DC Converter Topology."
    - Reimplementation of the contactor circuit code, microcontrollers, and XBee radios.
- Modify the contactor cables and battery pack so that the contactor switches between ground on the bottom of stack battery and the ground copper contact pad, detailed below in "Battery Sensing Contactor Position Implementation."
- Get battery voltages from the microcontroller and display them on a viewing device, such as a terminal display. The pack control panel currently has an LED that can be used to indicate pack health. The LED should be connected to PIN 7 of the microcontroller. The code will illuminate the LED only if all batteries are above a threshold voltage (defaulted to 10V).

Isolated DC/DC Converter Topology

Isolated DC to DC converter will be necessary to get the smart contactor circuit working without the problem of the negative terminal of the battery pack connecting to the ground of the ramp and giving up noise that disrupts and resets the microcontroller in the battery pack.

There are several different isolated topologies such as Flyback, Push-Pull, and Forward converters. I would suggest Single-Switch Forward for its efficiency. This topology is more complex than the flyback, which has a smaller component count, but is not as lossy.

A typical application of a Single-switch forward converter is shown in Figure 32 below.

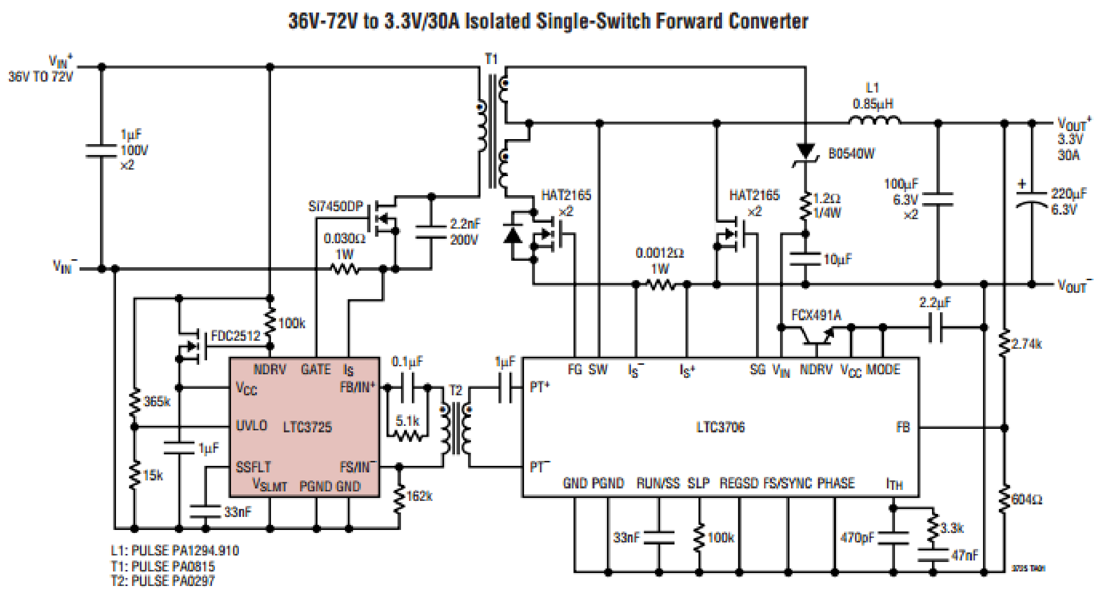


Figure 32: Typical Application for LTC3725 Single-Switch Forward DC/DC Converter

Implementing this type of DC/DC converter will separate the grounds of the smart contactor circuit from the negative battery terminal and the charger ground. Hence preventing the ground noise from affecting the microcontroller and the reset problem.

Sizing components and implementing such a system will require in depth study of the datasheet of the chosen DC/DC converter chip and bench testing. If there are any questions on the implementation, consult Professor Taufik (Power Electronics professor).

