Passive Balancing Battery Management System for Cal Poly Racing's Formula SAE Electric Vehicle

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Most importantly, thank you to my family and friends. Without your love and support, none of this would have been possible.

Abstract

This senior project aims to replace the current battery management system (BMS) on Cal Poly’s Formula SAE electric vehicle with a more versatile, advanced, and reliable system. A BMS manages a rechargeable battery by ensuring the battery device operator’s safety, protecting battery cell integrity, prolonging battery lifetime, maintaining functional design requirements, and sending optimal usage information to the application controller. Passive balancing maximizes a battery pack’s capacity by dissipating excess energy through heat to regulate cell state of charge.

1.0 Introduction

Cal Poly Racing, a student-led engineering team, competes in Formula SAE Electric, an international competition to design, build, and test a prototype electric vehicle against other universities [1]. Formula Electric vehicles require extensive electronic power systems, often rechargeable battery packs, which power the drivetrain [2]. The battery management system, or BMS, dictates the entire power system performance, optimization, and lifetime. Figure 1 below details the major systems in Cal Poly Racing's electric vehicle.

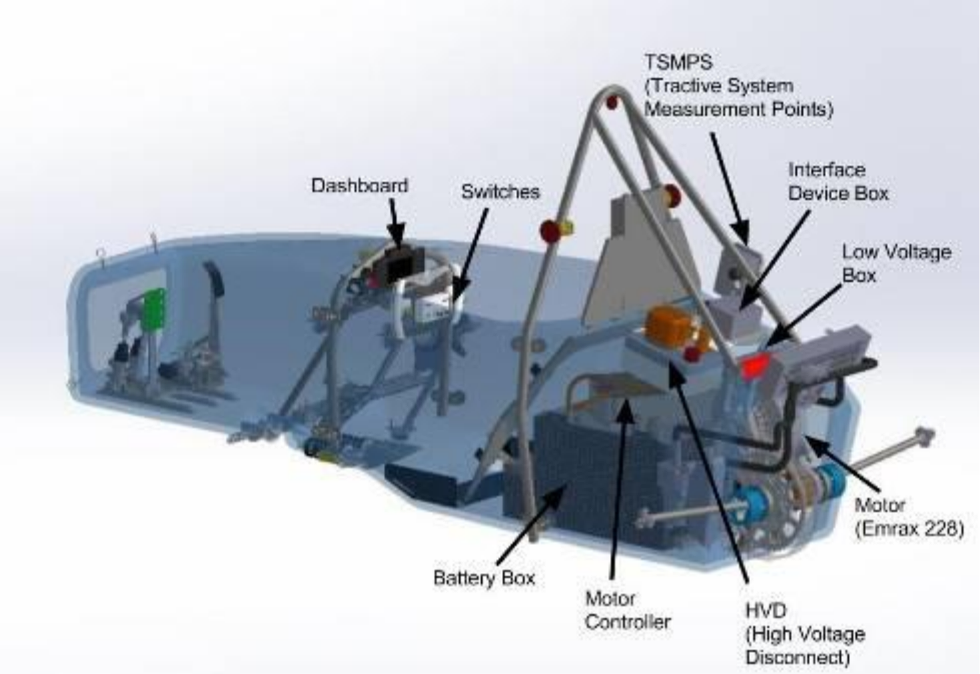


Figure 1: Cal Poly Racing's Electric Vehicle [3]

The vehicle battery pack consists of four modules containing 180 batteries each [3]. Cal Poly Racing has struggled to find a commercial BMS that fulfills competition requirements and provides optimization for custom setups. The current BMS fails desired standards regarding structural integrity, cost-effectiveness and feature versatility. Building a BMS for one out of the total four modules allows students next year to improve on designs accomplished this year. Figure 2 on the next page shows the current BMS module integration.

This senior project aims to provide the foundation for a custom BMS integrated into a single module with comprehensive sensing and high voltage control, robust protection, reliable interfacing, dynamic performance management, and detailed diagnostics.

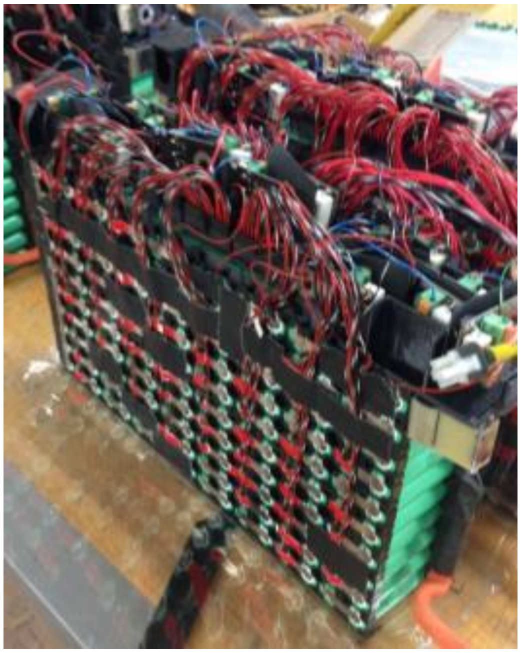


Figure 2: Current BMS Module Integration

This senior project plans to reach the following objectives during the allotted timeline:

1. Preliminary Circuit Simulations: Team simulates planned circuits and systems under a variety of conditions and environments using software such as LTSpice, MATLAB, and STAR-CCM+.

2. Schematic and PCB Design: Team designs circuit schematic and layout using Altium Software, or an equivalent program. Winter quarter, the designated design time, includes a preliminary and critical design review.

3. Ordering raw materials: Team acquires batteries, integrated circuits, electronic components, testing equipment from various manufacturers. Cal Poly Racing industry contacts streamlines acquisition.

4. PCB Assembly and Pack Integration: Team sends final PCB designs to Cal Poly Racing manufacturer contacts. Team populates boards with components, builds a single battery module, and integrates the two systems.

5. Test and Debug: Team tests the entire system in the Electrochemistry Lab on an existing custom test bench setup meant for high voltage battery systems. Testing validates different BMS functions under different conditions by using electronic test equipment and automation software.

The overall project goal aims to lay the foundation for a high-performance, modular, and versatile replacement BMS on the Cal Poly Racing Electric Car.

1.1 Background

Advancements in battery technology and the growing importance of sustainability have created a large demand for renewable lithium-ion energy solutions. A lithium-ion battery, a rechargeable battery where lithium ions move between the negative and positive electrodes, provides the highest energy density per weight, a low self-discharge, and low maintenance [4]. Common battery applications include consumer electronics, defense, automotive, and energy grids. Figure 3 below details typical ion flow in lithium-ion batteries.

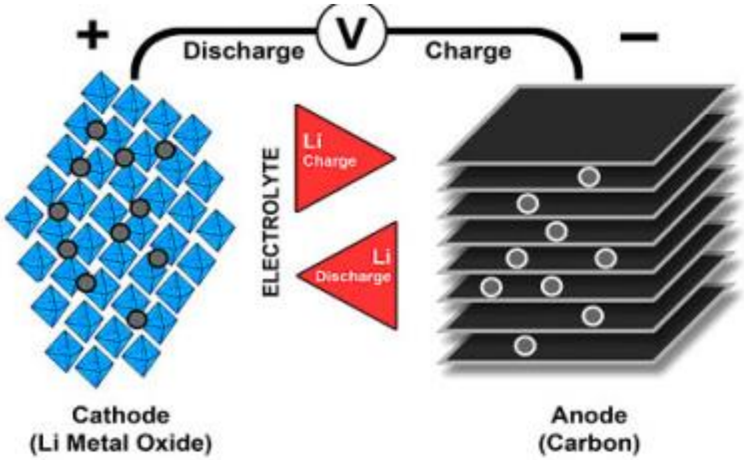


Figure 3: Ion Flow in Lithium-Ion Batteries [5]

According to a report by Zion Market Research, the global lithium-ion battery market, valued at around USD 31.71 billion in 2016, expects to generate revenue of USD 67.70 billion by the end of 2022 [6]. One application, electric vehicles (EVs), has seen explosive growth over the past years. According to the International Energy Agency, cumulative sales of highway legal EVs reached 2 million units, of which 38% sold in 2016 [7]. Figure 4 below shows the growth of the EV market from 2010 to 2016.

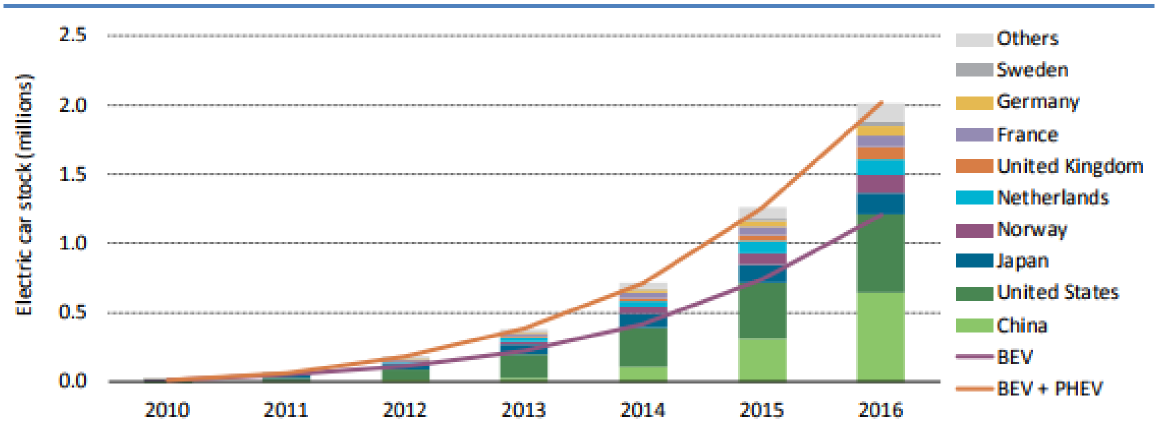


Figure 4: Evolution of Global Electric Car Stock, 2010-16 [7]

However, lithium-ion batteries need protection, their main disadvantage [8]. They need protection from over charge, over discharge, thermal runaway, and damage [4]. Without adequate protection, lithium-ion batteries become a significant safety risk. Damage and abuse may result in thermal expansion, fire, or explosion, depending on the severity [8]. Thus, engineers created battery management systems to combat these issues and give application specific optimization.

A battery management system, any electronic system that manages a rechargeable battery, protects the battery device's operator, protects cells from operating outside its safe operating area, prolongs battery lifetime, maintains battery in a state which it can fulfill its functional design requirements, and sends useful data to application controllers [9]. The five main functionalities which encompass BMS design include sensing and high voltage control, protection, interface, performance management, and diagnostics [9]. Figure 5 below shows a typical BMS block diagram.

