Electric Scooter Battery Management System

ECE 445 Design Document

Marco Palella, Will Newman, Chris Scheurer
Group 22
TA: David Null
2/27/20

1 Introduction

1.1 Problem and Solution Overview

Electric cars have become massively popular over the last 10+ years. What was seen before as a novel concept or gimmick will soon be seen every time you walk down the street. Other modes of electric transportation have also become popular in recent years, beginning with hoverboards and now with electric skateboards and small scooters. Companies like genZe, Mahindra, and Piaggio Group are breaking into the market, creating Mopeds as inexpensive as $7,300 [1]. Though this device is more popular in Europe and Asia, the market in America is growing. Cities like New York and Washington D.C. are beginning to see a transition into free-use electric scooters as well. Revel and Electrek are two companies mimicking the idea of VeoRide, but instead making mopeds the main use for transportation [2].

This influx of electric scooters means that there will be a demand for systems that regulate the DC battery charging process within these vehicles, along with making sure that a user can obtain diagnostics about this process. Because most electric vehicles use an 18650 lithium-ion battery pack, a system is necessary within it to regulate the charging/discharging process. This is necessary because lithium-ion batteries are fragile, and if too much power is drawn from them too quickly, they have the potential to explode [3]. Damage to batteries can occur from short circuiting, puncturing, overcharging, and overheating. The reason why lithium-ion batteries are more prone to complications is due to “thermal runaway,” a reaction that causes temperature and pressure within the battery to increase much faster than it can be dissipated. This overheating eventually leads to chemical fires, which are difficult to put out, and thermal runaway can also cause the batteries to explode [4].

The goal of this project will be to develop a modular system that has the potential to power a 72V electric scooter, and that can protect battery cells in the system from overcharge, rapid discharge, short circuits, and ensure that an equal charge is being supplied to all batteries in the system. When charging, the system will make sure that no cell exceeds a voltage of ~4.2 V. The 18650 lithium-ion cells we will be using have a maximum/full capacity rated voltage of 4.2 V, so charging them to any voltage higher than that will damage them. When discharging, 18650 cells are not to be used once they fall below ~2.5 V. The system will also make sure that no cell in the cell array falls below that threshold. When idle, the system will monitor temperature within the cell array to make sure that no cells are erroneously being drawn from which will unnecessarily strain the cells, decrease their lifespan, and cause potential fires. We chose to use lithium-ion cells for this project because they are much lighter than sealed lead-acid batteries and provide much more energy per unit volume than sealed lead-acid batteries.

1.2 Background

Fagen Scooters in Champaign, IL ordered its first electric motor scooter a few years ago in hopes of capitalizing on the electric transportation market. Unfortunately, the model that they ordered was very poorly designed and built by a company called Nümi. Through a few months of normal charging and discharging, the battery became bloated and damaged. In comparison to other electric vehicle battery failures, this outcome was one of the less dangerous ones. The scooter had absolutely no way of regulating the battery charging process, and if Tom Dillavou, owner of Fagen Scooters, had continued to use the battery through additional charge and discharge cycles, it could have potentially caught on fire.

The battery system on the scooter has failed, and even when operational, the scooter was not capable of monitoring its own battery health, discharge metrics, or charging metrics. As such, the scooter can no longer be sold. The company that manufactured the scooter, Nümi, has since gone out of business and Fagen Scooters has been unable to reach them for support or documentation of any kind. As it stands now, Fagen Scooters is stuck with a non-operational electric motor scooter, no product support, and no ability to upgrade the scooter with a robust battery management system once the scooter becomes operational again.

Because lithium-ion batteries are used in a range of applications, a variety of battery management systems have been created to accommodate these batteries. There are many products designed for laptops and small-voltage systems. Adafruit sells a board that can be used to monitor mp3 player, tablet computer, and cell phone power systems [5]. In addition, there are higher voltage battery management systems currently being created by Texas Instruments that will not only make sure batteries are operating in a healthy range, but they will also optimize battery discharge to make electric vehicles more economical [6]. The most important functionality for any of these systems, though, is temperature regulation, monitoring the rate of discharge and charging for the batteries, and prevent damage due to short circuits.

1.3 High-Level Requirements

- System must have a 12-cell lithium-ion battery pack that is at least 12 V, 10 Ah, and can supply 6 Amperes of current for 1 minute to a motor/load.
- System must be able to protect battery cells from overcharging/discharging by cutting current from a cell when the cell's voltage is greater than 4.2 V and less than 2.5 V.
- System must be able to warn a user if:
    - The battery pack exceeds a temperature of 45°C.
    - Any "bank" (group of 18650 cells connected in parallel) reports a voltage greater than 4.2 V or less than 2.5 V.
    - A bank reports a voltage reading of 4.2 V (fully charged).

1.4 Visual Aid for Scooter Battery Compartment and Specifications

Figure 1. Image of Electric Scooter Battery Compartment

Since our hope is to power an Electric Scooter for Fagen Scooters, our design will need to sit comfortably within a 9.5" X 12.5" X 4.5" compartment that contained the previous battery pack. This compartment is displayed above in figure 1. The battery pack must have a potential of 72V, it must have one positive lead and one negative lead that can easily be connected to the positive and negative terminals that go to the scooter's electronic motor controller.

2 Design

2.1 Power Module

Our 14.4V system requires two modules for operation: a power module and a battery management module. The power module will consist of four 18650 cell banks. Each bank will be connected in series with each other to provide the desired voltage. Additionally, there will be a temperature sensor connected to each bank with thermal glue. The output of all the sensors, along with the positive and negative lines for each bank, will be fed into the battery management system.