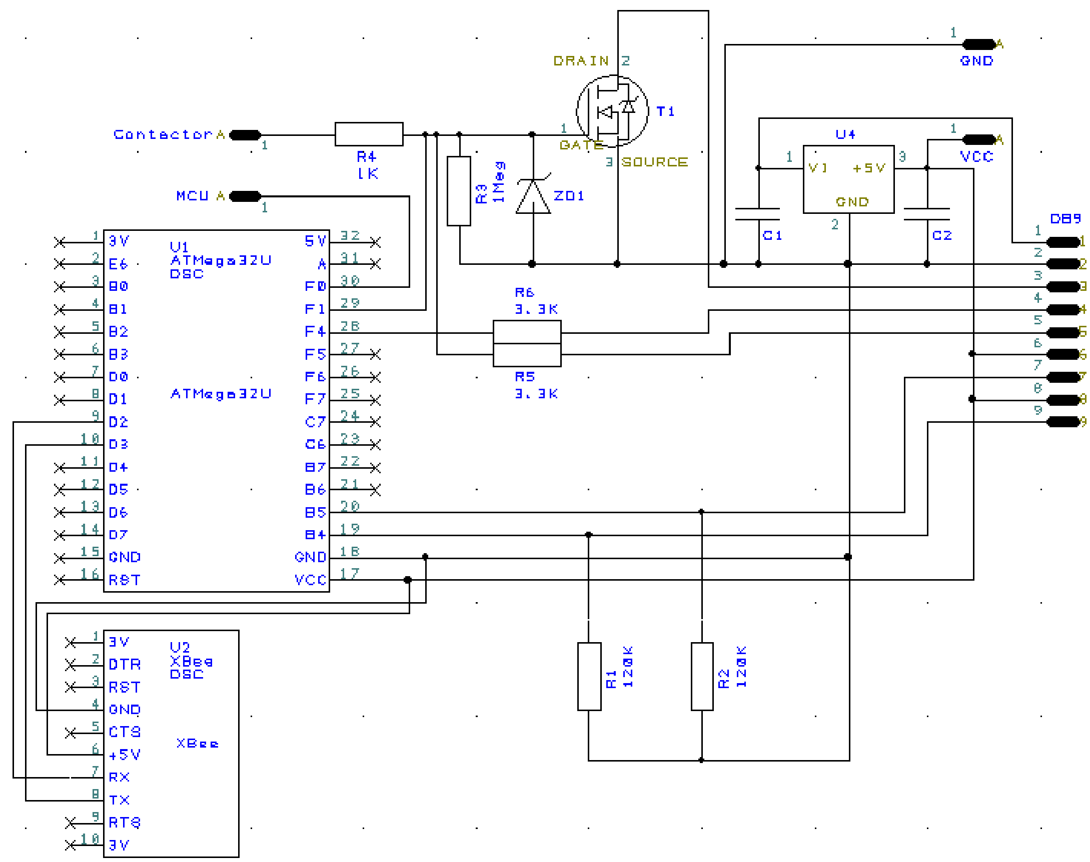


Figure 33: Schematic of Smart Contactor Circuitry with U4 linear regulator

The schematic in Figure 33 shows the current state of the smart contactor circuitry. The linear regulator shown on the schematic as U4 needs to be replaced with the isolated DC/DC topology shown above in Figure 32.

Battery Sensing Contactor Position Implementation

Future members can modify RBX Battery Pack B to enable the BMS system to monitor battery voltages. The design changes are outlined below and shown in Figure 34 and Figure 35.

1. Rotate the bottom of stack battery 180 degrees, as shown in the Figures.
2. Fabricate battery cables:
    a. Two cables to reach the new terminal locations from the contactor, shown in red in the second Figure.
    b. One cable to connect the positive terminal of the bottom of stack battery to the negative terminal of the next battery in the stack.
    c. One cable to connect the two terminals that were connected with the contactor before.
3. Fabricate a mount to support the negative battery pack terminal, which is no longer supported by the negative battery terminal.

4. Reinstall the BMS system: Connect all sense wires to their correct batteries, starting from 0V -> 216V. Battery terminals and sense wires have matching labels. Test by connecting the microcontroller to a USB port and monitoring the serial port, which is set to 115200 baud.

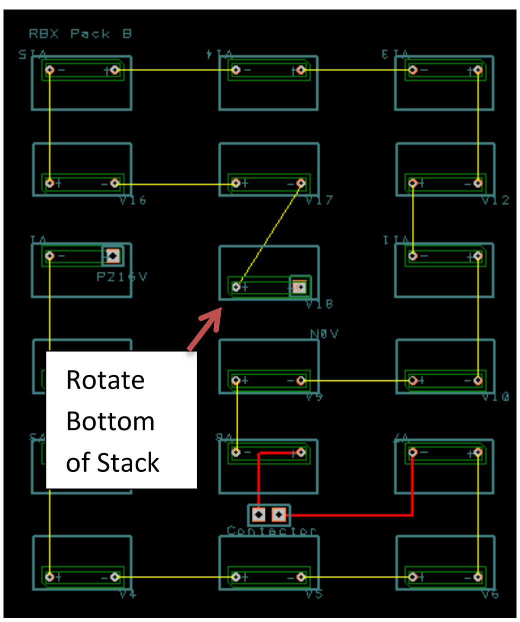


Figure 34: Current Battery Pack B

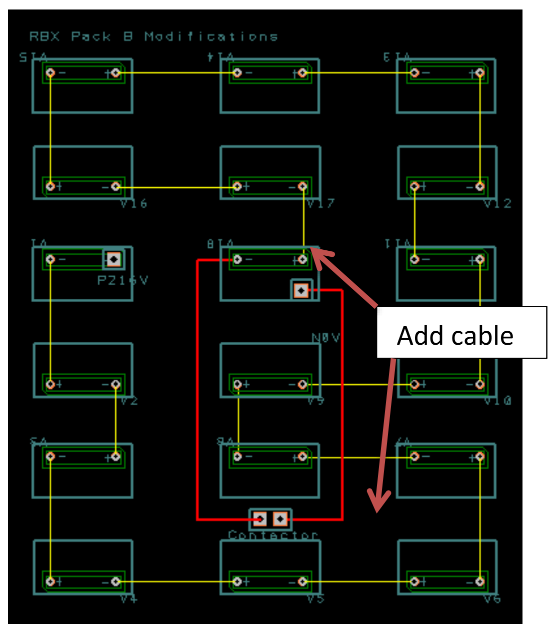


Figure 35: Battery Pack B with Modification

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Gantt Chart and Cost Estimate