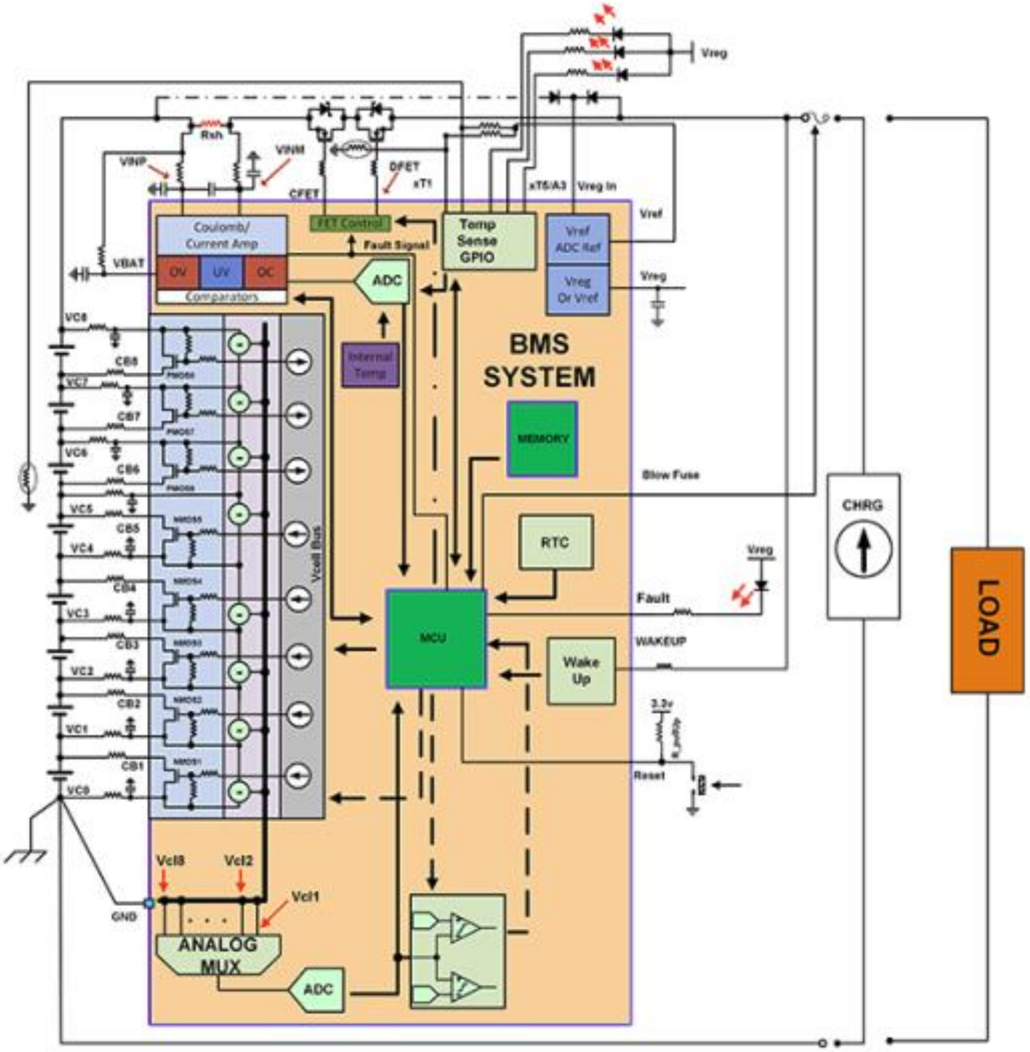


Figure 5: Battery Management System Example Diagram [10]

1.2 Team Members

Battery management and pack design are intrinsically interdisciplinary undertakings, combining electrical, chemical, and thermal energy management. This project brings together students from multiple disciplines including electrical engineering, mechanical engineering, computer engineering, and computer science. A breakdown of each discipline follows below:

1. Electrical Engineering
   Members: Alvin Ha, Nick Mah, Jason Zhou, Andrew Ferguson, Oliver Ousterman

   Team members must apply a variety of electrical engineering fundamentals and skillsets to design circuitry for sensing, high voltage control, protection, and other features. Students must design complex circuit boards containing application specific integrated chips (ASICS), passive and active components, microcontrollers, transceivers, and other electronics by using electronic design automation (EDA) software. Students must combine power electronic engineering with electrochemical knowledge to optimize usage of battery-powered systems. Students must analyze design simulations with software tools such as MATLAB and PSpice. Students must manufacture each system and validate design with electronic measurement tools.

2. Mechanical Engineering
   Members: Max Wu

   Team members must apply a variety of mechanical engineering fundamentals and skill sets to design the packaging, structure, connections, and thermal management. Students must design the BMS packaging according to the existing battery box space and configuration limitations. Students must ensure structural integrity and resistance to vibrations. Students must account for all safety risks such as improper structure insulation. Students must consider methods to handle battery-generated heat and its effect on the system.

3. Computer Engineering/Computer Science
   Members: Japsimran Singh, Nick Mah

   Team members must apply a variety of computer engineering and computer science fundamentals and skill sets to build the interface, performance management, and diagnostic systems. Students must design the CAN bus communication for range estimation, data recording, and data reporting. Students must program microcontrollers to analyze battery module information including voltage, current, and temperature. Students must devise performance management algorithms used to calculate state-of-charge (SOC), power limits, cell balancing, abuse detection, and state-of-health (SOH). Students must ensure BMS communication with the main automotive control unit.

1.3 Current System Analysis

Cal Poly Racing currently uses an Elektromotus BMS containing a 12V control unit with A/B type cell modules. The table below details the most important limitations.

Table 1: BMS Limitations

Limitations	Comments
Designed for prismatic cells	Previous generations of the electric car utilized prismatic cells. Since Cal Poly Racing switched to 18650 small cylindrical cells, the BMS cell boards waste a significant amount of space, crowding the overhead area of the battery modules.
No state-of-health or state-of-charge capability without pricey add-on	Cal Poly Racing greatly desires this data to determine performance characteristics of the battery pack.
Very slow charging and balancing time.	The current system takes approximately 4 hours to charge and top balance. Any time saved improves system performance and team efficiency.
Prone to breaking and shorting	As seen in the previous Figure 2, the current setup, not meant for a cylindrical cell topology, poses certain safety risks mitigated with band-aid solutions. For example, the cell boards, prone to shorting due to their vertical position, are separated by small pieces of rubber. An abundance of failure points, size restrictions, and sub-optimal configuration necessitate a more streamlined design.
No temperature monitoring	The electronics team designed a standalone temperature monitoring board placed alongside the BMS. This board takes up a significant amount of space and contributes to wire clutter due to the large number of thermistors.
No customization with other Cal Poly Racing Systems	A custom BMS solution designed with other Cal Poly Racing in-house electrical systems in mind, such as the power distribution module, analog CAN boards, and new MCU architecture, allow for a more modular platform better suited to fulfilling specific team needs.

2.0 Customer Needs, Requirements, and Specifications

Cal Poly Racing team members, the main senior project customers, consist of full-time students, primarily engineers, who build Formula SAE vehicles as an extracurricular activity. The expected users, electrical and computer engineering students, typically have technical aptitude designing and integrating complex electronic systems. However, teams often have a short timeline to design, build, and test each new automotive system, which leads users and managers to search for sub-optimal market solutions with quick implementation time. This senior project aims for implementation into next year's car (2018-2019) to enable adequate design time.

Initial customer needs formulated through discussion with Nick Mah, a Cal Poly Formula SAE ex-lead and collaborator on this project. Nick's e-car design expertise and in-depth knowledge of Formula SAE rules allowed for accurate communication of system needs. Further discussion with Jason Zhou and Japsimran Singh, who worked on similar projects, expanded initial ideas. Needs refined by sourcing additional literature on battery management system design, primarily Dr. Gregory Plett's ECE5720: Battery Management and Control course at the University of Colorado, Colorado Springs, and the official Formula SAE competition rulebook.

Each marketing requirement designates an essential battery management system aspect. Sensing and high voltage control measures voltage, current, temperature, control contactor, pre-charge, ground fault detection, and thermal management. Protection systems protect against over-charge, over-discharge, over-current, short-circuit, and extreme temperatures. The interface provides range estimation, communications, data recording, and data reporting. Performance management estimates state-of-charge (SOC), computes power limits, and balances/equalizes cells. Lastly, diagnostics provide abuse detection, state-of-health (SOH) estimation, and state-of-life (SOL) estimation. Table 2 on the next page details the project requirements and specifications.

Table 2: Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1,2,4,5	System must monitor 18650 lithium-ion Samsung INR 25r cells in an 18 series 10 parallel topology	Based upon Formula Electric's desired battery module topology, chemistry, and form factor.
1,2	System must measure DC voltage ranging from 2.5V to 4.2V with an accuracy of 20 mV.	Accurate battery voltage sensing guards against damage when crossing under-voltage or over-voltage threshold.
3,4,5	Each distributed system module must communicate with the centralized controller with RS232 or CAN.	Formula Electric's chosen topology combines centralized and distributed system facets, both require communication between each module.
2,5	System must provide 3 power output LEDs driving small relays for hardware fault shutdown.	The LEDs represent voltage, current and temperature. They allow engineers to diagnose specific BMS areas.
3,4	System must calculate common battery characteristics including state-of-charge, state-of-health, and power limits and report them to the main controller.	SOC, SOH, and power limit computations allow BMS to best determine performance characteristics of a battery pack.
1,4	System must monitor and balance cell charge.	Balancing maximizes a pack's capacity by regulating a cell's state of charge.
1,2,4	The system must maintain pack temperature within range of 45°C to 55°C.	Ideal operating temperature range for chosen lithium ion batteries.
2	High voltage system must remain galvanically isolated from low voltage components	Compliance Formula SAE rule EV1.2.7 [1]
1,5	System must measure cell temperature at the negative terminal.	Compliance Formula SAE rule EV3.6.3[1]
2,6	The maximum power drawn from the battery must not exceed 80kW.	Compliance Formula SAE rule EV2.2.1 [1]
2,6	The maximum voltage must not exceed 300 VDC	Compliance Formula SAE rule EV1.1.2 [1]
1,4,6	System must monitor pack whenever the tractive system	Compliance Formula SAE rule EV3.6.1 [1]

	activates, or the battery connects to a charger.	
1,2,6	The system must measure cell voltages every 30ms, keeping the cells inside the allowed minimum and maximum cell voltage levels stated in the cell data sheet.	Compliance Formula SAE rule EV3.6.2 [1]
1,2,6	The system must measure battery temperature every 30ms and keep cells below the limit stated in the data sheet or below 60°C.	Compliance Formula SAE Rule EV3.6.3[1]
1,6	The system must measure at least 30% of the total cells in the battery pack.	Compliance Formula SAE Rule EV3.6.6[1]

Marketing Requirements

1. The system must provide sensing and high-voltage control.
2. The system must protect against abuse/failure
3. The system must interface with main controller
4. The system must manage performance management
5. The system must provide diagnostics
6. The system must follow all Formula SAE competition rules and guidelines.

3.0 Functional Decomposition

Figure 6 below shows the BMS level 0 block diagram. BMS inputs and outputs, chosen based on reference research, provides an overview of different BMS functionalities [1] [9] [11]. A typical BMS topology measures cell voltage and cell temperature. A BMS also measures the battery pack's total current and input charging power. The BMS processes information digitally and sends commands to each subsystem. Outputs include output charging power, output pack current, and other useful information such as state-of-charge, which quantifies battery characteristics. Table 3 on the next page discusses the functional design requirements.