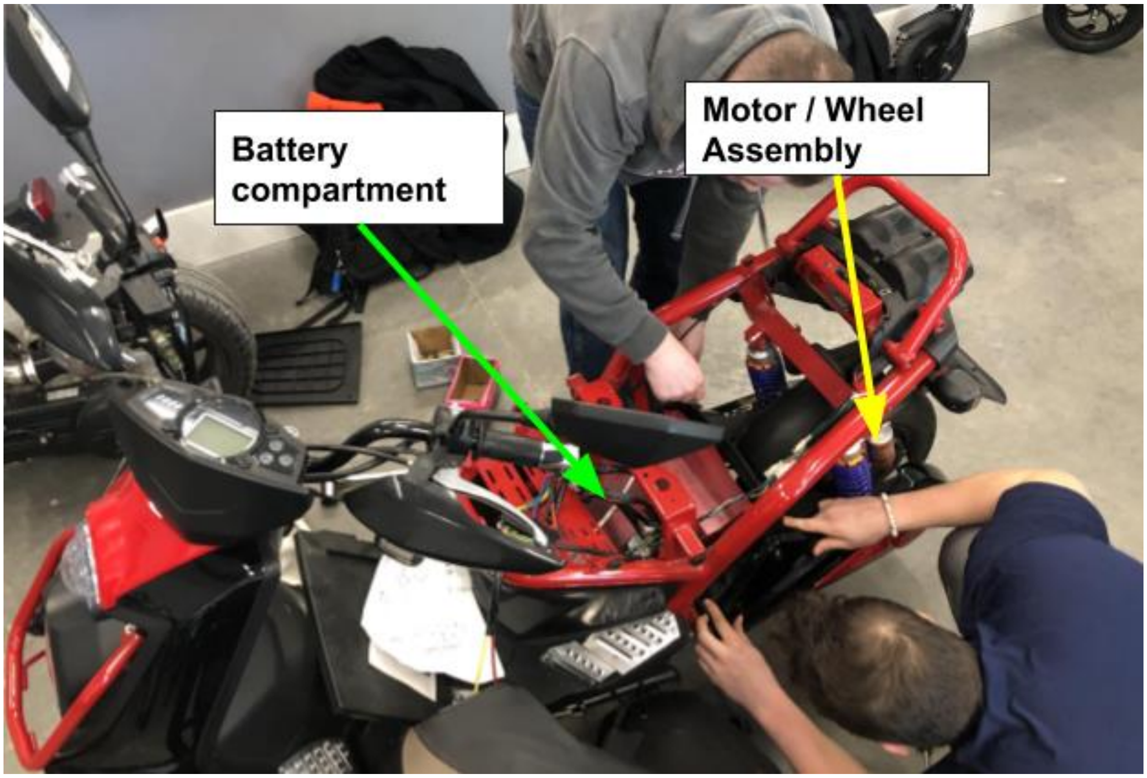

Figure 1.1 Visual Aid

Figure 1.2 Visual Aid

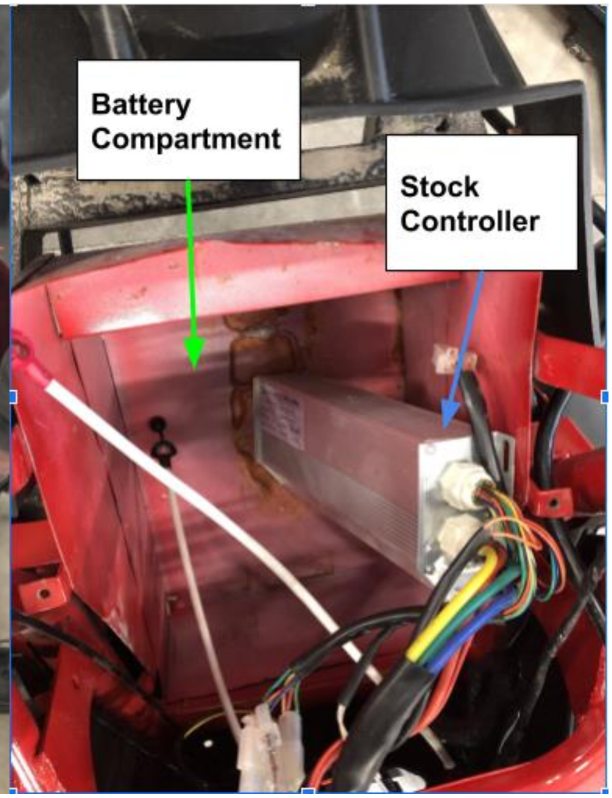

Figure 1.3 Visual Aid

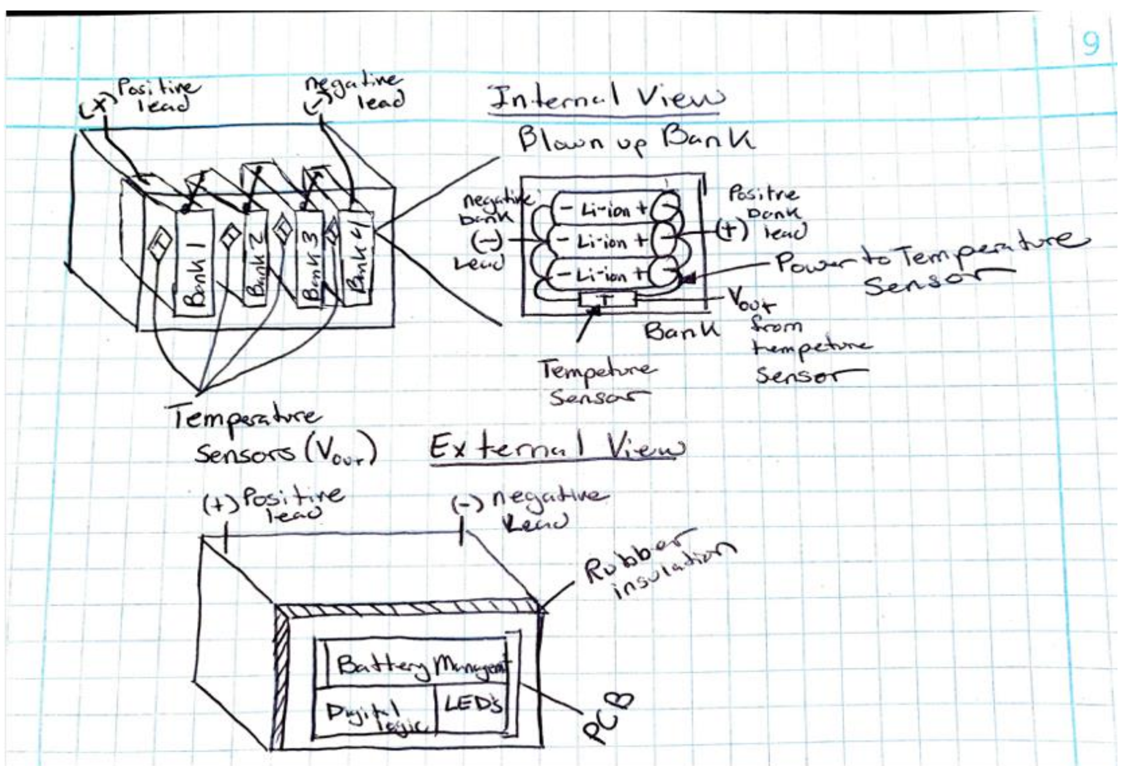

Figure 2. Physical Layout of a Battery Module

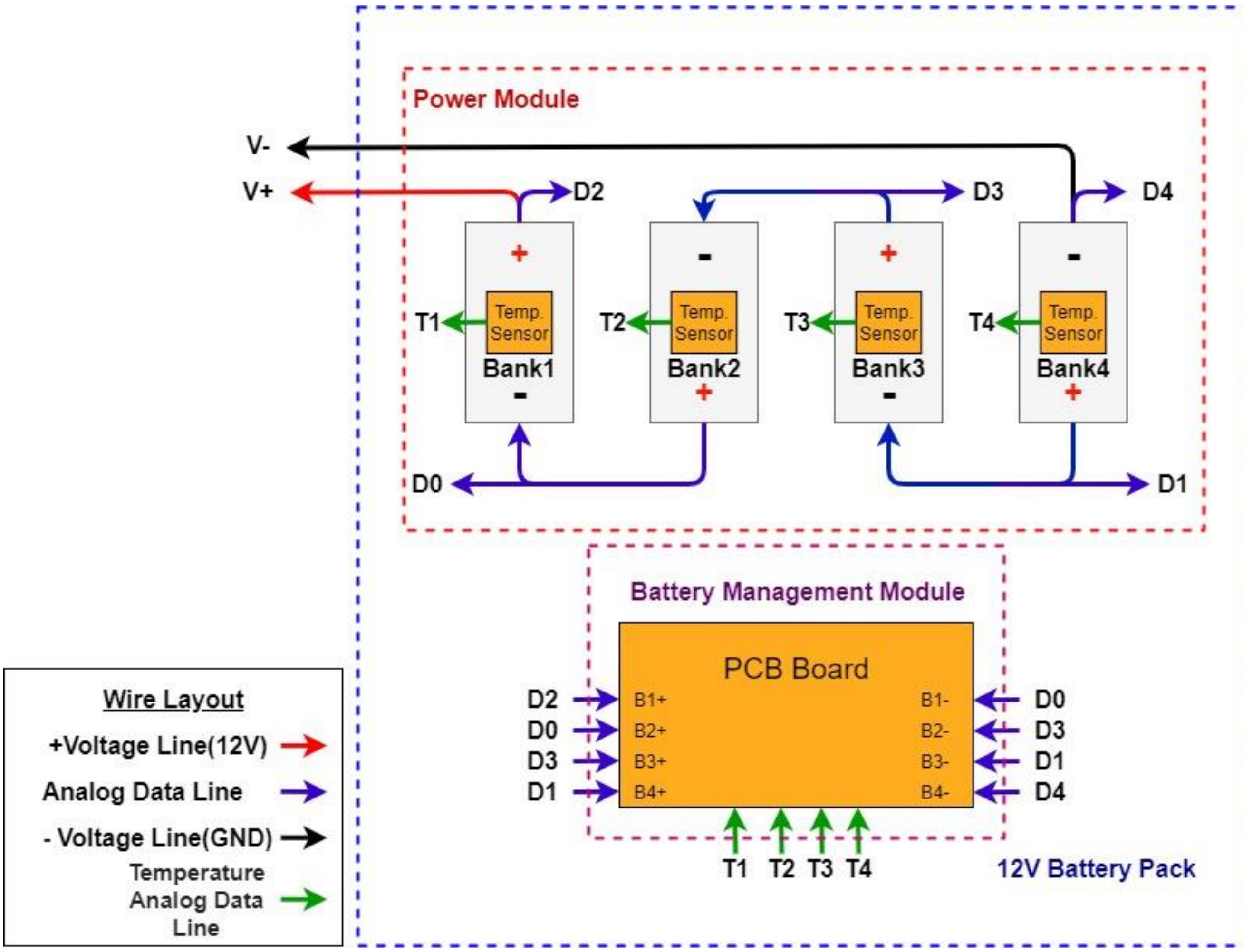

Figure 3. Block Diagram of Battery Pack

Inside the Battery Management Module lie four submodules: The Management Module, the Logic Module, the LED module, and the Short Circuit Module. The Management Module consists of several IC/resistor/capacitor units that will ensure that cells do not overcharge, do not discharge too quickly, and do not charge too quickly. One of these identical IC/resistor/capacitor units will be wired in parallel with each bank of the battery pack. These IC/resistor/capacitor units make up the Management Module. The Logic Module takes in analog temperature values from each thermostat and sends a 5 V "high" signal to the LED Module if a thermostat is above a certain threshold. This module also contains a circuit that will supply power to the LED module when the battery voltage reaches full charge. The LED Module consists of several LEDs that will relay information to the user. Finally, a Short Circuit Module will prevent damage to the battery pack if it is ever shorted.