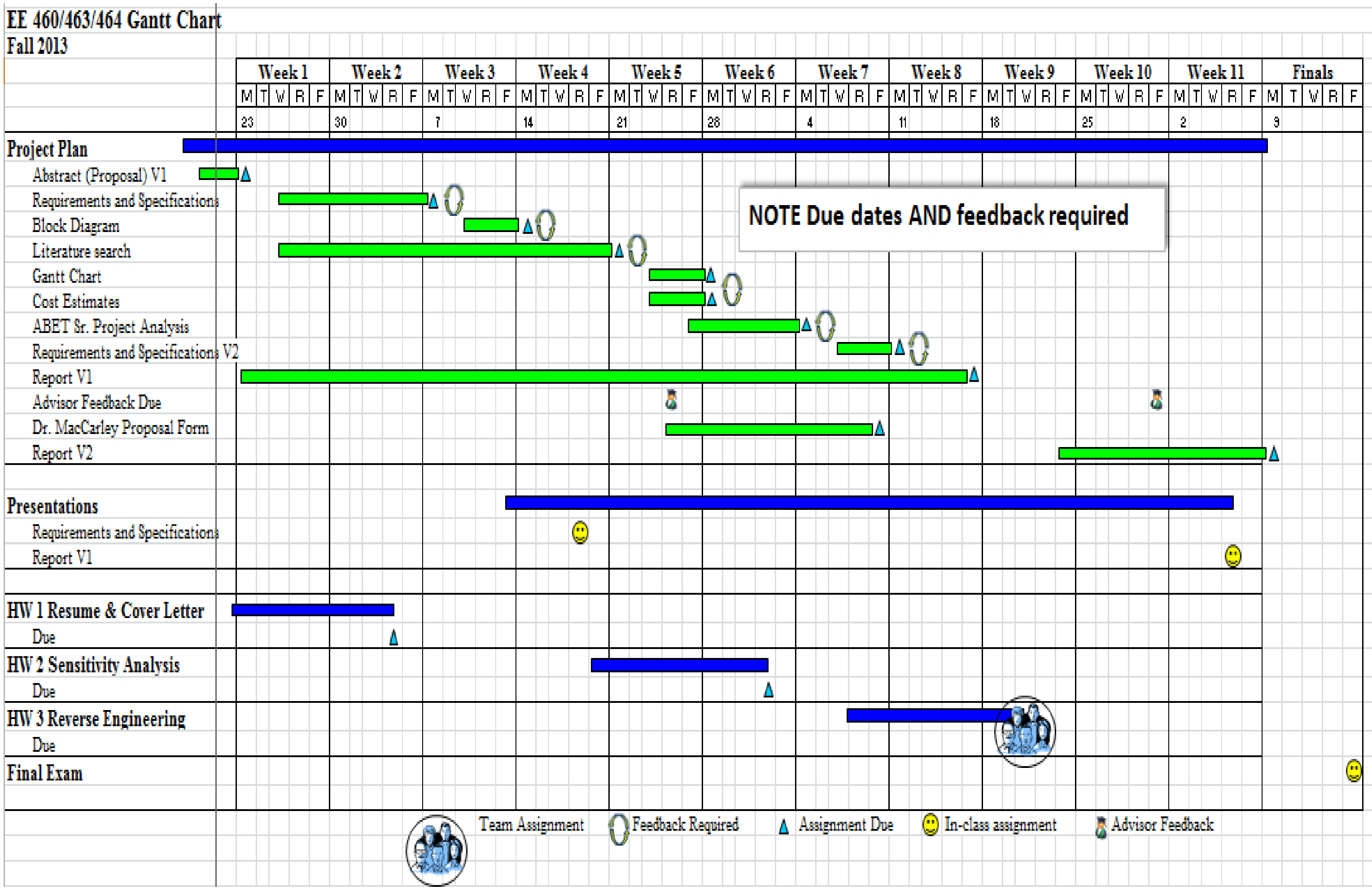

Figure 36: Fall Quarter Senior Project Plan Gantt Chart

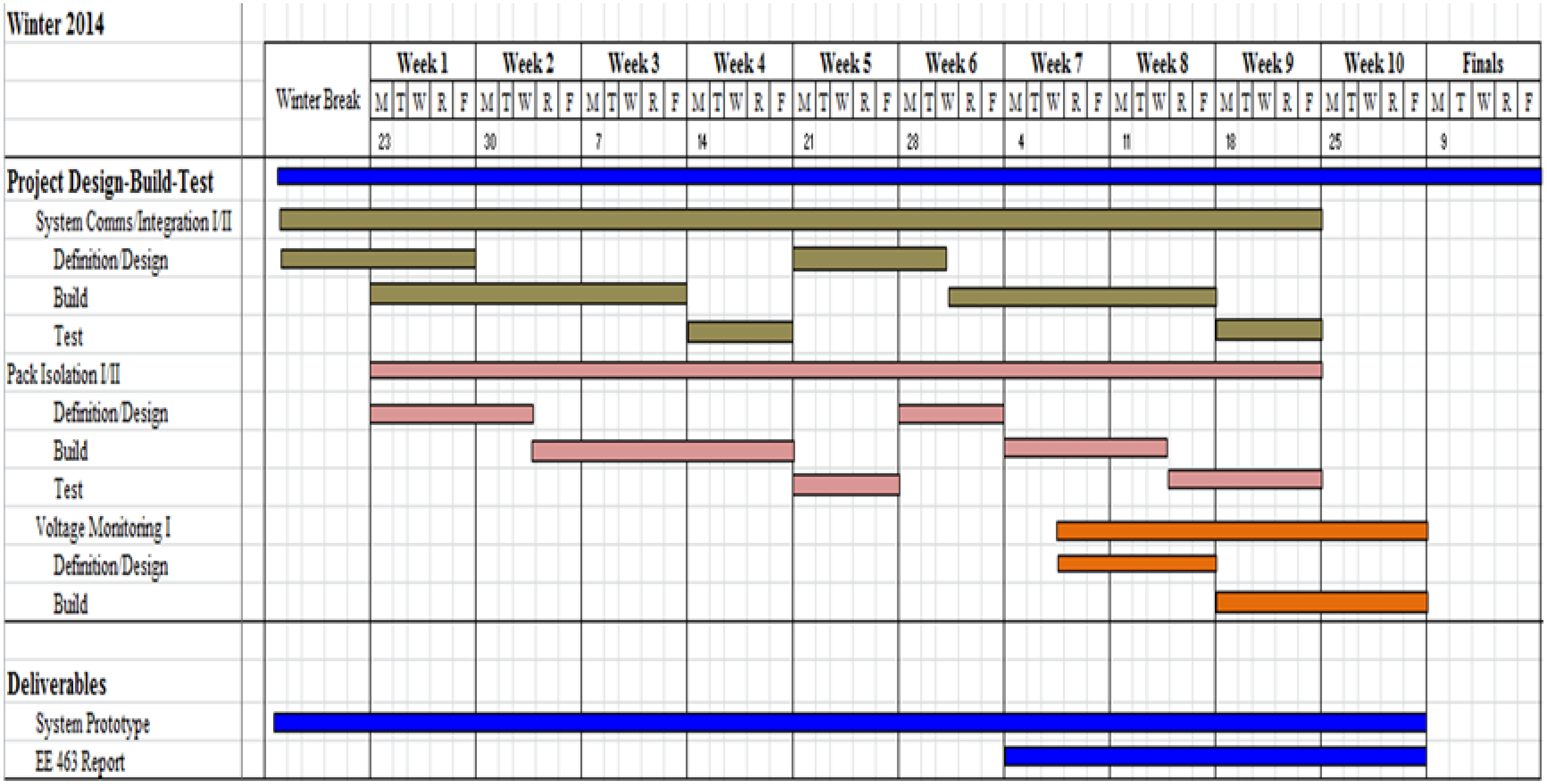

Figure 37: Winter Quarter Senior Project Gantt Chart

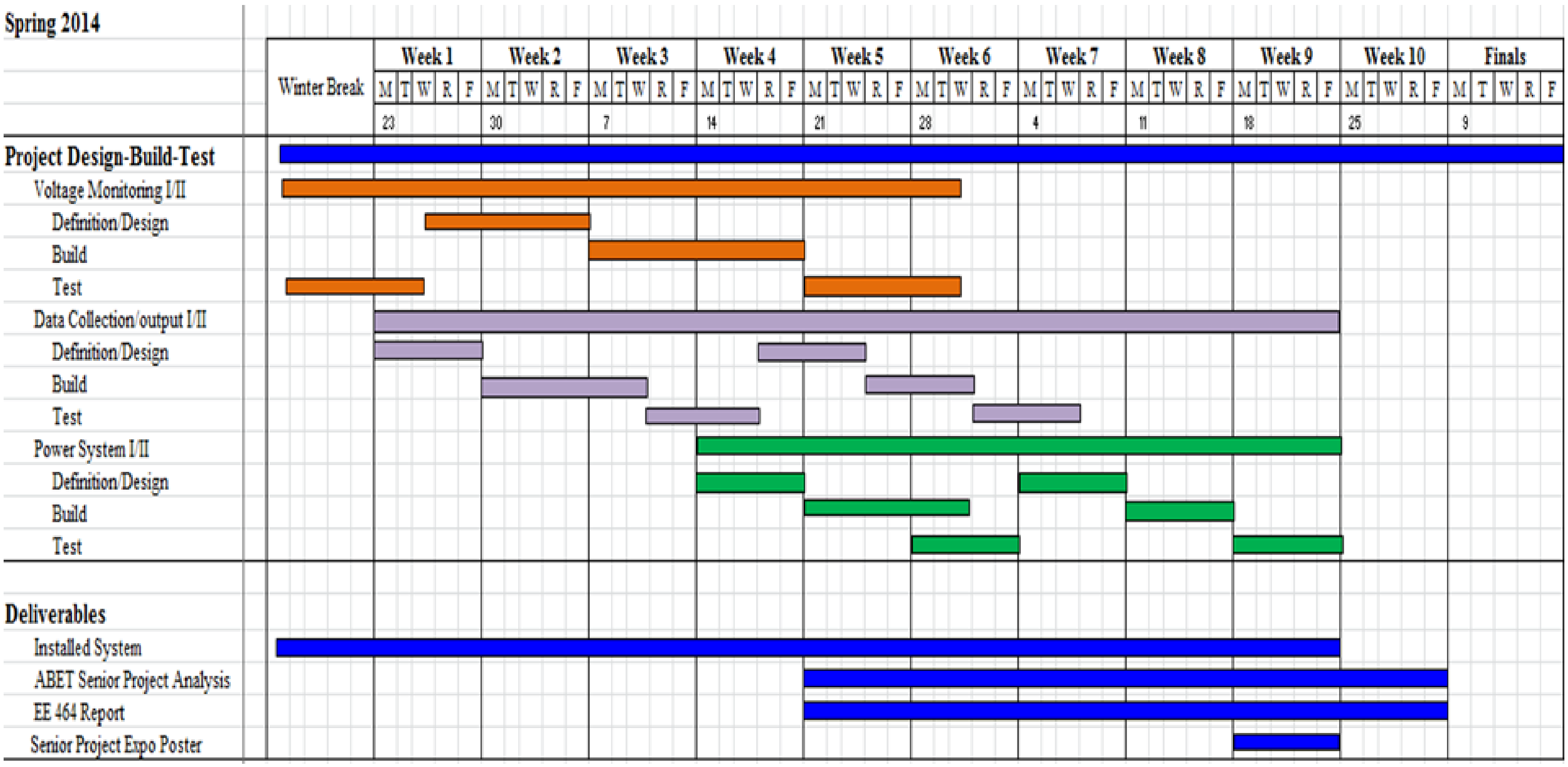

Figure 38: Spring Quarter Senior Project Gantt Chart

Cost Estimate

The cost estimate shown in Table 6 below includes all of the necessary parts required to build the system. Donations have not been accounted for. Free parts will make the end cost significantly lower.

Table 6: Cost Estimate Per Unit

Item	Description	Quantity	Individual Cost	Total Cost
High Current Contactor	Contactor able to handle approx. 500A	2	$110	$220
Wire Spool (Red and Black)	Connect Components	2	$10	$20
ATMega32U Microcontroller	Controls signals and communication	2	$15	$30
LTC6803-3	Battery Management Chip for voltage readings	10	$20	$200
XBee Communication Module	RF communication modules for packs	2	$33	$66
Printed Circuit Board	Circuit board to mount BMS chip and components	10	$30	$300
Passive Components	Resistors, Inductors, Capacitors, Diodes, etc.	1	$40	$40
			Total Parts Cost	$876

Some of our donated parts include the contactors, 9 LTC6803-3 BMS chips and a breakout board for testing the BMS chips.