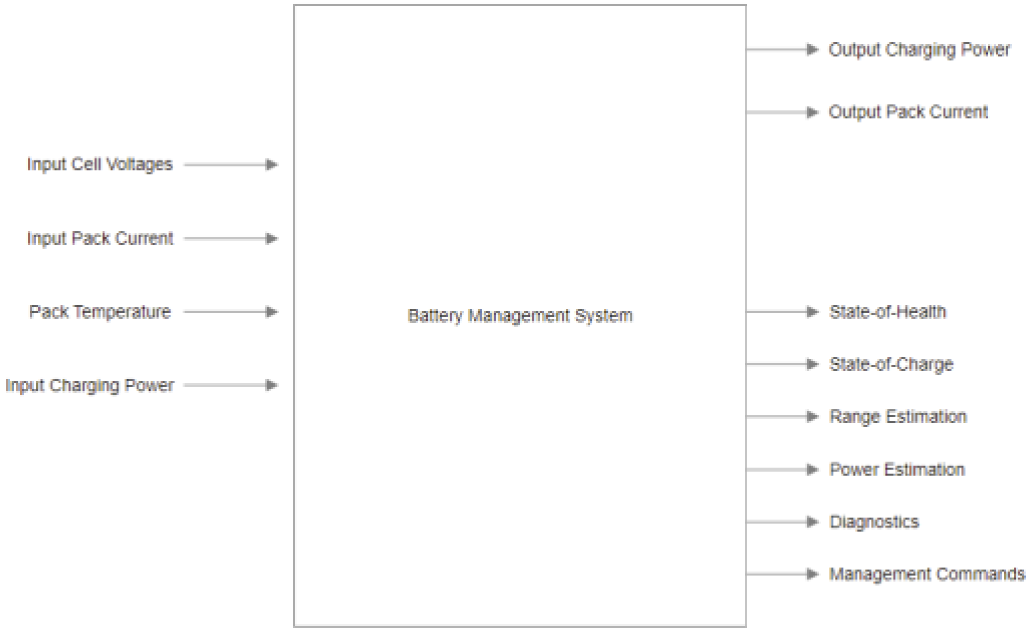


Figure 6: Level 0 Block Diagram

Table 3: Battery Management System Functional Design Requirements

Module	Active Balancing Battery Management System for Large Scale Lithium-Ion Packs
Inputs	- Input Cell Voltages: 4.2 V Peak - Input Pack Current: 200 A Peak - Pack Temperature: 60°C Peak - Input Charging Power: 1210 W Peak

Outputs	- Output Charging Power: 1210 W Max - Output Pack Current: 200 A Peak - State-of-Health: 5 V Peak* - State-of-Charge: 5 V Peak* - Range Estimation: 5 V Peak* - Energy Estimation: 5 V Peak* - Power Estimation: 5 V Peak* - Diagnostics: 5 V Peak* - Management Commands: 5 V Peak* * Indicates digital signals placed on a CAN BUS with 5V Logic
Functionality	**Input Cell Voltages:** Measure ten parallel battery voltages for characterization and protection. **Input Pack Current:** Measure total current from the battery. **Pack Temperature:** Measure battery temperature to ensure operation within optimal range. **Input Charging Power:** Detect charger connection and measure input power **Output Charging Power:** Recharge batteries **Output Pack Current:** Regulate and adjust total pack current. **State-of-Health:** Quantifies cell aging process expressed in percentage from 0-100%. Often measured from present capacity and resistance. **State-of-Charge:** Proportion of available charge compared to total charge available when fully charged expressed in percentage from 0-100% **Range/Energy/Power Estimation:** Provide possible range, available energy, and available power information. **Diagnostics:** Provide operational data, damage reports, and battery characteristics **Management Commands:** Communicates with main automotive controller to coordinate different systems

Figure 7 below shows the BMS level 1 block diagram. Team members researched typical BMS subsystems, topologies, and methods to determine each block [2] [8]. The first block, voltage measurement, measures ten cell voltages in parallel, typically with analog-to-digital converters. The output, a single digital signal, contains voltage data sent to the microcontroller. The second block, temperature measurement typically uses thermistors or thermocouples to measure pack temperature. The output, a digital signal, sends temperature data to the microcontroller. The third block, a current shunt, measures current through a four-wire interface shunt. It outputs unregulated analog current to the cell balancer and protection and sends current data to the microcontroller. The fourth block, a power distribution module, detects and measures the input charging power. It sends relevant data to the microcontroller as well as routes the power through the cell balancer and protection. The fifth block, the microcontroller, coordinates all the systems and calculates state-of-health, state-of-charge, range estimation, power estimation, diagnostics, and management commands using user defined algorithms. The sixth block, cell balancer and protection, takes commands from the microcontroller on optimal balancing procedure and provides cell-level protection. This block outputs charging power to the connected cells and outputs regulated pack current to the load.

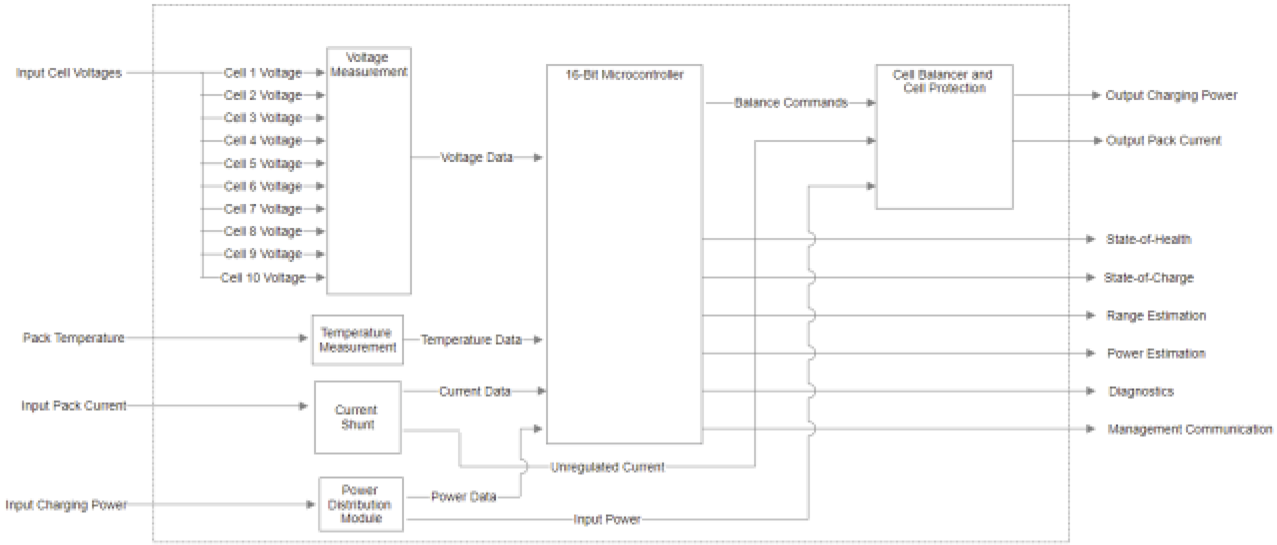


Figure 7: Level 1 Block Diagram

Table 4: Voltage Measurement Functional Design Requirements

Module	Voltage Measurement
Inputs	- Cell voltage #1-10: 4.2 V Peak
Outputs	- Voltage Data * * Indicates digital signals placed on a CAN BUS with 5V Logic

Functionality	The first block, voltage measurement, measures ten cell voltages in parallel, typically with analog-to-digital converters. The output, a single digital signal, contains voltage data sent to the microcontroller.

Table 5: Temperature Measurement Functional Design Requirements

Module	Temperature Measurement
Inputs	- Pack Temperature: 60°C Peak
Outputs	- Temperature Data: 5 V Peak * * Indicates digital signals placed on a CAN BUS with 5V Logic
Functionality	The second block, temperature measurement typically uses thermistors or thermocouples to measure pack temperature. The output, a digital signal, sends temperature data to the microcontroller.

Table 6: Current Shunt Functional Design Requirements

Module	Current Shunt
Inputs	- Input Pack Current: 200 A Peak
Outputs	- Current Data: 5 V Peak * - Unregulated Current: 200A peak * Indicates digital signals placed on a CAN BUS with 5V Logic
Functionality	The third block, a current shunt, measures current through a four-wire interface shunt. It outputs unregulated analog current to the cell balancer and protection and sends current data to the microcontroller.

Table 7: Power Distribution Module

Module	Power Distribution Module
Inputs	- Input Charging Power: 1210 W Peak
Outputs	- Power Data: 5 V Peak * - Input Power: 1210 W * Indicates digital signals placed on a CAN BUS with 5V Logic.
Functionality	The fourth block, a power distribution module, detects and measures the input charging power. It sends relevant data to the microcontroller as well as routes the power through the cell balancer and protection.

Table 8: Microcontroller Functional Design Requirements

Module	Microcontroller
Inputs	- Voltage Data: 5 V Peak* - Current Data: 5 V Peak* - Temperature Data: 5 V peak* - Power Data: 5 V Peak* * Indicates digital signals placed on a CAN BUS with 5V Logic
Outputs	- State-of-Health: 5 V Peak* - State-of-Charge: 5 V Peak* - Range Estimation: 5 V Peak* - Energy Estimation: 5 V Peak* - Power Estimation: 5 V Peak* - Diagnostics: 5 V Peak* - Management Commands: 5 V Peak* * Indicates digital signals placed on a CAN BUS with 5V Logic
Functionality	The fifth block, the microcontroller, coordinates all the systems and calculates state-of-health, state-of-charge, range estimation, power estimation, diagnostics, and management commands using user defined algorithms.

Table 9: Cell Balancer and Cell Protection

Module	Cell Balancer and Cell Protection
Inputs	- Voltage Data: 5 V Peak* - Unregulated Current: 200A Peak - Input power: 1210 W Peak * Indicates digital signals placed on a CAN BUS with 5V Logic
Outputs	- Output Charging Power: 1210 W Peak - Output Pack Current: 200 A
Functionality	The sixth block, cell balancer and protection, takes commands from the microcontroller on optimal balancing procedure and provides cell-level protection. This block outputs charging power to the connected cells and outputs regulated pack current to the load.

4.0 Project Planning

This senior project began at the beginning of EE 460 on September 14th, 2017 and plans to end a couple of weeks before the end of EE 462 on May 28th, 2018. The project timeline, divided into three academic quarters, starts with research and planning during fall quarter, design during winter quarter, and manufacturing/test during spring quarter. Each category contains project goals and deadlines on dates according to reasonable expectations set by the project group.