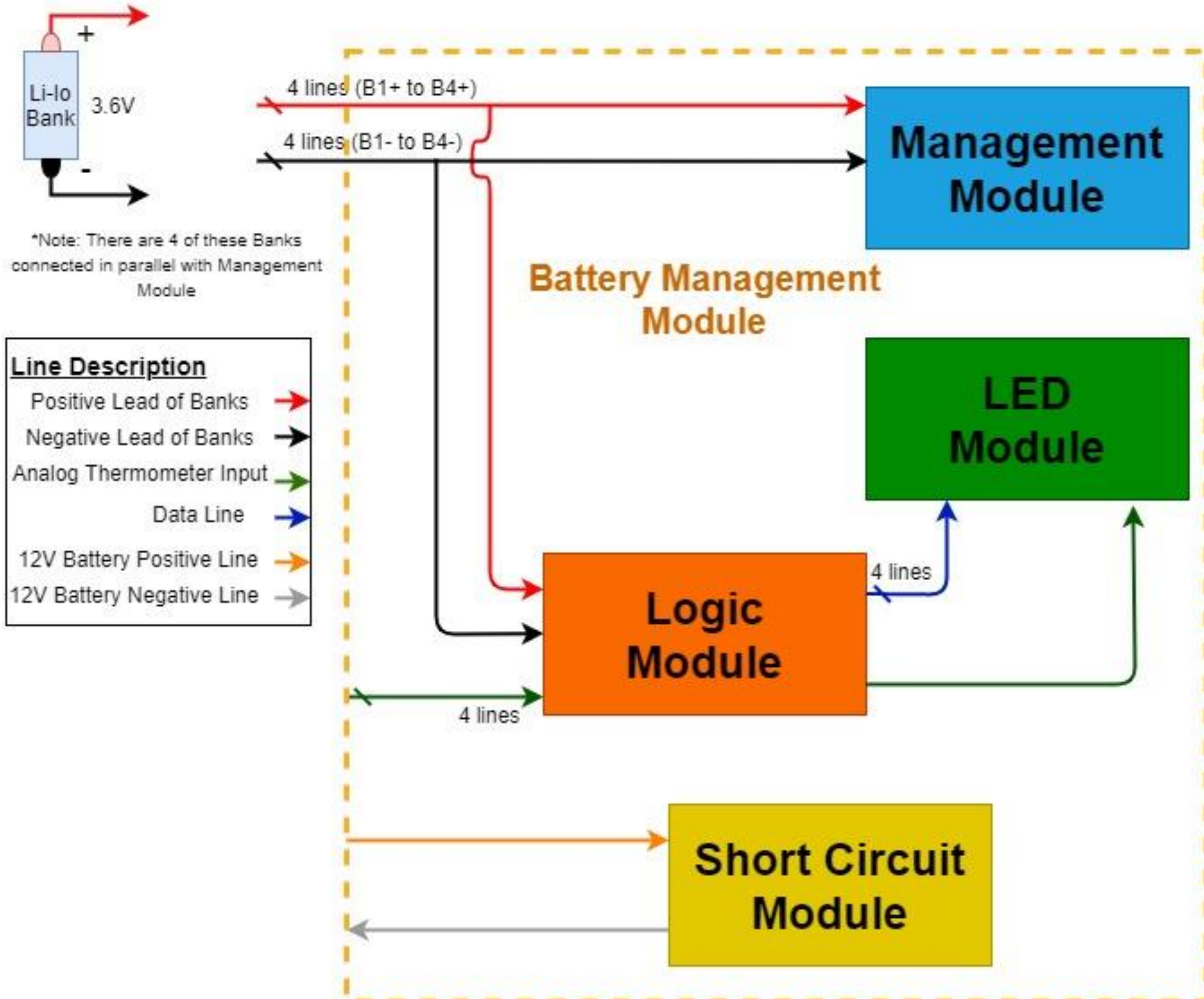

Figure 4. Block Diagram of Battery Management Module

For our project, we will be designing one of the 14.4 V modules necessary for the 72 V scooter system. Our hope is to use five of these 14.4 V modules to power the 72 V electric scooter at Fagen Scooters. The electric scooter contains several modules of note that will need to be considered when designing our system. The first scooter module is the charging system, which converts alternating current from the wall to direct current that can charge the scooter's battery. The other scooter module is the electronic motor controller, which oversees all the electronics on the scooter. This motor controller is what the battery system will be connected to. There are also two loads within the scooter: the 72 V motor and its accessories (small dashboard, headlights, etc.).

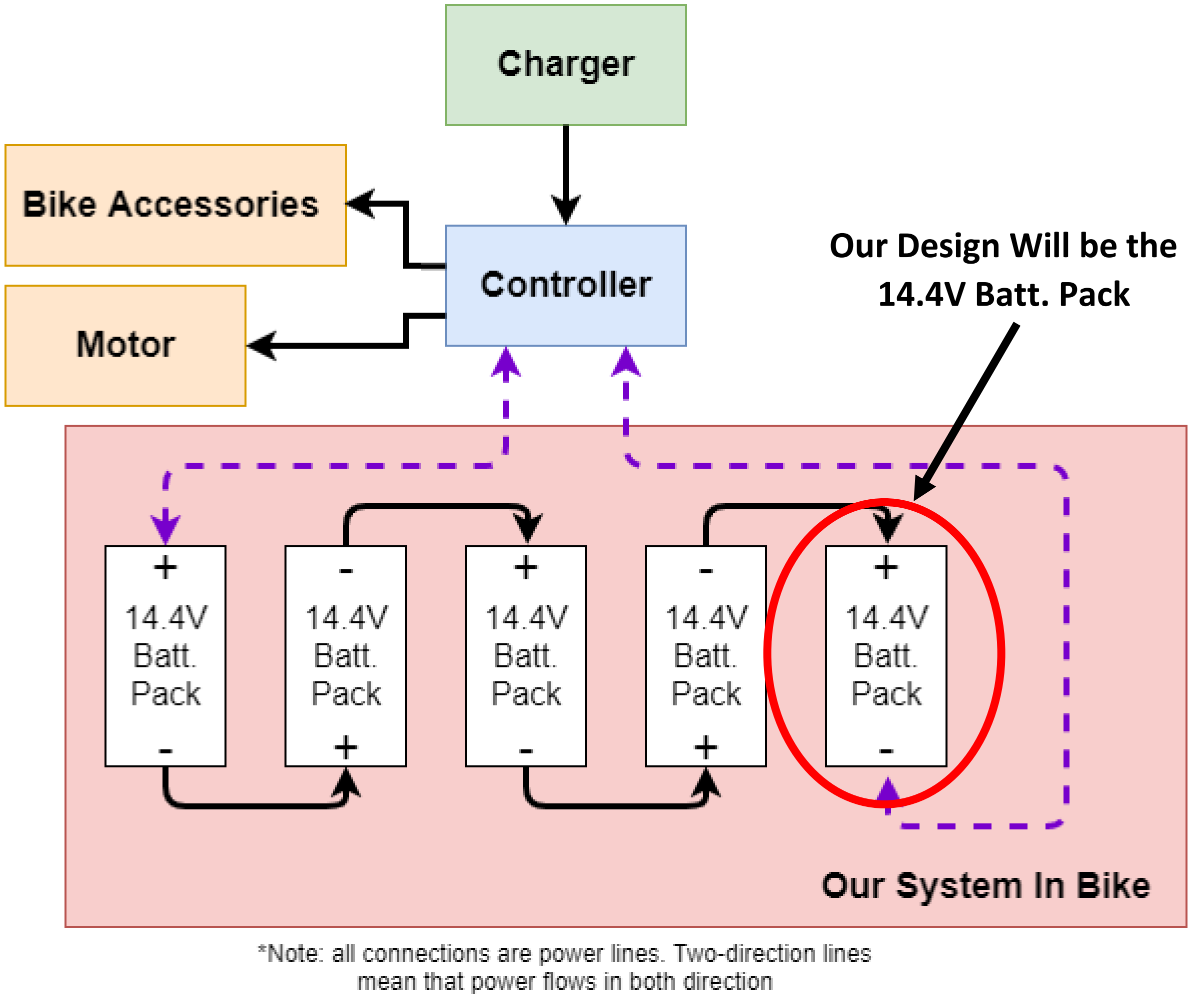

Figure 5. Block Diagram of Scooter System

2.2 Power Module

The power module is where our system will be localizing all power conversions and power systems. The essential components of this module are the battery (which acts as a power supply) and the interface with the charging system. The module must be able to deliver power in accordance with the high-level requirements and must be laid out so that it can be added to for arbitrary end user requirements.