Bill of Materials

Model Number	Description	Quantity	Individual Cost	Total Cost
LEV200A6NAA	Kilovac DC Contactor	2	Free	$0.00
LTC6803IG-3#PBF	Battery Management Chip	10	$13.86	$138.60
ATMega32U	Microcontroller controls signals and communication	2	$15	$30.00
Arduino UNO	Controls battery sensing	2	$25	$50.00
XBee Communication Module	RF communication modules for packs	2	$33	$66.00
Printed Circuit Board + tax and shipping	Circuit board to mount BMS chip and components	20	$10.30/ea +$22.33	$228.33
TSSOP-48 to DIP-48 SMT Adapter	Breakout board to implement surface mount chip to breadboard for testing	1	$7.39	$7.39
MCP1700-3302E	IC Voltage Regulator LDO 3.3V	4	$0.44	$1.76
RFD14N05L-ND	MOSFET N-CH 50V 14A	4	$0.81	$3.24
1N5919BGOS-ND	Diode Zener 5.6V 3W Axial	4	$0.43	$1.72
374-1210-1-ND	Sensor Reed SPST	5	$1.11	$5.55
377-2047-ND	BOX 6.02”x4.01”x1.50” enclosure	6	$8.50	$51.00
A1922-ND	4 Pin Connector (female)	5	$0.20	$1.00
A30980-ND	4 Pin Connector (male)	5	$0.19	$0.95
B82X0	1/2”x1/8”x1” Magnet blocks	10	$2.32	$23.20
660-SG73S2ATTD101J	100 Ohm SM Resistor	180	$0.058	$10.44
660-RK73H2ATTD1002F	10k Ohm SM Resistor	165	$0.008	$1.32
611-Y100AA2C203NQE	C&K Keylock Switches	2	$15.33	$30.66
651-1984617	2 Pos Terminal Block	45	$0.368	$16.56
651-1984620	3 Pos Terminal Block	30	$0.546	$16.38
80-C0805C105Z4VACTU	1uF SM Ceramic Capacitor	30	$0.032	$0.96
77-VJ0805V104MXBPBC	0.1uF SM Ceramic Capacitor	15	$0.060	$0.90
660-RK73B2ATTD472J	4.7k Ohm SM Resistor	5	$0.080	$0.40
78-BZX384C7V5-E3-08	5.6V Zener Diode	165	$0.038	$6.27
77-VJ0805V475MXQTBC	4.7uF SM Ceramic Capacitor	165	$0.040	$6.60
963-LBR2012T100K	100uF SM Inductor	60	$0.079	$4.74
78-RS07J	Vishay diode	35	$0.170	$5.95
358-R9-104L-12-G	LED Panel Mount Indicator	6	$1.940	$11.64
			Total Parts Cost	$721.56

*Note: This Bill of Materials is for the complete implementation of the project. Not individual costs. Most unused components and miscellaneous items (solder, electrical tape, etc) have not been included.

Appendix A – ABET Senior Project Analysis

Project Title: RBX Battery Safety and Sensing

Student's Name:	Isaac Kim Ben Froelich
Advisor's Name:	Art MacCarley

1. Summary of Functional Requirements

The Rapid Battery Exchange system replaces and charges battery packs in an electric shuttle van. When the battery pack in the van becomes drained, the van drives onto an exchange ramp, which removes the dead battery pack and replaces it with a charged one. The van continues operation while the ramp changes the dead battery pack. This system allows almost continuous operation of the van, eliminating battery charge wait time.

The RBX Battery Safety and Sensing system disconnects the battery inside the pack when not in use inside the electric van or being charged by the battery chargers. The mechanism makes a 216 Volt battery docile to the environment as it breaks the circuit inside the battery pack. The battery pack also comes with a sensing feature which measures the voltage of each battery within the battery pack and outputs the voltage levels to a terminal.

2. Primary Constraints

The biggest limiting factor which impacts the approach to the project is the cost of an industrial grade contactor able to handle approximately 500 Amperes supplied by 18 lead-acid car batteries. This one part can cost several hundred dollars which is more than the budget for senior projects. This may lead us to attempt to build a contactor from scratch which will make the scope of the project more into mechanical work which we would like to avoid if possible.

Another specification that may cause problems is converting a 216 Volt source into approximately 3.3 Volts while keeping power efficiency loss to a minimum. Ideally, buying a part from TI or another semi-conductor company will make the circuit small but if this option turns out to be too costly, we will build a buck regulator using a power diode and inductor rated to handle the desired output voltage.

The current RBX ramp and van communicate using XBee radios (IEEE 802.15.4). The battery pack must also communicate over this protocol. Implementing a 3-point network could prove difficult. In addition, the battery pack frame leaves limited space for the contactor and circuitry, which must fit inside of the pack. Logging data requires external memory and an organization system, which may be difficult to implement, especially indexing data points by date and time.

3. Economic

The project components use human and financial capital by employing corporations and individuals in the manufacturing, vending, and shipping processes. These benefits accrue from the time of purchase through delivery. The components also constitute manufactured capital, which uses natural capital, such as silicon and metals. These impacts occur when the components are manufactured. The list below breaks down manufacturing and operating costs. Table 5 contains the calculations that yielded a manufacturing cost of $257 per battery pack.

- Human Capital
    - Two workers per battery pack at $20 per worker.
    - $40 per battery pack
- Financial Capital
    - Contactor - $130 per battery pack
    - Voltage sensors (18) - $1 per battery → $18 per battery pack
    - Circuitry (PCB printed offsite) - $0.25 per battery pack
    - Buck regulator - $1 per battery pack
    - TI MSP430 Microcontroller (2) - $22
    - Total Financial Capital - $171.25
- Manufactured or Real Capital
    - Solder stations - $2,000
    - Circuit Testing Machines - $10,000
    - Wire Spool - $20
    - Total Real Capital - $12,000
- Natural Capital
    - Electricity Bill - $500 per month

TABLE 5

COST ESTIMATE PER UNIT

Item	Description	Quantity	Individual Cost	Total Cost
High Current Contactor	Contactor able to handle approx. 500A	1	$150	$150
Wire Spool (Red and Black)	Connect Components	2	$10	$20
TI MSP430 Microcontroller	Controls signals and communication	2	$11	$22
Voltage Regulator (3.3V)	Drop source voltage to 3.3V	5	$1	$5
Voltage Sensors	Measure voltage	20	$1	$20
Multiplexor	Outputs desired voltage	2	$2	$4
			Total Parts Cost	$221
Labor	$20/hr * 3 laborers (1 hrs)	1	$20	$60
			Total Cost	$281

The development cost is highest in the beginning when purchasing parts for the project, but as the project continues, additional unforeseen parts are required. The cost of the parts obtained later in the project lifetime should be less than the beginning cost because the project is built around the main expensive parts.