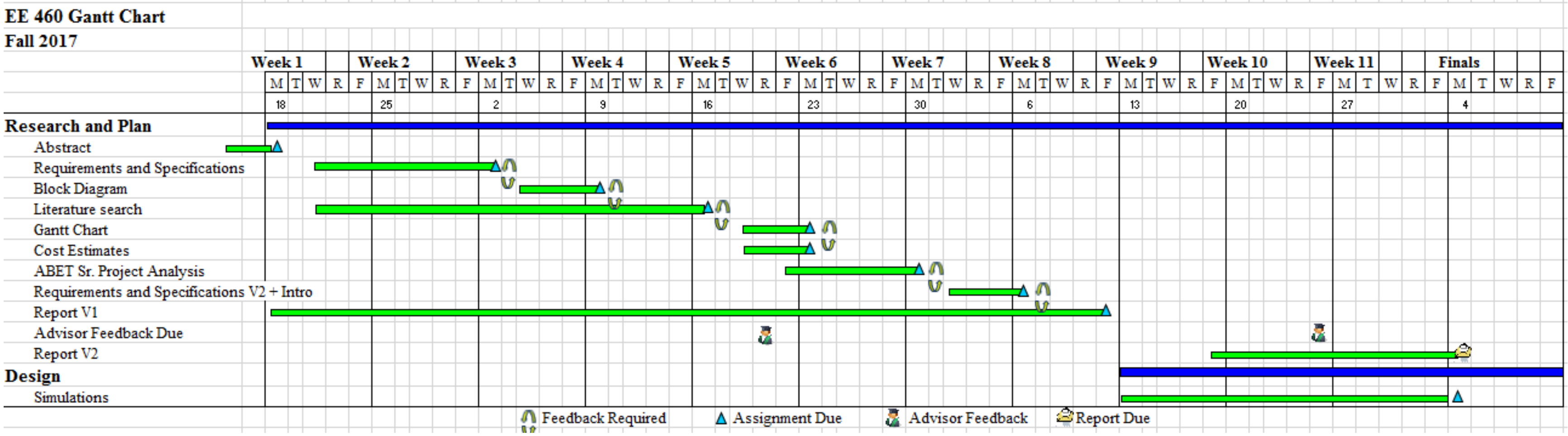


Figure 8: Fall 2017 Gantt Chart

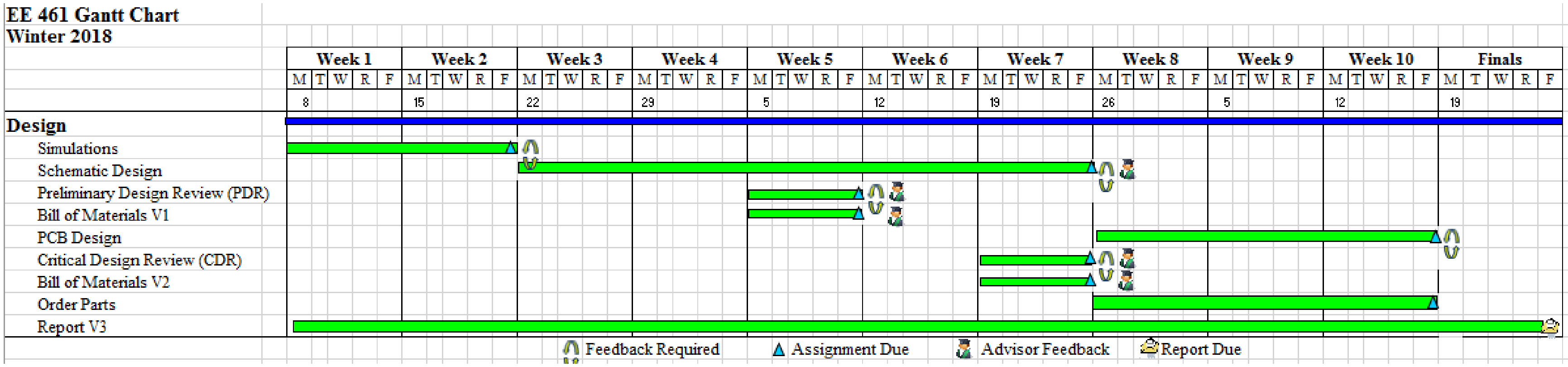


Figure 9: Winter 2018 Gantt Chart

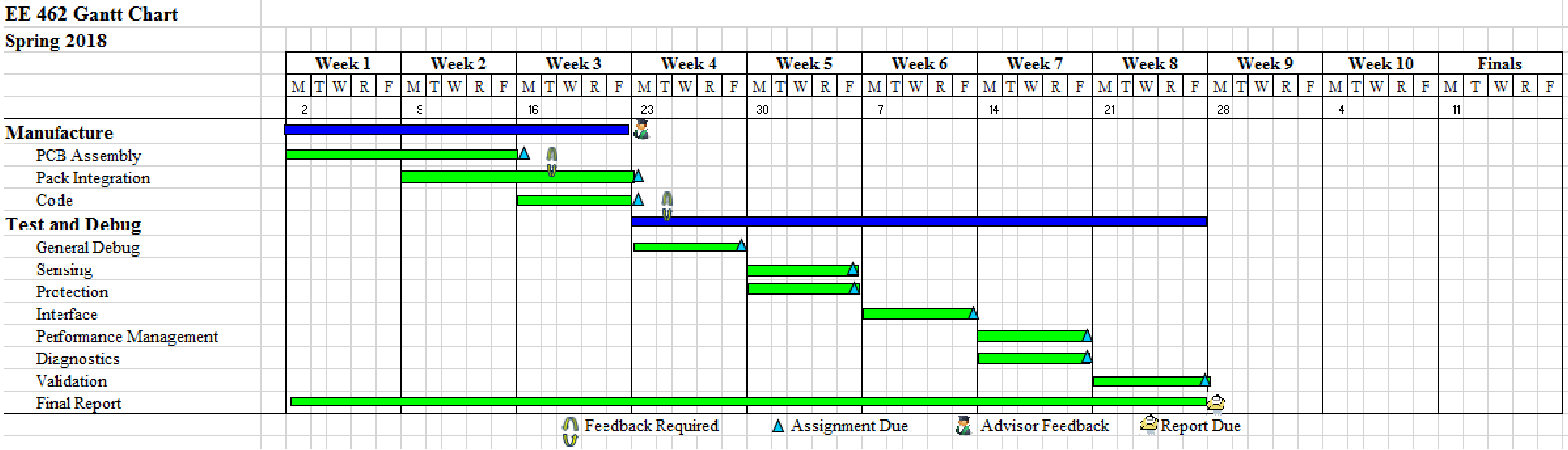


Figure 10: Spring 2018 Gantt Chart

4.1 Estimated Project Costs

This senior project primarily partners with Cal Poly Racing which allows access to their members, knowledge, and equipment. Additional materials and samples from Cal Poly Racing industry contacts leverages the CPConnect budget. This project, completely standalone from club activity, isn't subject to club design reviews and allocated funding this year. However, during Cal Poly's 2018-2019 academic year, this senior project will be fully integrated into the electric vehicle as an official project, which opens the opportunity for MESFAC and other funding sources.

Additionally, this senior project partners with Sharpell Technologies, a company focusing on building high-performance custom battery packs for the automotive, defense, and energy grid sectors. While the company currently supports the project with material and equipment resources, future opportunities, including monetary support, may result depending on the project success.

Project costs were estimated initially using the formula found in *Design for Electrical and Computer Engineers* by Ford & Coulston [12]. See Appendix B for the initial breakdown.

A second estimate was formed during the CPConnect Proposal. CPConnect granted this senior project **$5,000** until December 15th, 2018. See Appendix C for the final breakdown.

Proposed budget divides into operating expenses and manufacturing costs. Non-computer supplies and materials, estimated to cost **$3000** for multiple design revisions, includes battery management integrated circuits, electronics, controller area network transceivers, opto-isolators, passive/active components, wires, lithium-ion batteries, microcontrollers, nickel strips, Kapton tape, solder, spot welder leads, safety equipment, custom holders, terminals, and test leads. Computer supplies and materials, estimated to cost **$20**, includes office supplies and poster boards. Software and software licenses, estimated to cost **$480**, includes four Altium student edition PCB design software. Membership dues and subscription, estimated to cost **$40**, includes Cal Poly Racing yearly membership dues. Contracted services, estimated to cost **$1460**, include likely PCB manufacturing costs according to Cal Poly Racing information. In addition, the budget requested will be leveraged by additional materials, samples, and equipment from industry contacts and existing team members. The total cost of this project is **$5000.**

Budget validated by comparing overall project cost to consumer price of similar off-the-shelf battery management system solutions. Prices below come from company product websites and requested quotes. Estimated prices from Elithion Inc. ($1348.12), OrionBMS ($1162.50), and Elektromotus ($1456.85) have an average value of $1322.49. The addition of design, manufacturing, and production costs show the requested budget is within reason.

4.2 Major Equipment, Facilities, and other Resources

The electrical engineering Electrochemistry Lab (20-130) provides most of the necessary equipment and lab space. This lab, also used by Cal Poly Racing, contains 16 research benches and an open-space projects area. Each station includes an oscilloscope, function generators, power supplies, and digital multimeters. Additionally, the lab includes a custom automated lab bench with electronic loads, programmable power supplies, acquisition units, and source meters for energy storage characterization, life, and reference performance testing. Other equipment includes a Sunstone spot welder, various hand tools, and safety equipment.

4.3 Final Products and Dissemination

Project completion results in a fully-functional BMS integrated into a single battery module. The project will be presented during the Cal Poly Electrical Engineering senior project expo, along with project plans and acquired data. During the Cal Poly academic year 2018-2019, this project and its designs will be improved and implemented into the Cal Poly Racing Electric car for use in the Formula SAE electric competition. At the competition, the Cal Poly Racing team presents the entire electric car, including this senior project, to a panel of industry professionals who assign points to each university by reviewing each vehicle subsystem in depth. During the presentation, team members defend their design choices in front of a wide-ranging audience consisting of other universities, companies, and engineers.

5.0 Project Design

The following section is a comprehensive description of the project design. This section will be divided into functional blocks. Basic design background information is below.

Battery Pack Specifications

- Max Voltage = 300 V
- Nominal Voltage = 259.2 V
- Minimum Voltage = 180 V
- Max Output Current = 1000A for < 1s
- Max Nominal Current = 200 A
- Max Charging Current = 8 A
- Total Number of Cells = 720
- Cell Configuration = 72s 10p
- Total Capacity = 6.48 kWh, 23.328 MJ
- Number of Cell Stacks = 4

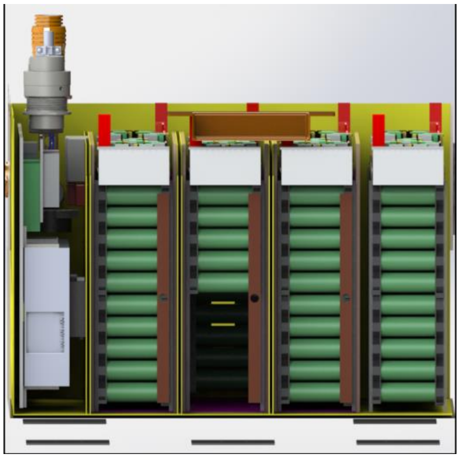


Figure 11: Cal Poly Racing's Battery Box

Objectives

- Build custom system for Cal Poly Racing
- Add foundation for state of charge measurements
- Reduce number of wiring failure points
- Optimize for small cylindrical 18650 cells
- Improve charge and balance time
- Add integrated temperature sensing board
- Improve overall system robustness

After reviewing customer needs and requirements, the team determined a digital balancer in a master-slave topology would fit Cal Poly Racing's needs the best. The team compiled a list of different BMS integrated circuits on the market and found Linear Technology's LTC6811 BMS family fit our needs.

From the LTC6811-1 datasheet,

"The LTC®6811 is a multicell battery stack monitor that measures up to 12 series connected battery cells with a total measurement error of less than 1.2mV. The cell measurement range of 0V to 5V makes the LTC6811 suitable for most battery chemistries. All 12 cells can be measured in 290µs, and lower data acquisition rates can be selected for high noise reduction [13]."

For complete hardware schematics, please refer to Appendix D.

5.1 Overview

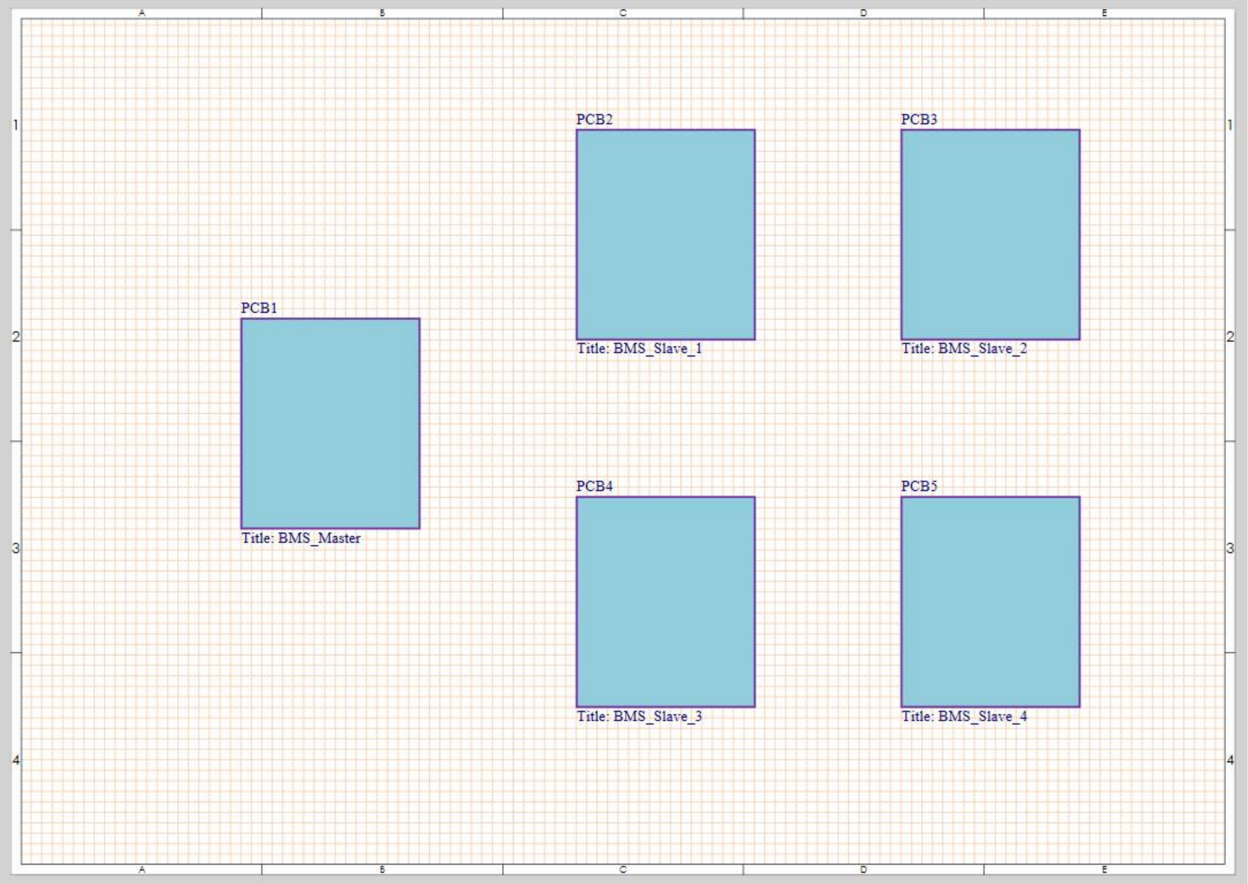


Figure 12: BMS Overview

Figure 12 above shows an abstraction of the BMS. Since Formula SAE mandates that cell segments must contain a maximum static voltage of less than 120 VDC, Cal Poly Racing divided their battery pack into four sections [1]. Since each section is functionally identical, we chose a hybrid master-slave distributed BMS topology.