2.2.1 Battery System

The battery system will be the primary power source for the end user's applicable system and our BMS will be a layer of protection around this battery pack. The configuration of the battery can be arbitrary but for testing and proof of concept purposes the battery must be at minimum a 12 V, 10 Ah, battery providing at least 10 A. The battery pack will be built from an array of 18650 lithium-ion cells. It will be removable and rechargeable via an external charging system (constant voltage, constant current). In order to supply 14.4 V, it will contain at least 12 cells: 4 in series, 3 in parallel. There will be flexibility with the number of cells in parallel. If an end user needs more capacity for their desired application, they can add more 18650 cells in parallel to gain that extra battery pack capacity. Each 18650 cell has a nominal voltage rating of about 3.6 V. Setting 4 cells up in series provides about 14.4V. A sketch can be seen below. Each parallel "bank" of cells will feed into a Cell Balancing/Overcharge Protection circuit where they can be individually controlled to prolong cell life and perform better.

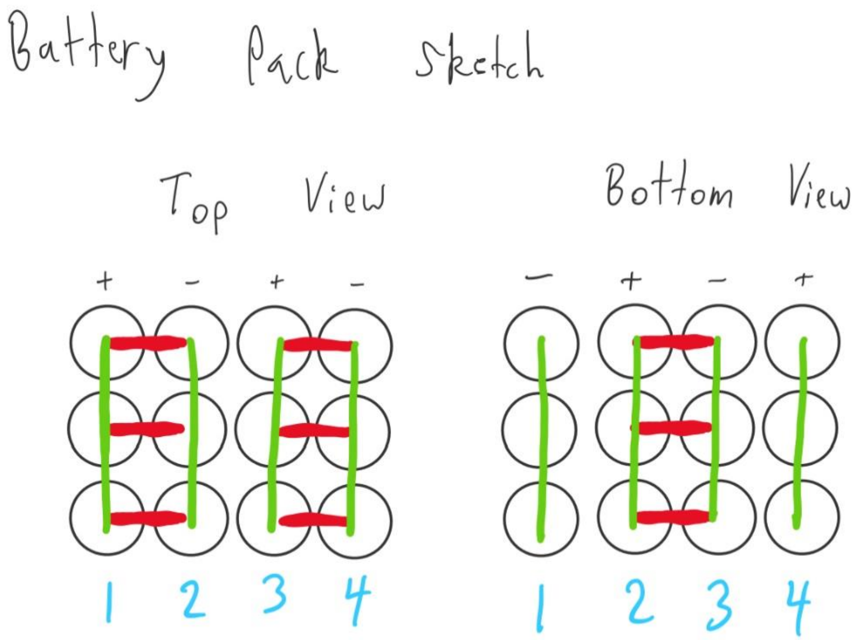

Figure 6. Drawing of a single 4 Series, 3 Parallel battery pack arrays. The green lines represent metal strips that will be spot welded to the + and – terminals of each 18650 cell in a "bank" (indicated by the blue numbers) to make the necessary parallel connections. The red lines represent metal strips that will be spot welded to each cell in a horizontal row in order to make the necessary series connections.

Requirement	**Verification**
1. Outputs a maximum of 10 A and a voltage between 14 V and 14.8 V with a storage capacity of 10 Ah	1. Connect a Power resistor of 1.2 Ohms to the battery and make sure the battery is supplying 10 Amperes of current with a DMM 2. Use a DMM to measure the voltage across the battery to ensure the correct voltage range. 3. Connect the battery to a 1.2 Ohm power resistor and measure the current output of the battery, along with the voltage drop of the battery. Make sure power is being outputted by the battery for at least an hour.

2.3 Battery Management Module

The battery management module will be our primary layer of defense against battery damage. The module will handle unsafe usage conditions such as imbalanced charging, unhealthy current draw, and more.

2.3.1 Balanced Charging Circuit

Lithium-ion batteries are very picky about the charging conditions supplied to the system. The Balanced Charging sub circuit will correct this by forcing near ideal conditions on the battery when charging and inhibiting the battery from receiving additional power when fully charged. This submodule will also prevent excessive discharge and charging, which can cause damage. This will be done by measuring changes in voltage across cells, and if the change is too rapid, MOSFETs are used to cut current flow for a period of time. See section 2.6 for a schematic of this circuit.

Requirement	**Verification**
1. Balanced charging system must be able to increase the voltage of all cells at the same rate 2. Be able to charge several batteries in parallel	1. Charge three batteries using a digital power supply; measure the voltage across one of the batteries with a DMM. Continually charge the batteries until the battery that is being measured reaches 3.2V. At this point, cut power, and measure the voltage across each battery. Make sure that the voltage drop of each battery is within 2% of 3.2V 2. Put three batteries in parallel and charge them with a digital power supply. Measure the current going into each battery using a DMM. Ensure that the current going across each battery is within 2% of each other

2.3.2 Short Circuit Protection

Due to external system damage or general wear and tear of the batteries short circuits can occur which can severely damage the entire battery pack.

Requirement	Verification
1. Short Circuit Module must be able to make the battery line an open circuit when a current of 30 Amperes runs through the line.	A. Short the battery and ensure that no current is running across the battery with a DMM. Make sure to run this test with a single battery so that if this circuit fails, damage will be minimal.

2.4 Diagnostic Module

2.4.1 LED Module

The LED Module will be an LED display with each LED indicating if something needs to be serviced. Three LEDs will correspond to each battery bank indicating bank charge with no light indicating a drained or dead bank. A red LED will show when discharged (~0.9 volts), a yellow LED will light when the battery is between discharged and half charged (between 0.9 and 1.8 volts), the green LED will light when the battery is between half charged and full (between 1.8 and 3.6 volts). Another Orange LED will correspond to active thermal mitigation and light when the thermal protection feature is active.

Requirement	Verification
1. Thermal protection must activate at temperatures greater or equal to 45°C 2. Banks must light the LEDs that correspond to the current voltage range and all voltage ranges below.	1. Apply heat to the thermal sensor torn away from battery. Measure the ambient temperature 4 inches from the battery with a thermometer, and when the ambient temperature reaches 45°C, 2. Charge the battery pack and observe as lights turn on. Then remove part of a battery bank to test that damaged banks will not light the LED.