The manufacturing cost is highest in the beginning also, since the machines and labor needed to produce the part will be a major cost but eventually sales will offset the non-recurring costs to produce profit for the company.

The experiment requires labor to solder components. Mechanical manipulation of the circuit housing is also necessary.

The original estimated cost of component parts is approximately $170. For the prototype, we will build the contactor circuitry on prototyping board rather than manufacturing a PCB.

Most of the cost will be paid by the school's senior project budget and remaining cost will be taken from the EVEC (Electric Vehicle Engineering Club) funds.

The RBX Battery Safety and Sensing will profit $150 per battery pack selling the product at $300 and electric vehicle companies will benefit from its battery sensing capabilities while consumers and mechanics will benefit from the safety features.

The estimated development time is 6 months, starting from January through May.

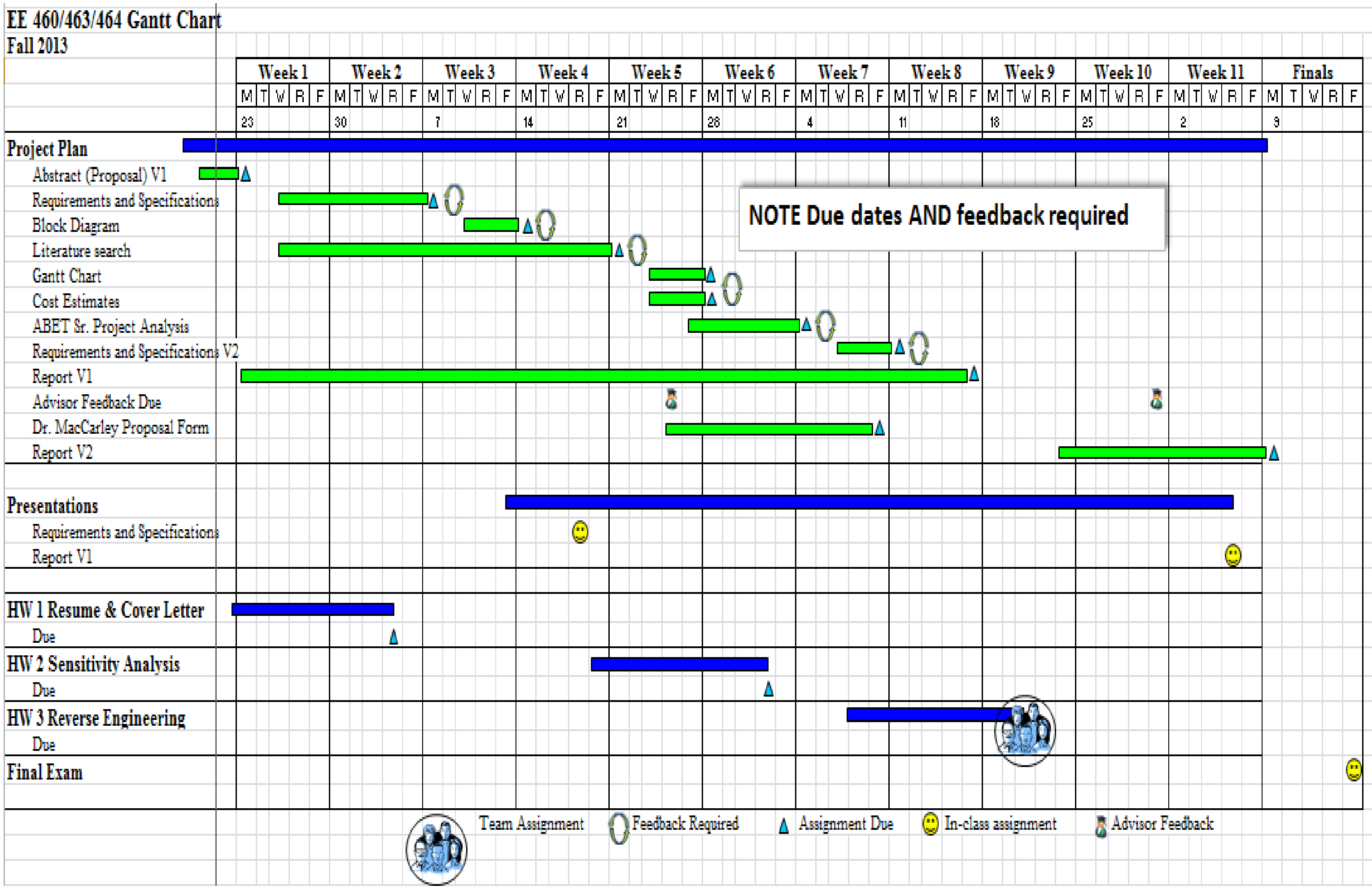

Figure 39: Fall Quarter Senior Project Plan Gantt Chart

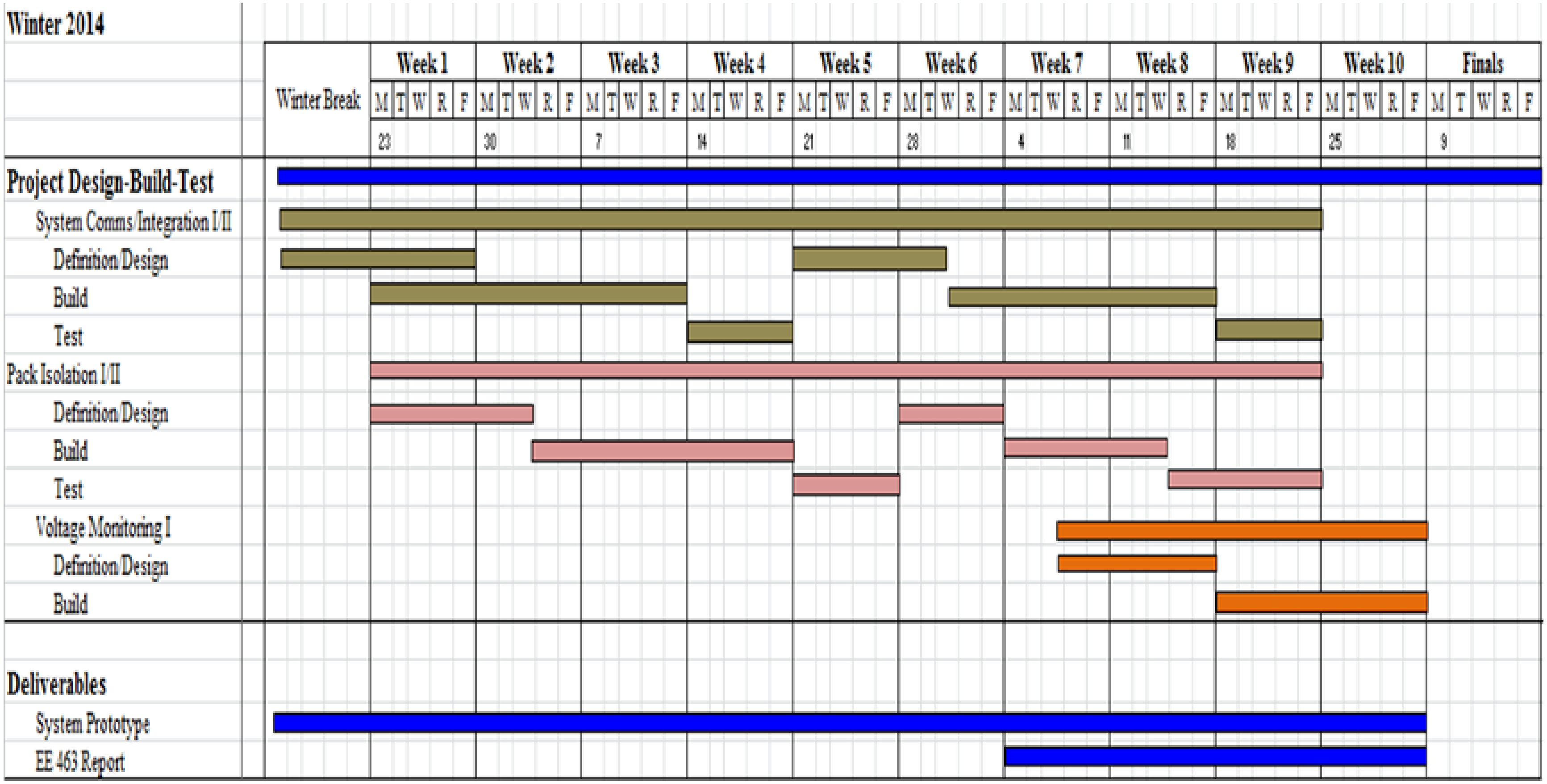

Figure 40: Winter Quarter Senior Project Gantt Chart

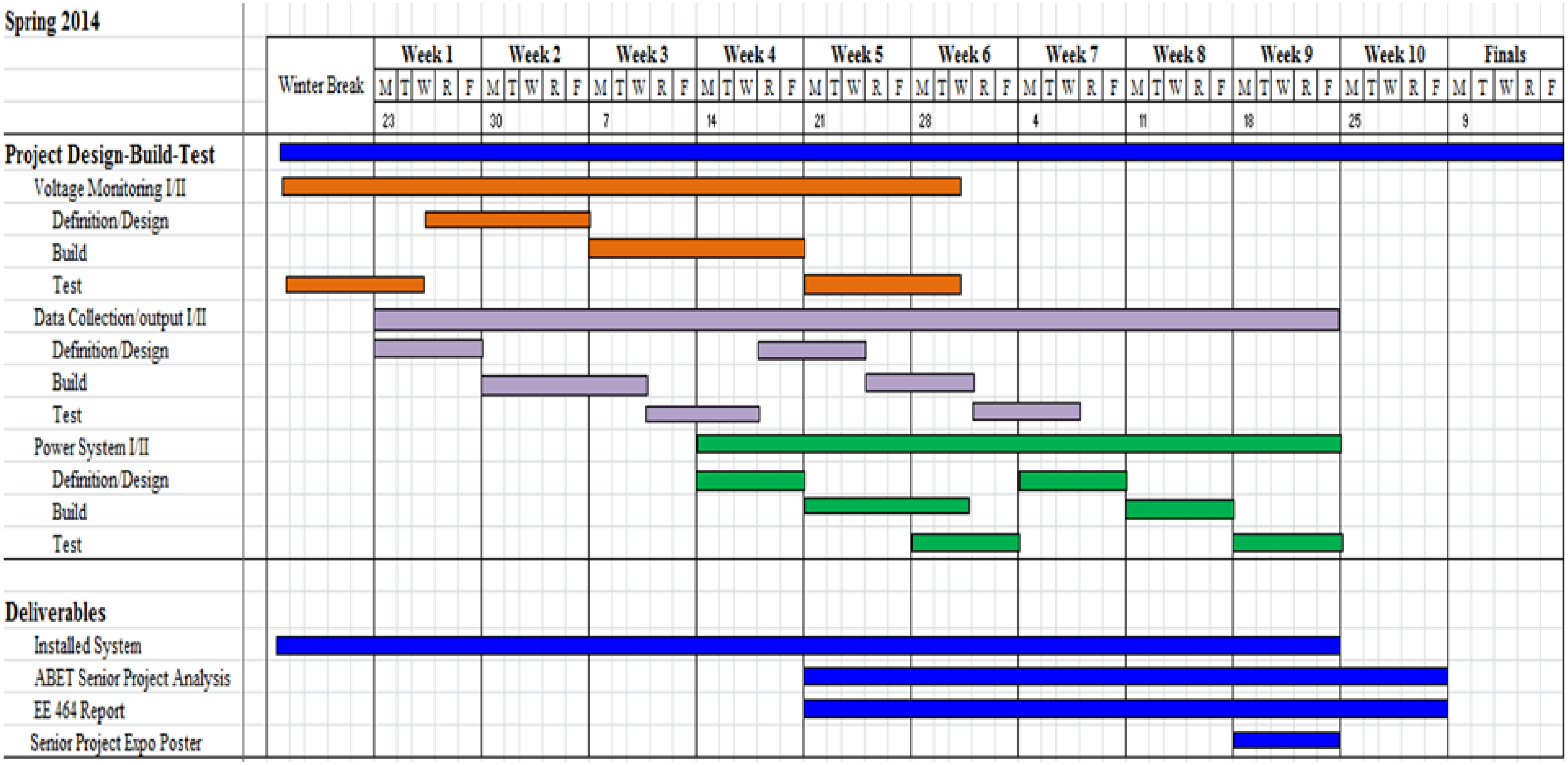

Figure 41: Spring Quarter Senior Project Gantt Chart

4. If manufactured on a commercial basis:

8,127 electric vehicles were sold in the US in September 2013 [21]. This corresponds to approximately 97,000 vehicles annually. If 25% of vehicles opt for this battery pack system (2 packs per vehicle), and the product obtains a 10% market share, ~4,850 battery packs would sell per year.

Manufacturing cost

- $281 per device

Purchase price

- $650 per device

Profit per year

- 4,850 * ($650 – $281)
- $1.05 million per year

5. Environmental

Electric machines used in manufacturing consume power. This will create environmental impact differing depending on the type of power plant being used. If coal, the environment will suffer more pollution than nuclear, hydro or wind based plants.

Directly, toxic battery acids and chemicals in electronics can damage ecosystems. Indirectly, the usage of electricity can lead to construction of more power plants which will affect environments with industrialization and pollution. Many animals may lose their homes.

The production of the RBX Battery Safety and Sensing improves battery disposal as the battery management will keep batteries running longer and properly which increases the lifespan. This positively effects the environment by reducing chemical waste.

6. Manufacturability

A few challenges in manufacturing this product include:

- The distribution of both hardware and software since the software for checking battery status is also produced.