A hybrid master-slave distributed topology places a single board on top of each cell module. While some academics may disagree on BMS topology terminology, the team considers this system distributed because the electronics are not grouped and housed separately from the cells [4]. Each cell module communicates to the master through a daisy chained communication line. The electronics team placed the master board inside the Low Voltage Box which is separate from the main battery housing.

5.2 BMS Master Schematic Design

The BMS Master handles all computations and communications between the slave modules and the main control unit of the electric vehicle. Figure 13 below shows the overall master system which contains three major blocks: microcontroller, communications, and relay driver. Figure 14 below shows a 3-D render of the master board

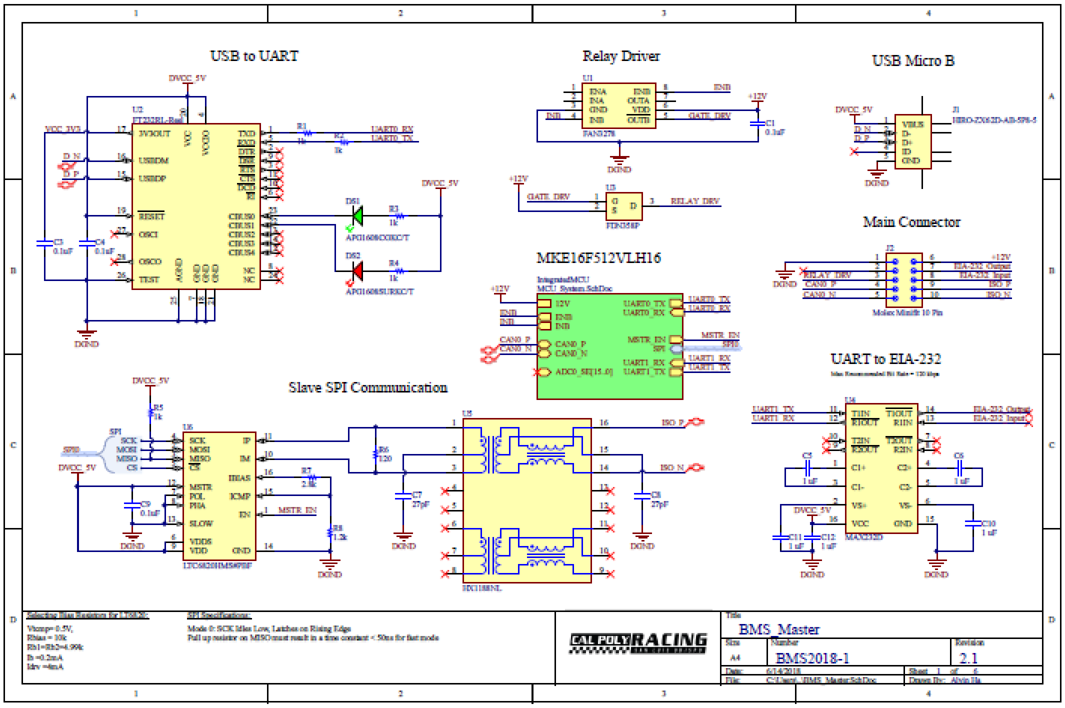


Figure 13: BMS Master Schematic

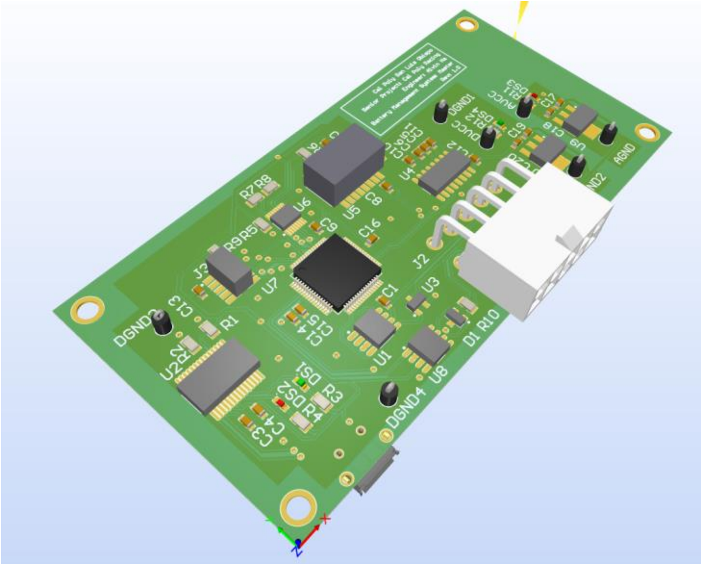


Figure 14: BMS Master 3-D Render

5.2.1 Microcontroller

The BMS master features an MKE16F512VLH16 NXP Kinetis KE16F 160Mz Cortex-M4F microcontroller as the heart of the BMS master [14]. Figure 15 below shows the level 1 microcontroller schematic.

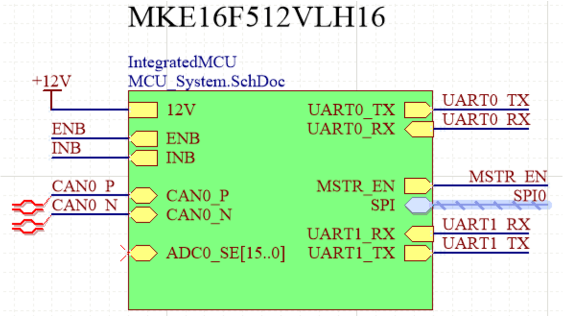


Figure 15: Integrated MCU Level 1 Block

The BMS project was developed alongside the Cal Poly Racing ARM MKE1xF MCU Replatform computer engineering 2018 senior project by Nathan Hong, Derek Lung, Japsimran Singh, and Bevin Tang [15]. Both projects were developed in tandem for the electric car and share many hardware and software designs, including the microcontroller. The BMS team focused primarily on hardware while the ARM Replatform focused primarily on software. The ARM Replatform abstract is listed below [15].

> “After Cal Poly Racing’s electrical team began to hit the technical limits of the ADC and other I/O features of the current 8-bit Atmel AT90 microcontroller unit, it became clear that an upgrade was due. This replatforming project takes the functionalities of the old, 8-bit architecture, and aims to provide a 32-bit version using the ARM MKE1xF MCU. With the idea of having a working PCB as a stretch goal, the scope of the library development was limited to enable base functionality. Thus, the only libraries developed were for the Timer, ADC, SPI, UART, and CAN. Additionally, this document discusses the software and hardware development processes, as well as details on how to use specific components of the newly developed MCU platform. With this upgrade, the platform should be capable of supporting a diverse feature set to meet the needs of many future projects to come.”

The following sub-sections will discuss only the microcontroller hardware design. For a comprehensive software overview including setup, capabilities, and justifications, please view reference 15.

Figure 16 below shows the level 2 microcontroller schematic which includes 3 blocks: power, microcontroller, and communication. A description of the communication sub-block can be found in the overall communication section.

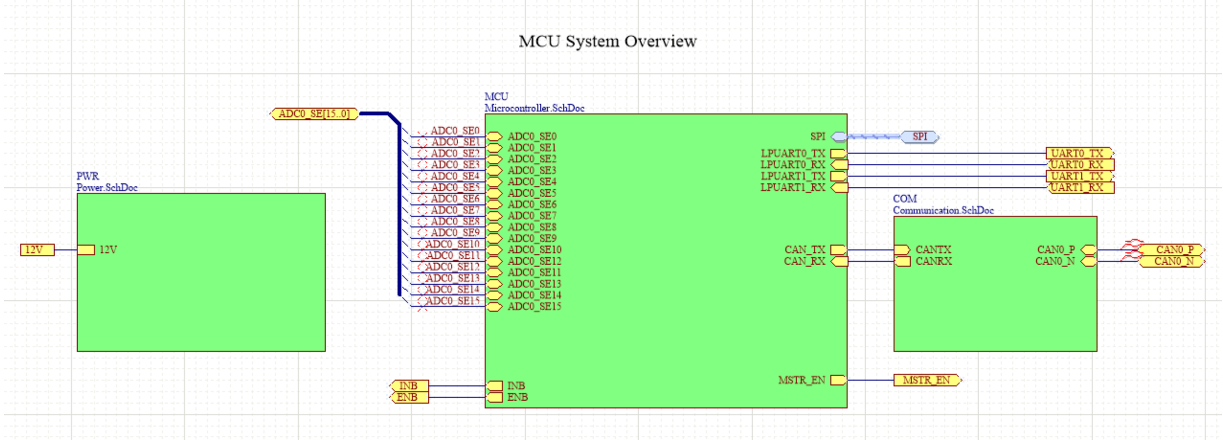


Figure 16: MCU Overview

Power

Since the MCU system was designed as a "plug and play" hierarchal block, analog and digital power were separated to accommodate mixed signal boards. Analog circuitry requires steady noise-free power rails which can be contaminated by digital circuitry which are generally noisy because of constant switching [16]. The power design features two LM340MP voltage regulators to convert 12V from the electric car's low voltage box to a 5V supply [17]. The team considered a switching power supply topology but decided against it due to its complexity. Figure 17 below shows the power circuitry schematic.

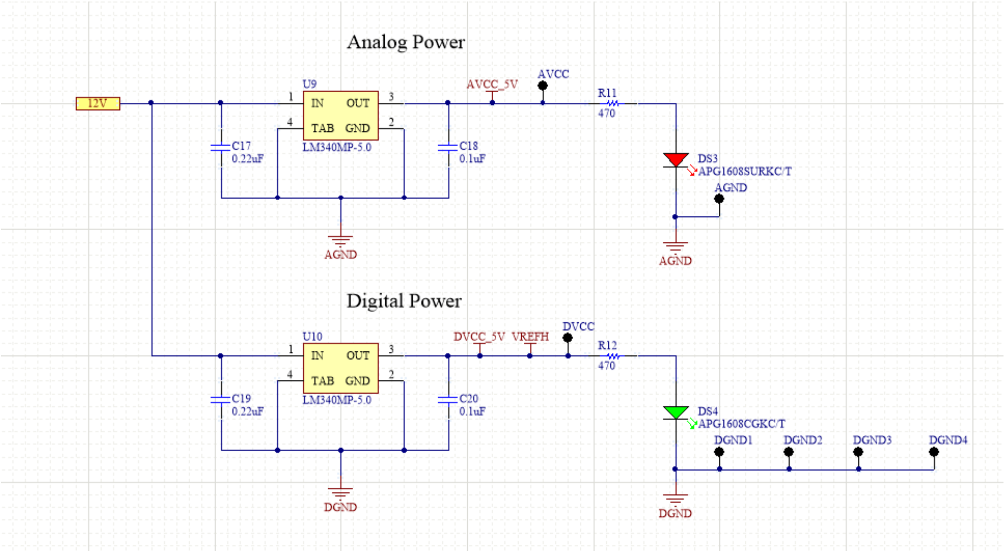


Figure 17: Analog and Digital Power

Microcontroller

The team designed the MKE16F512VLH16 schematic with advice from NXP on integrating their MCUs into schematics. The KE1xF microcontroller is built on the ARM Cortex-M4 processor with stronger performance and higher memory densities in multiple packages [14]. The device offers up to 168 MHz performance with integrated single-precision floating point unit and digital signal processor [14]. The microcontroller is currently configured to support CAN, UART, JTAG, SPI, and an 11 channel ADC. Figure 18 below shows the microcontroller schematic.