2.4.2 Thermal Protection

Lithium-ion cells are notorious fire hazards when not properly maintained. To prevent the worst-case scenario of the cells catching fire thermal protection needs to be implemented. This will be prevented by measuring the temperature of each battery bank using an analog thermometer. If the thermometer reads a temperature rated above a certain threshold, then current will be cut from the main line.

Requirement	Verification
1. Thermal protection circuit must be able to send a high (5V) signal when a battery bank exceeds a temperature of 45°C	1. Apply heat from a heat gun to a thermal sensor torn away from the battery. Measure the resistance across the thermal sensor to ensure that it is changing.

2.4.3 Analog Logic system

The Analog Logic system will convert the analog data coming from the thermal sensors and the battery banks into the appropriate voltage ranges for the LED display panel. This will be done with operational amplifiers, TTL logic chips, and other passive components and should be reliable across expected voltages.

Requirement	**Verification**
1. The passive components must get voltage information from the banks and thermal sensors without any large draw from the batteries themselves	1. As battery is charging, measure the current from the battery into the logic module, this should be on the order of micro amps or below. 2. At full charge, measure the current from the battery to the logic module, this should be on the order of micro amps or below. 3. Verification of the applied voltage ranges will be done with the Thermal protection and LED Modules as those will fail if the logic module cannot convert the data properly.

2.5 Battery Charger

To charge the electric scooter, we will require an AC/DC Power adapter. This device takes AC power from a wall outlet and converts it to a static DC signal. The charger has no means of limiting power draw from the batteries, which means that the Battery Management Module will be controlling the power coming from the charger. The charger we will be using is rated at 72V, can push a maximum of 3 Amperes, and is rated at 28 Ah.

2.6 Battery Balancing and Overcharge Protection Circuit Schematic

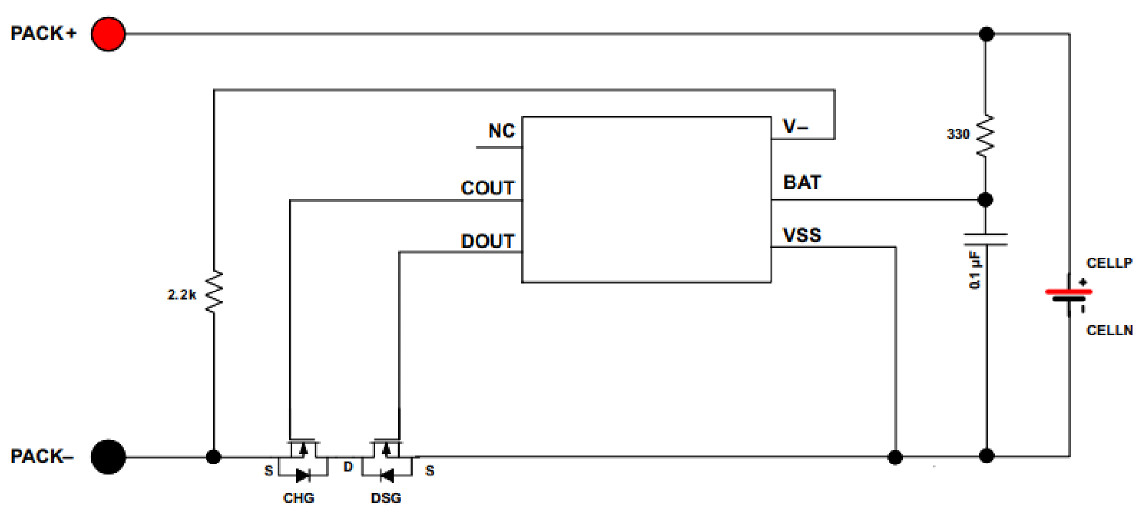

Figure 4. *Circuit layout of the TI BQ2970 battery management IC chip*

To regulate overcharge, discharge rate, and charge balancing, we will be using the Texas Instruments BQ2970 IC chip. Each battery bank will have one of these ICs connected in parallel with them; the IC measures the voltage across the battery bank and uses two external MOSFETs to control current flow in the battery. This chip is designed for lower voltage power systems; however, they will also be effective on higher voltage power systems as well. This is due to the device using only voltage to regulate the system [8].

2.7 Tolerance Analysis

After consideration, we have concluded that the most important aspect of our project is to make sure that all cells within the entire pack we will create behave as intended in order to satisfy end user operation. This means that we need to ensure that we are using the cells in the pack as they were designed to by the manufacturer, LG. As previously mentioned, we will be using 18650 Lithium-ion cells. The specific cells that we will be using are model number LG INR18650 M36T [9].

We need to ensure that the pack we design, and build, will fare well in hot and cold weather. The LG cells we are using are rated for discharge at 24°C; however, the cells can handle temperatures between -30°C to 60°C. Using the cells at different temperatures will result in different maximum discharge rates, shown by the graph below [9]. In order to maintain health, safety, and longevity of the cells, we will aim to use these cells at no higher temperature than 45°C as mentioned previously in our discussion of the temperature sensors. At this temperature, we can still get the maximum current discharge possible without running the risk of major health risks to the cells.