- Implementing a streamlined process of connecting the contactors since they are fairly large and must fit inside the battery pack.
- Implementing a solder system for the PCB and peripheral components.

7. Sustainability

The RBX Battery Safety and Sensing device needs routine maintenance to keep the system from corroding and losing conductivity. Since the system is made of several electrical components, the connector to the terminal must be kept tidy to keep the connections intact and free from folding and stretching. The wireless safety system may also require maintenance because there must be reliable communication between the XBee radio modules.

This project makes the electric G-Van battery packs safer and more efficient. The system monitors each of the 18 batteries in the battery pack to assure that each battery is balanced charge and one is not depleting faster than another. This will be sensed via voltage readings on each battery. This data is fed into a control system which will keep the battery depletion on each cell consistent. This allows batteries to be monitored and maintained so they last longer.

Some challenges that may arise while making upgrades to the project are the mechanical expertise that is needed to create a mechanical contactor. The limited space inside the battery pack may also pose a problem for the mechanical contactor.

8. Ethical

The Rapid Battery Exchange supports the Utilitarian view of ethics because it will bring the greatest good for the greatest number of people. Currently, the world is in a petroleum shortage which is driving up the cost of fuel. Furthermore, the pollution generated by using fossil fuels causes environmental and health problems. These issues affects all species. There must be a change in fuel source to survive, and electricity can be one of the cleanest options. Current electric cars have the critical flaw of having to charge overnight or long hours during the day. To bypass this flaw, the Rapid Battery Exchange will be able to emulate filling up a tank of gasoline for gas cars. It only takes two minutes, and the depleted battery can be charging while the charged battery is being used.

This also enables long trips using electric cars. This has been a major issue with the electric car of today but once battery packs become standardized, gas stations may also hold battery exchange stations for long road trips to be viable. The government might have to step in to standardize the energy source just as they have with gasoline car tanks and nozzles.