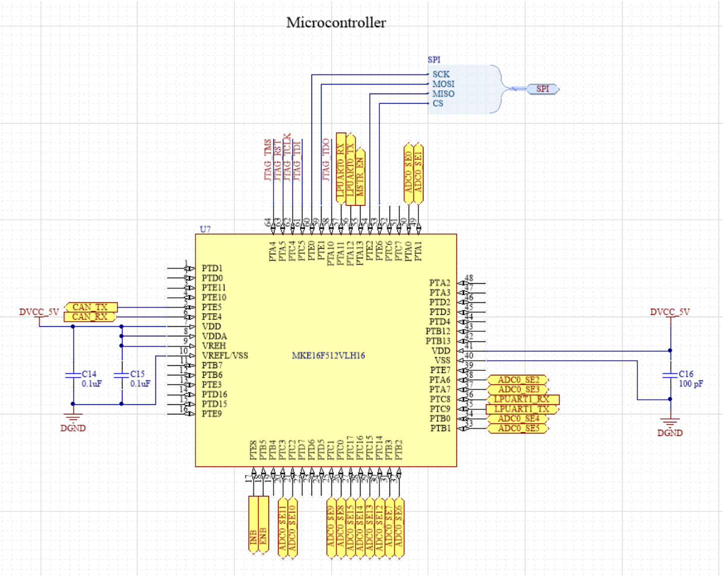


Figure 18: MKE16F512VLH16 System

The team selected a 10-position header pin (2x5) for the JTAG Connector. JTAG is used for debugging and programming of the NXP microcontroller. Figure 19 below shows the connector schematic.

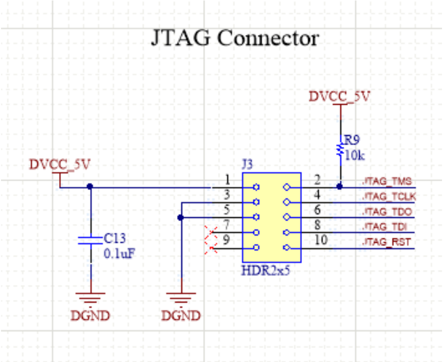


Figure 19: JTAG Connector

5.2.2 Communications

CAN

The BMS Master uses a Controller Area Network (CAN) standard to communicate with the vehicle's main control unit, a National Instruments sbRIO FPGA. The team selected the MCP2561 CAN transceiver, an updated version of the MCP2551 in previous Cal Poly Racing designs. The MCP2561 is a Microchip Technology second generation high-speed CAN transceiver [18]. Figure 20 below shows the CAN circuit schematic.

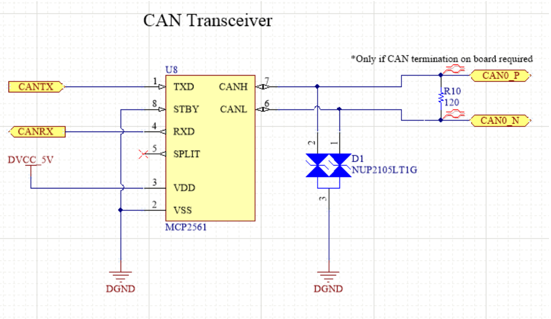


Figure 20: CAN Transceiver

USB to UART

The design implements a common FT232R FTDI chip which converts USB to serial UART with features such as single chip USB to asynchronous serial data transfer, no required USB specific firmware programming, and data transfer rates from 300 baud to 3 MBaud at TTL levels [19].

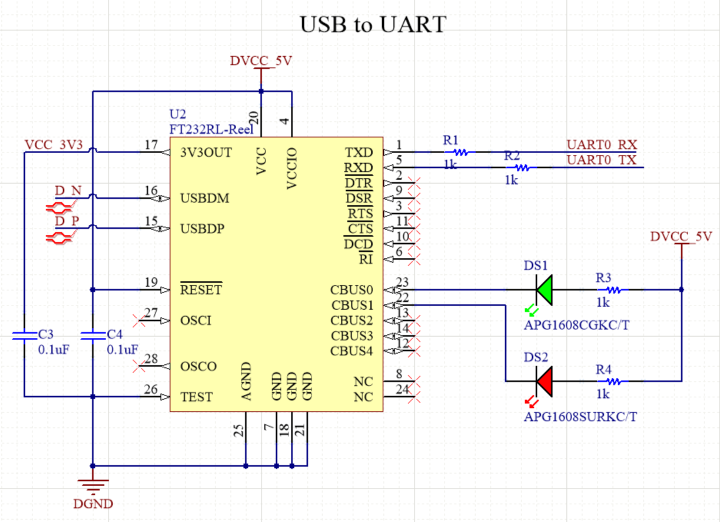


Figure 21: USB to UART

The BMS master uses a standard Micro-USB B bottom mount connector due to its slim profile. Cal Poly Racing is moving from USB Mini B to USB Micro B because of its greater availability.

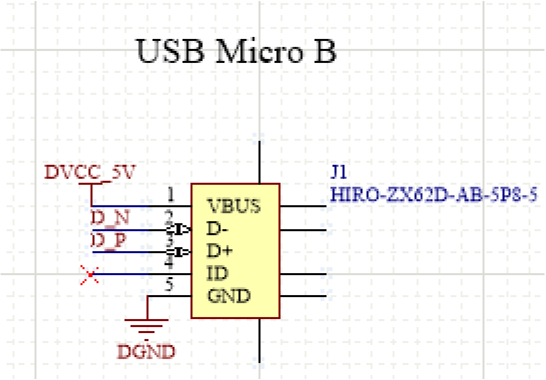


Figure 22: Micro USB Connector

SPI

The BMS master communicates with each slave using Linear Technology's isoSPI isolated communications interface. The LTC6820 features 1 Mbps isolated SPI, simple galvanic isolation using standard transformers, bi-directional interface over a single twisted pair, and very low EMI susceptibility and emissions [20]. The LTC6820 converts standard SPI signals (CS, SCK, MOSI, and MISO) into differential pulses. The selected SPI mode, Mode 0 (POL = 0 and PHA =0), latches data on a rising clock edge. Following some datasheet advice, the team selected bias resistors which set the bias current to 0.5 mA as a tradeoff between power consumption and noise immunity. In a typical CAT5 twisted pair, these settings allowed for communication up to 50 meters [20]. Figure 17 below shows the isoSPI schematic.

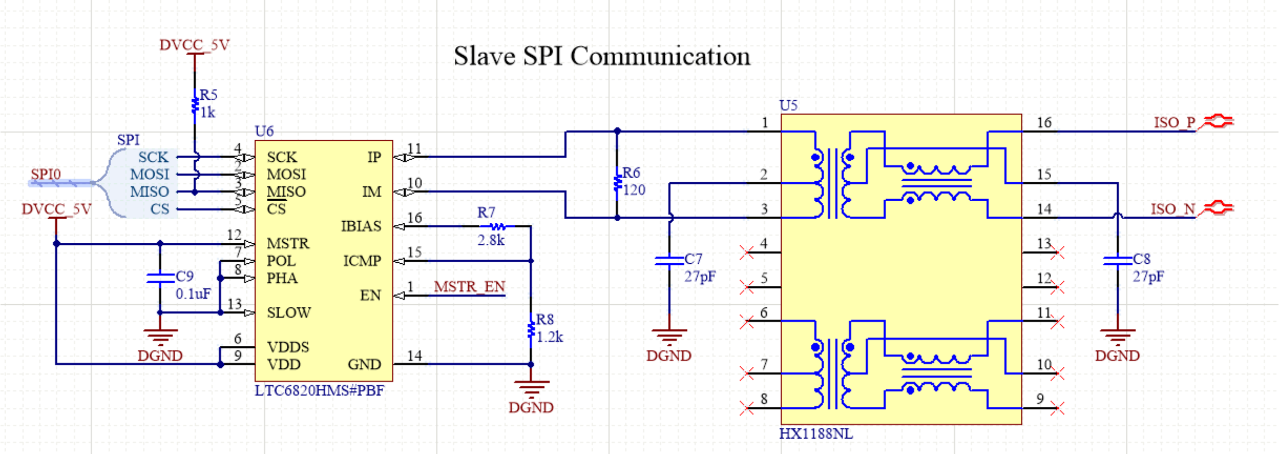


Figure 23: isoSPI Communication Setup

The isoSPI signals have programmable pulse amplitudes up to 1.6V, and pulse widths of 50ns and 150ns [20]. To meet these requirements, the team chose a transformer having a magnetizing inductance ranging from 50 µH to 350 µH, and a 1:1 or 2:1 turns ratio. In addition, the team selected a transformer with a center tap and common mode choke for optimal common mode noise rejection. The datasheet recommended several transformers including 10/100BaseTX Ethernet transformers. From this list, the team selected the HX1188NL transformer from Pulse Electronics. Figure 18 below shows an example of isoSPI pulses.

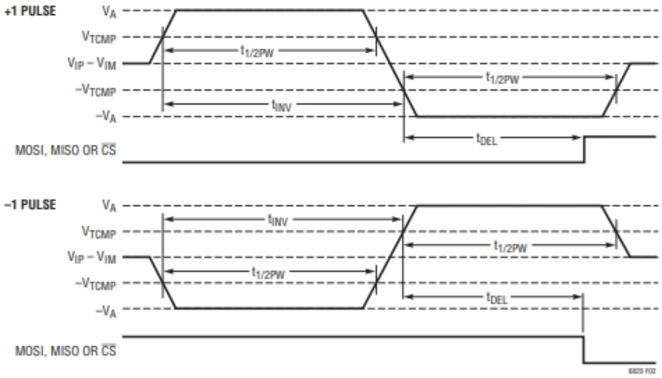


Figure 24: isoSPI Differential Pulse Detail [20]

RS-232

The BMS master also implements serial RS-232 using a common MAX232D chip from Texas Instruments. The MAX232D is a dual device driver/receiver that includes a capacitive voltage generator to supply TIA/EIA-232-F voltage levels from a single 5V supply [21]. This chip converts UART serial communication into RS-232 levels at a maximum recommended bit rate of 120 kbps. Figure 19 below shows the MAX232D schematic.

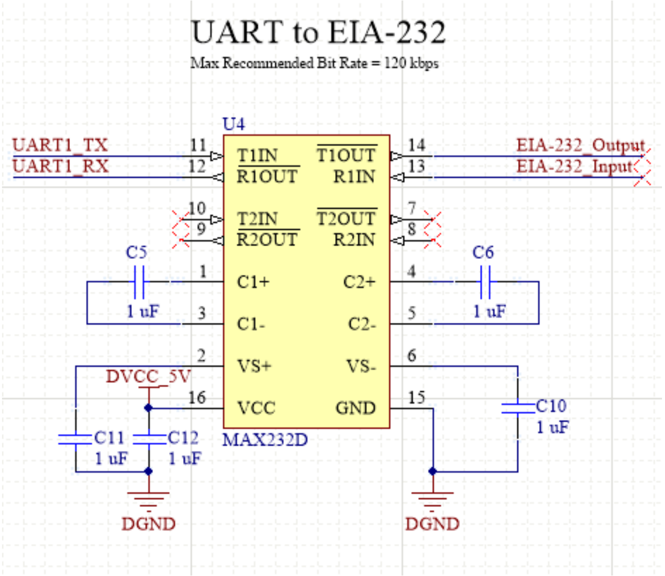


Figure 25: UART to EIA-232

5.2.3 Relay Driver

Cal Poly Racing requires a relay driver for an Accumulator Isolation Relay (AIR) which shuts down the tractive system if critical voltages or temperatures are detected. The team calculated a maximum current draw of 0.5A. The design features a FAN3278 low voltage PMOS-NMOS bridge driver and FDN358P single p-channel MOSFET. Figure 26 below shows the driver schematic. Figure 27 and 28 below show the LTSpice simulation.