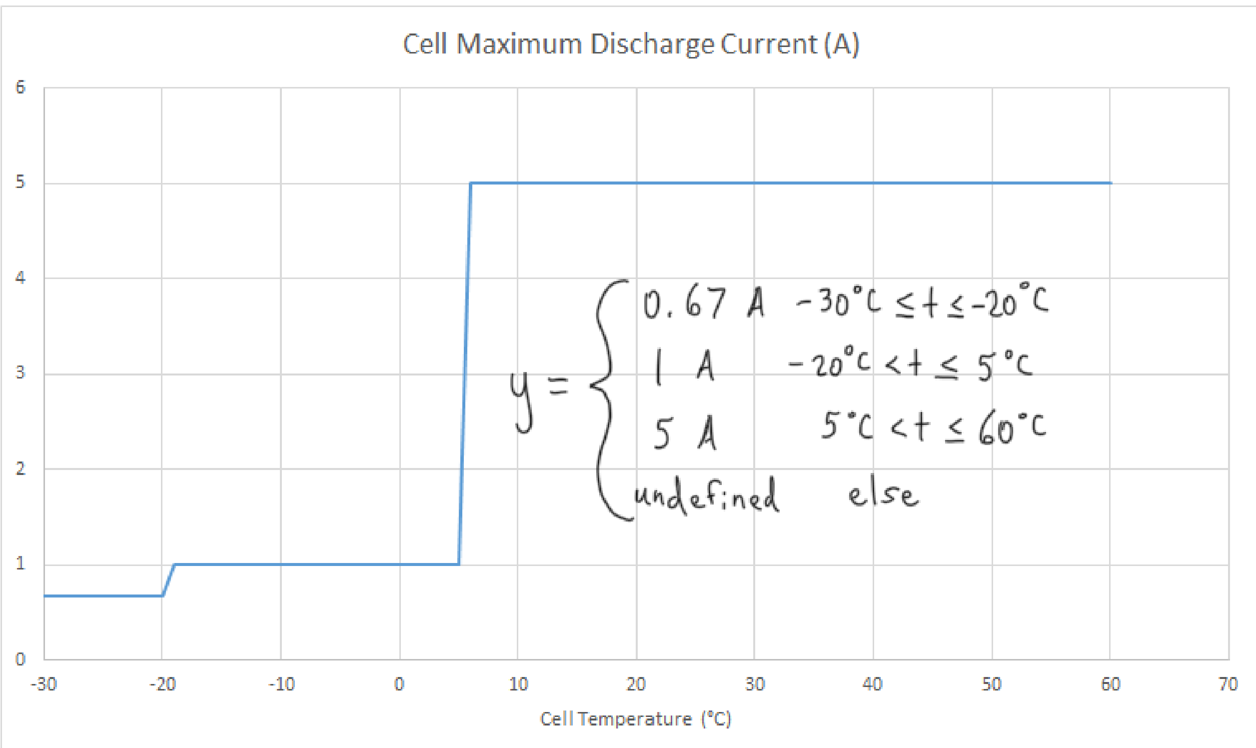

Figure 5. *Maximum discharge current for the LG INR18650 M36T cells we are going to use*

In addition, ambient temperature around the battery pack will play a major part in the capacity we will be able to get out of our cells. As shown in the graph below created from data from the specifications sheet [11], we get a function of energy capacity for an ambient temperature in degrees Celsius. According to the graph we created, the ambient temperature we should aim to keep our 14.4 V pack at is between 24°C and 50°C. We can assume that the capacity for temperatures between 24°C and ~50°C are only 100%, since it is impossible to have energy capacity greater than 100%. At temperatures above 50°C, we see that there is a bit of a drop off, considering the data point at 60°C and only 95% capacity. Inevitably, there probably will be cases where an end user uses the pack in temperatures higher than 50°C, but because our temperature regulator can detect that and disconnect, we can protect our cells and maintain cell health and longevity. In the same regard, there will be cases where cells are used in colder weather like 0°C. These cells are able to handle these harsh conditions as well, but at a reduced capacity of about 80%. Because of our temperature sensor, cells should never reach temperatures above 45°C, and we cannot guarantee any kind of functionality of the cells when the temperature falls below -30°C (from the graph above). We can use the function given in the graph below to calculate what kind of capacity can be expected for usage between -30°C and 45°C. We simply plug in the ambient temperature we are interested in, and we can get a capacity percentage of the 12.5 Wh rated capacity.

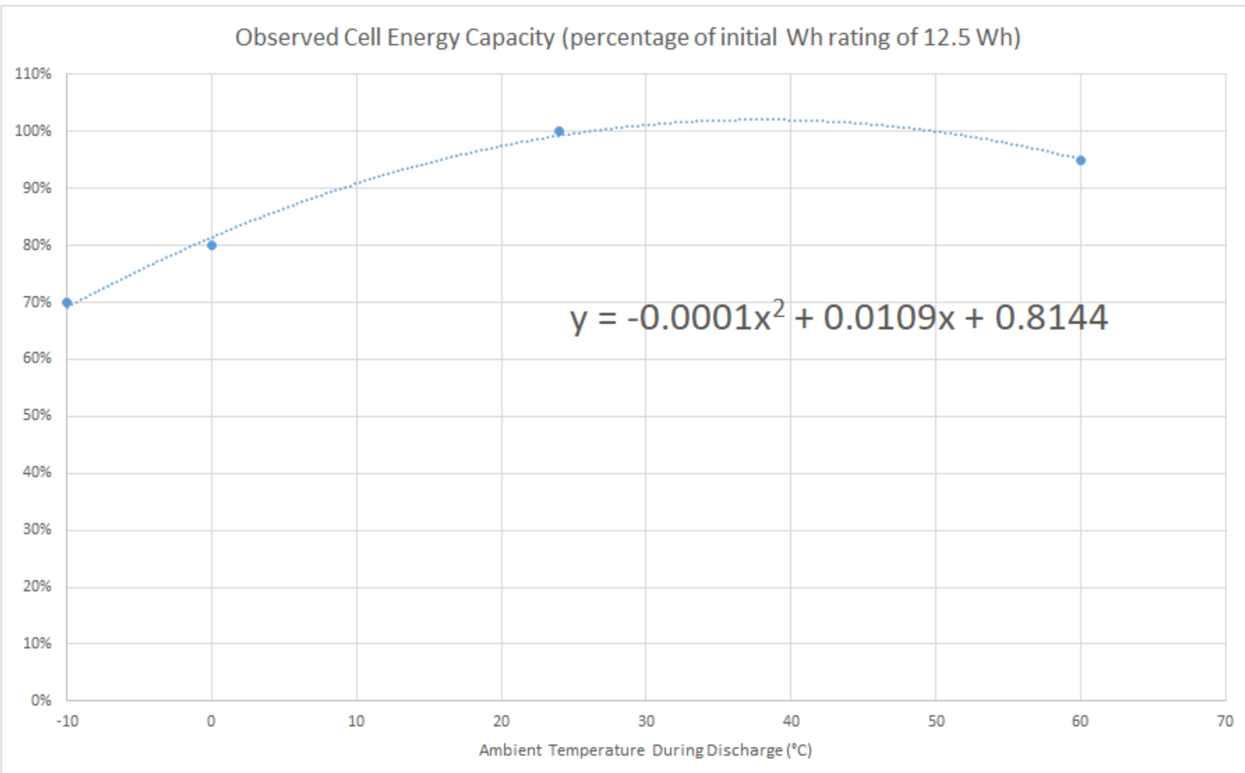

Figure 6. *Maximum discharge current for the LG INR18650 M36T cells*

3 Costs

Our estimated working cost will be $36/hr, with an average workload of 8 hours per teammate. We plan on completing 80% of our final design this semester, and we are excluding costs for a final casing, the components of the electric scooter, and the charger:

$$3 * \frac{\$36}{hr} * \frac{8\ hr}{week} * \frac{16\ weeks}{semester} * \frac{1\ semester}{0.8} = \$17{,}280$$

The cost for building a Modular battery pack is as follows:

Part	**Cost(prototype)**	**Cost(Bulk)**
18650 Lithium-Ion Batteries	$48.00	$35.00
PTC Resettable Fuse	$1.16	$6.18
TI BQ29700DSET Li-Io Battery Management IC	$3.08	$0.39
PCBs (PCBWay)	$5.06	$2.95
18650 Li-Ion Cell Battery Bracket Cylindrical Holder	$2.65	$1.50
Thermal Sensor (LM20)	$2.99	$1.29
Assorted Passive Components (Resistors, Capacitors, Diodes, MOSFETs, LEDs)	$12.00	$0.40
Total	$74.94	$47.66

Since we need four of these Modular Packs to create a 72V device for the electric scooter, our total cost becomes $17,579.80.