IEEE code of ethics states, “to improve the understanding of technology; its appropriate application, and potential consequences.” The RBX improves upon our current automotive technology and make it plausible to make longer trips using electric vehicles. It also states that engineers should “reject bribery in all its forms.” Sadly, bribery is a big issue when it comes to electric cars because of the automotive and gasoline industry. Politicians that have been bribed will try to slow the electric car technology but engineers must rise above their influence.

9. Health and Safety

The battery pack voltage presents a safety risk. When under maintenance and assembly, the 18 batteries in series will be split into two sets of 9 batteries in series, so touching some of the battery leads may have up to 108 Volts across them. Much of the manufacturing concerns come from wiring the batteries in series to put into the battery pack. Connecting each battery to a voltage sensor may cause complications also since batteries are able to supply large amount of current.

10. Social and Political

Many corporations in the automobile and gasoline industry are doing everything within their power to slow the advancement of electric cars. Tesla has been dealing with court cases from the automobile and gasoline industry for many different issues. Until electric vehicles become widely accepted by consumers, the project will not be of much use. Electric vehicles didn't start making a breakthrough until the release of the Tesla Model S which is being sold worldwide.

The RBX project will impact electric vehicle owners directly because they will be able to exchange a dead energy source with a full one just as gasoline cars do when filling up a tank of gas. Indirectly, this Rapid Battery Exchange affects the gasoline and automobile industry since it provides an alternative to what was once a monopoly on motor transportation.

The stakeholders do not all benefit equally because the gasoline industry will lose business as the world slow transitions out of fossil fuel vehicles. The electric companies will win out but will also need to build more power plants to source energy all of the electric cars.

11. Development

Through this project, we learned about many new technologies and improved skills in others:

- PCB Layout
- Fiberglass plate fabrication (contactor plate)
- Metal fabrication and welding (contactor control panel)
- Using a logic analyzer to observe SPI and UART data lines
- Coding software cyclic redundancy check algorithms
- Soldering very narrow pitch surface mount ICs by hand
- Configuring XBee radios
- Embedded C programming
- General fabrication skills
- Systematic circuit troubleshooting
- Using application specific battery management IC's

Many of the sources used are shown below.

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