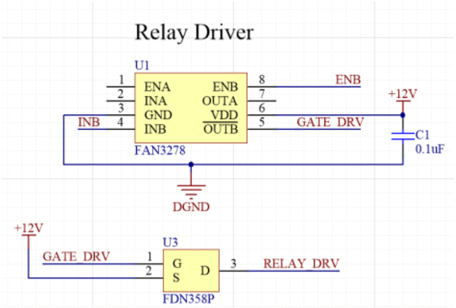


Figure 26: Relay Driver

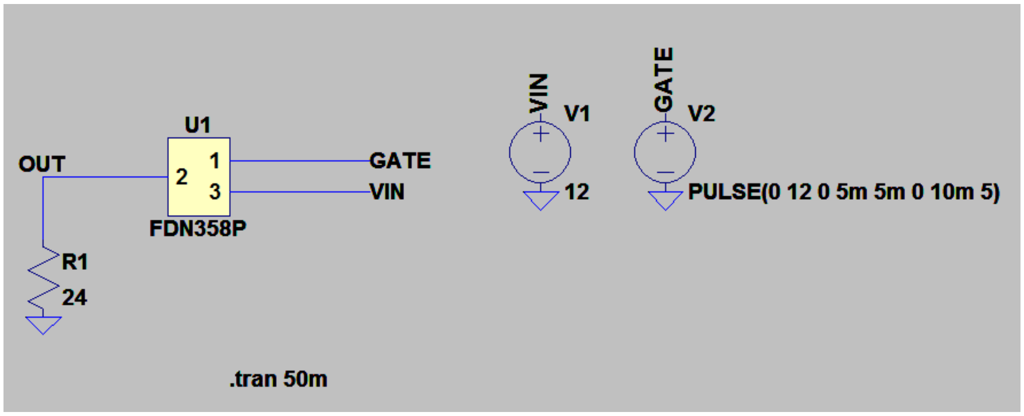


Figure 27: LTSpice Relay Simulation

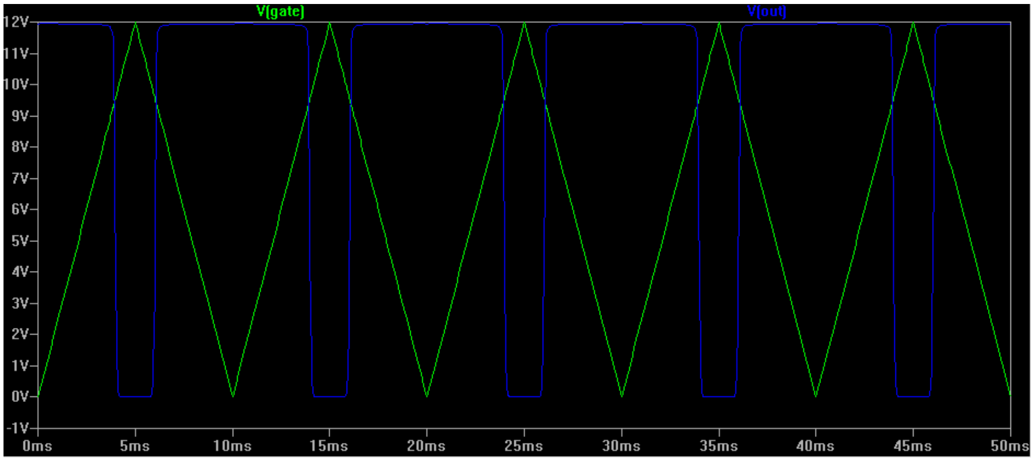


Figure 28: LTSpice Relay Waveforms

5.3 BMS Master Layout Design

The BMS Master fits on a 2x4 inch two-layer PCB with 2 oz copper traces. The PCB contains two major sections: power (green square) and the microcontroller (yellow). Since every communication chip is affected by trace length, the PCB design attempts to build around the main 10-position connector located at the bottom of the board. For manufacturing simplicity, all the components except the bottom mount USB are located on one side. Figure 29 below shows the BMS 2-D layout while Figure 30 shows the BMS 3-D layout.

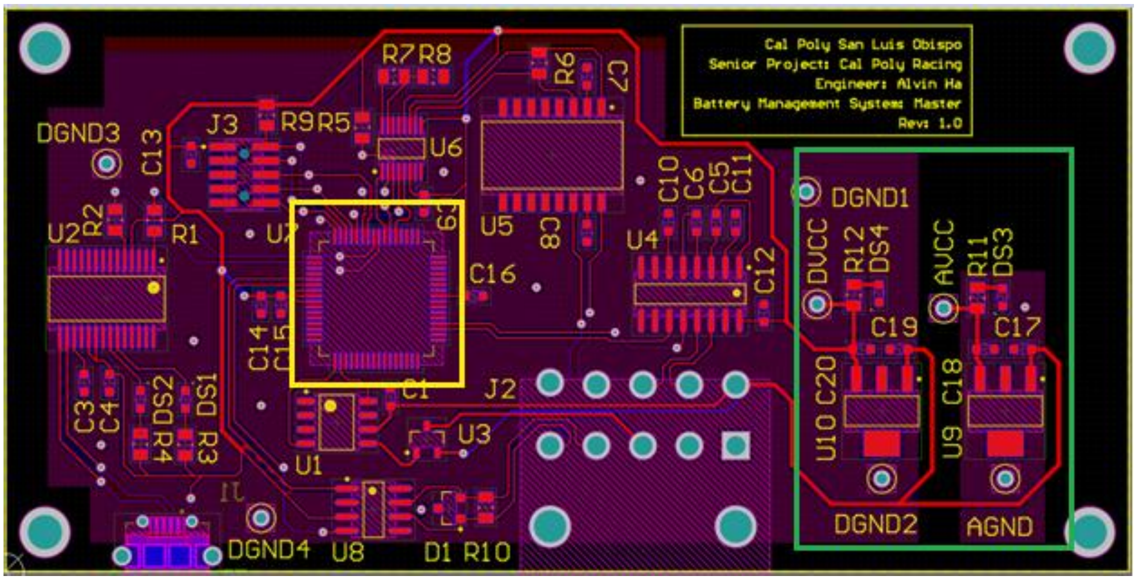


Figure 29: BMS Master 2-D Layout

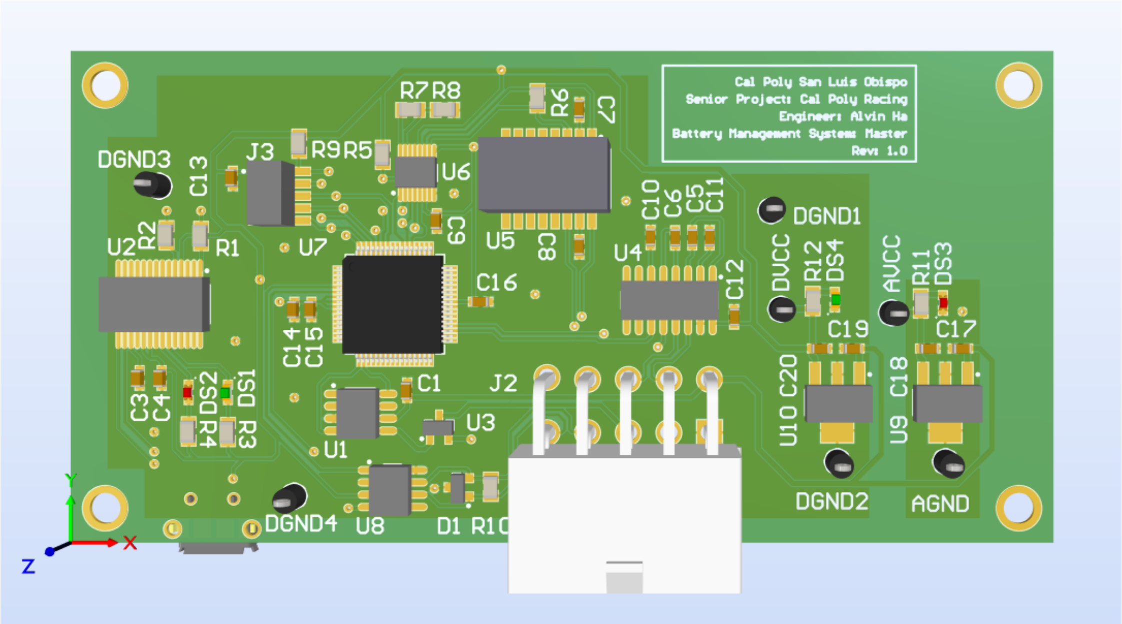


Figure 30: BMS Master 3-D Layout

5.4 BMS Slave Schematic Design

The BMS Slave focuses on monitoring and protection built around Linear Technology's LTC6811-1 multicell battery monitor. The BMS Slave schematic has a flat design with repeated circuitry heavily based on Linear Technology's DC2259A, the development board for the LTC6811 [22]. The circuitry is divided into three main categories: the main battery monitor integrated circuit (IC), isolated transformers, and cell balancers. Figure 31 below shows the overall BMS Slave schematic. Figure 32 below shows the 3-D render of the BMS Slave.

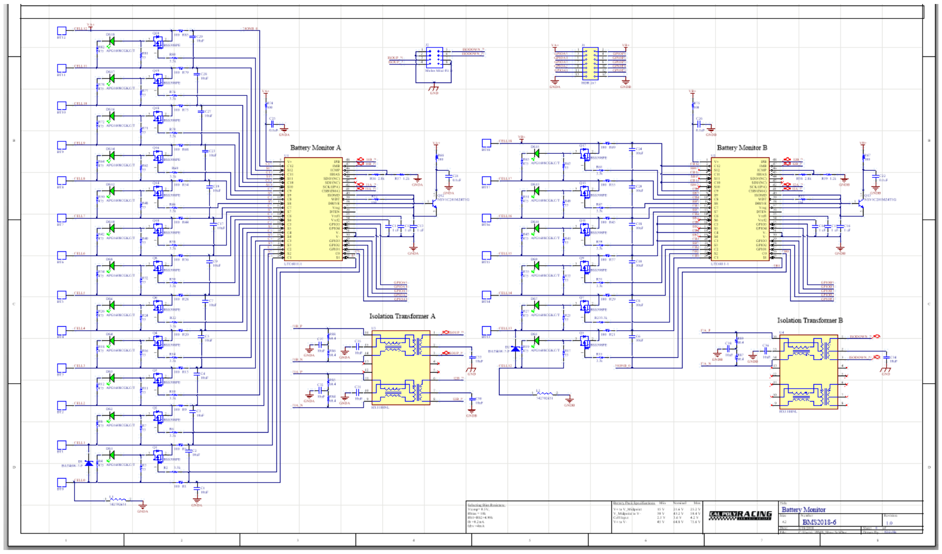


Figure 31: BMS Slave Board

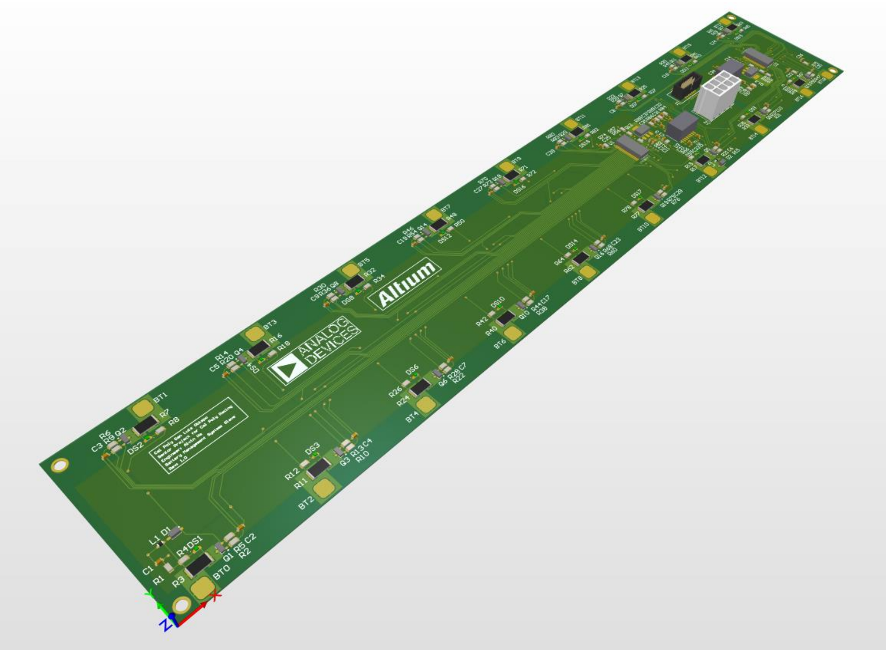


Figure 32: BMS Slave 3-D Render

5.4.1 Main Battery Monitor

After comparing different BMS chipsets, the team decided to implement the LTC6811 from Linear Technology. The LTC6811 is a multicell battery stack monitor that measures up to 12 series connected battery cells with a total measurement error of less than 1.2mV [13]. Multiple LTC6811 devices can be connected in series, permitting simultaneous cell monitoring of long, high voltage battery strings [13]. Figure 33 below shows the LTC6811 schematic.