4 Schedule

Date	Marco	Will	Chris
2/25	Create Design for Circuits in BMS and work on Design Document	Get Motor Characterized, and work on Design Document	Research best batteries and get them ordered and work on design document
3/3	Keep working on design for BMS, and begin working on PCB schematics	Model Simulated load for test bed	Create a bill of materials and order sensors
3/10	Complete schematic and board layout of first 14.4V PCB	Have an impulse response that models the controller on the scooter	Create CAD sketches of battery casing
3/17	Solder components onto board	Create documentation for power lines on controller	Purchase Battery Casing and start verifying battery module
3/24	Test BMS for voltage overdraw/under draw, shorting, and balance.	Order components for load that will model scooter motor	Verify Short Circuit Module and Logic/LED Module
3/31	Fix bugs discovered in testing and begin full scaling the BMS to a larger battery pack	Begin work on battery case design	Adjust PCB design to fix any bugs and purchase four more boards once design is validated
4/7	Finish PCB for larger battery pack and order it	Order parts for battery case and help debug BMS	Assemble PCB onto battery pack to complete a single 14.4V module
4/14	Debug issues with new PCB and solder components	Test Motor to ensure it is working as a model of the motor	Build 72V Battery Pack
4/21	Test BMS for voltage overdraw/under draw, shorting, and balance.	Assemble BMS onto battery pack	Run code on larger PCB and debug accordingly
4/28	Implement system into scooter	Implement system into scooter	Implement system into scooter
5/5	Prepare final presentation	Work on final report	Work on final report

5 Ethics and Guidelines

5.1 Ethics

There are no major ethical concerns with our proposed project, we aim to be beyond compliant with IEEE and ACM standards of ethics in not falsifying our work and treating all group members equally [11]. Our project does not have any conflicts of interest nor does it negatively impact the public good, if anything our project aims to improve the public good by preventing potentially dangerous battery conditions. Indeed, since our project neither uses people as a means to an end and maximizes the public good it passes both the Kantian and Utilitarian paradigms of good ethics [12].

5.2 Safety

There are 3 major safety concerns involved in our project. The concern that will be solved the fastest is the assembly of our battery. The way this risk is mitigated is by having the machine shop do the spot welding and general mechanical assembly. This makes the overall score of the Operational Risk Management (ORM) low. The second most concerning issue is the fact that the scooter relies on a 72 V electrical system for the motor. We plan to mitigate this risk via the one hand rule and careful partner checking of the circuit before testing, as well as the additional safety training required per the class website. We would also like to implement an emergency kill switch into the circuit while testing, but this will not be immediately available over all the ORM for this element scores moderate. The most dangerous part of our design will be working with the charging scenario, as this will rely on wall voltages. Per the class safety page, a TA must check and clear our circuit before the device can be plugged into the wall. The TA clearances combined with the further safety training required for working with high voltages will work to mitigate the risk however the ORM for this situation is still high and will have to be closely monitored. End user safety should also be considered and according to the US Department of Energy the current state of the scooter doesn’t comply with electric vehicle standards as the battery is unprotected from over charge and thermal expansion hazards [13].

References

[1] Future lab, Top 7 Electric Scooters (Dec 7,2018). Accessed: Feb,24, 2020 [online videos]. Available: https://www.youtube.com/watch?v=84wjrHvZW_4

[2] M Toll, "Hey America, you ready for electric mopeds? Because here they come!" Electrek.co https://electrek.co/2019/10/11/revel-electric-moped-scooter-sharing-expansion/ (accessed Feb 24 2020)

[3] Escooterguide, "Electric Scooter Batteries: Ultimate Guide" electric-scooter.guide https://electric-scooter.guide/guides/electric-scooter-batteries/ (accessed Feb 24 2020)

[4] "The Hazards of Lithium batteries", A Newsletter of Tufts EHS,Vol 8 pp 3-4 Accessed: Feb, 24, 2020, [Online]. Available:https://viceprovost.tufts.edu//ehs/files/The-Hazards-of-Lithium-Batteries.pdf

[5] Adafruit Power Boost 500 Basic, Mouser Datasheet, 22 Aug 2018. [Online]. Available: https://www.mouser.com/datasheet/2/737/adafruit-powerboost-932879.pdf

[6] S. Chon, J Beall, "Intelligent Batter Management and Charging for Electric Vehicles", Texas Instruments, 2017, Accessed 25 Feb 2020. [Online]. Available: http://www.ti.com/lit/wp/spry304a/spry304a.pdf

[7] LM20 2.4-V, 10uA, SC70,DSBGA Temperature Sensor, Texas Instruments, Jan 2015. [Online]. Available:http://www.ti.com/lit/ds/symlink/lm20.pdf

[8] BQ297xx Cost-Effective Voltage and Current Protection Integrated Circuit for Single-Cell Li-ion and Li-Polymer batteries, Texas Instruments, January 2020, [online]. Available: http://www.ti.com/lit/ds/symlink/bq2970.pdf

[9] Yong-Hoon Kim, "Product Specification: Rechargeable Lithium Ion Battery, Model: INR18650 M36T 12.50Wh," Oct. 18, 2017. https://cdn.shopify.com/s/files/1/0697/3395/files/lg_m36_datasheet.pdf?3063

[10] Easy One, *How to Make A Battery Charger Li-ion Battery 18650* (Aug 30,2017). Accessed: Feb 24, 2020 [online video]. Available:https://www.youtube.com/watch?v=FBrARHY6d-M

[11] IEEE Code of Ethics, 7.8, IEEE, [online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html

[12] R Rubel, *Ethics and the Military Profession: The Moral Foundations of Leadership*, 4th ed. US, Pearsons, 2011

[13] US Dep of Energy, office of Energy Efficiency and Renewable Energy, *Electric Car Safety, Maintenance, and Battery Life.* [Online}. Available: https://www.energy.gov/eere/electricvehicles/electric-car-safety-maintenance-and-battery-life