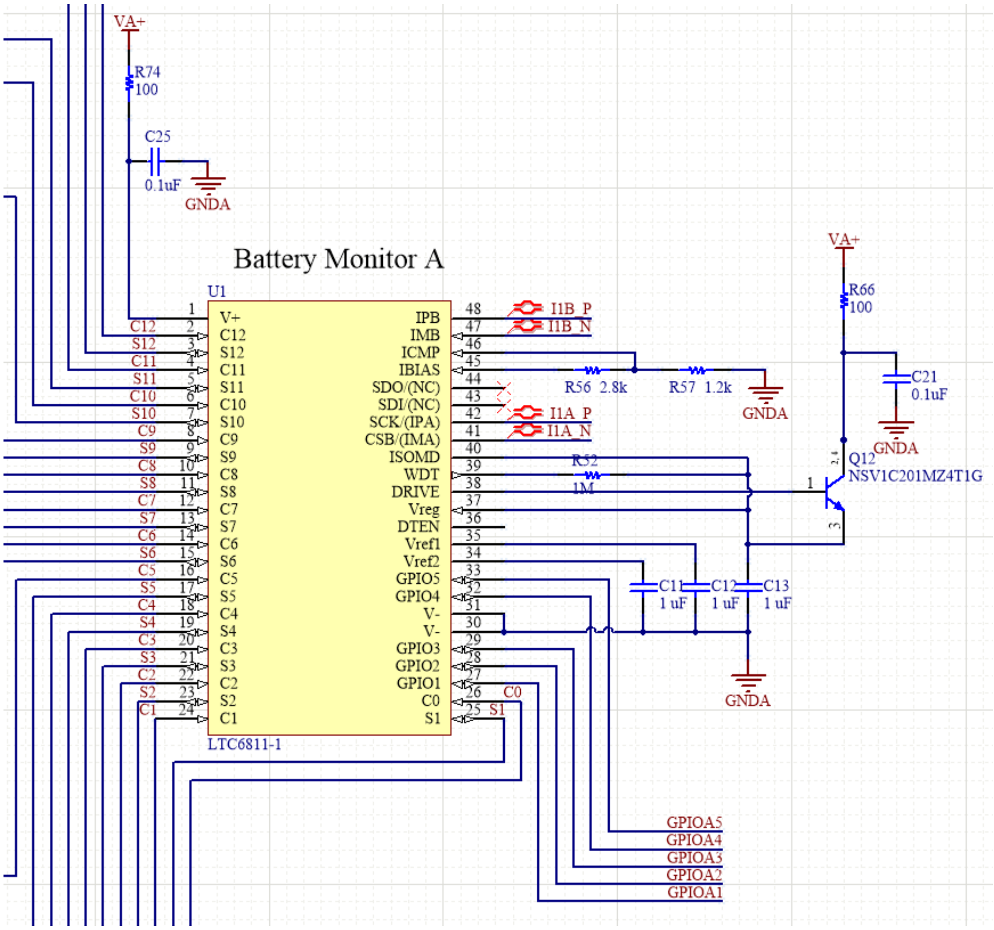


Figure 33: LTC6811 Battery Monitors

Each LTC6811 can monitor up to 12 cells in series. The BMS Slave design includes Battery Monitor A which monitors 12 cells and Battery Monitor B which monitors 6 cells for a total of 18 cells in series. The BMS Slave is powered directly off the cell stack and uses an NSV1C201MZ4 NPN transistor as a linear regulator to supply the V_{reg} input pin.

Like the LTC6820, the team selected bias resistors which set the bias current to 0.5 mA as a tradeoff between power consumption and noise immunity.

For a detailed description of the LTC6811 functionality, please view the datasheet listed as reference 23. Figure 34 below describes the different LTC6811 states of operation.

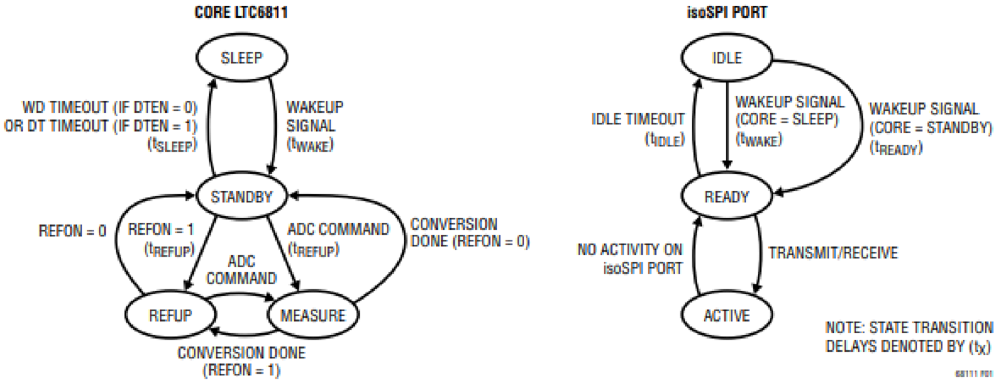


Figure 34: LTC6811 Operation State Diagram [13]

5.4.2 Isolation Transformers

The LTC6811 uses the same isoSPI communication protocol detailed in the BMS Master SPI section. The BMS Slave implements the same ethernet isolation transformer for communication over twisted pair. The LTC6811s have daisy-chained communication for communication robustness. Figure 35 below shows one of the isolation transformers.

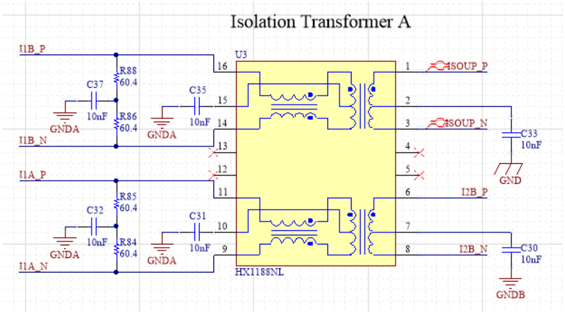


Figure 35: Isolation Transformer A

The BMS Slave uses a Molex Mini-fit Jr connector according to standards set by Cal Poly Racing. Figure 36 below shows the connector schematics

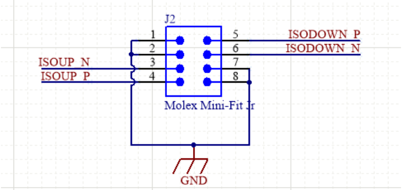


Figure 36: Molex Mini-fit Jr

5.4.3 Cell Balancer

For a comprehensive discussion on battery balancing including balancing theory, different methods, and the recommendation for Cal Poly Racing, please view Alvin Ha's recommendation report listed in Appendix E.

The LTC6811 implements passive balancing using external resistors and transistors to remove excess energy from the most charged cell. The BMS Slave contains 18 sets of the same components since each cell needs its own circuitry. The design is heavily based on Linear Technology's DC2259A development board [22]. Figure 37 below shows an example of the balancing components.

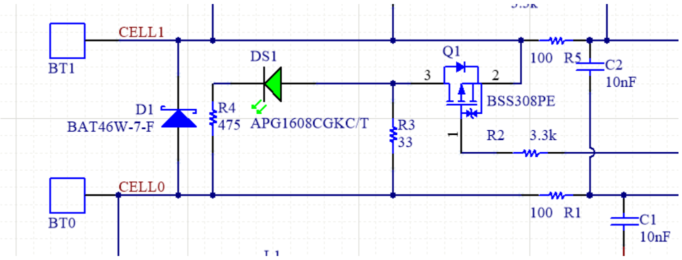


Figure 37: Balancing Circuit

Using the equations listed in reference 13, the balancing components were designed for a balance current of 0.1 A, which can correct a 5% imbalance of the total 25 Ah pack in approximately 12.5 hours. According to information from Jon Munson, a Linear Technology Senior Applications Engineer, Cal Poly Racing's battery pack should only develop about 1 mAh of imbalance after a single cycle. The balancing circuitry can correct 1 mAh of imbalance in approximately 36 seconds.

5.4.4 Temperature Monitoring

Formula SAE requires monitoring the temperature of 30% of all the batteries in the pack. Due to time constraints and the difficulty of finding a solution, this senior project allocates space and GPIO signals for another group to implement a comprehensive temperature monitoring solution. Figure 38 below shows the 2x7 header pin used.

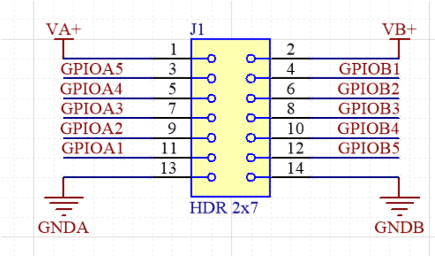


Figure 38: GPIO Connector for Future Integrated Temperature Solutions

5.5 BMS Slave Layout Design

The BMS Slave was designed on a 14.3x2.5’’ inch two-layer PCB with 2 oz copper traces. The dimensions of this board fit the exact space on top of each battery module. The PCB contains two major sections: cell balancing (green squares) and the LTC6811 associated circuitry (yellow). Each cell circuitry is connected to a rounded pad where the nickel bus bars are soldered directly on. For manufacturing simplicity, all the components are located on one side. Figure 38 below shows the BMS 2-D layout while Figure 39 shows the BMS 3-D layout.

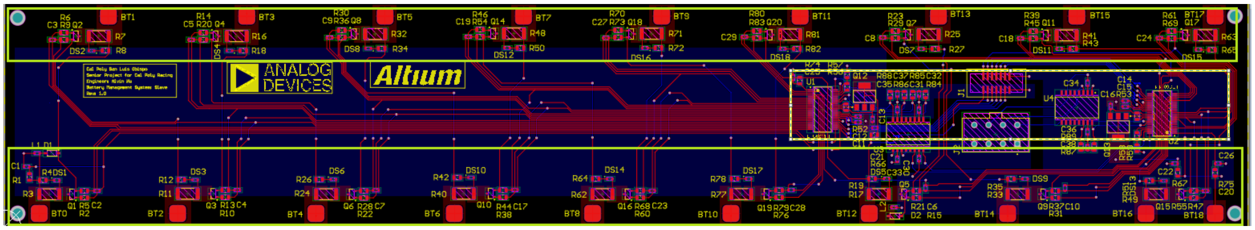


Figure 39: BMS Slave 2-D Layout

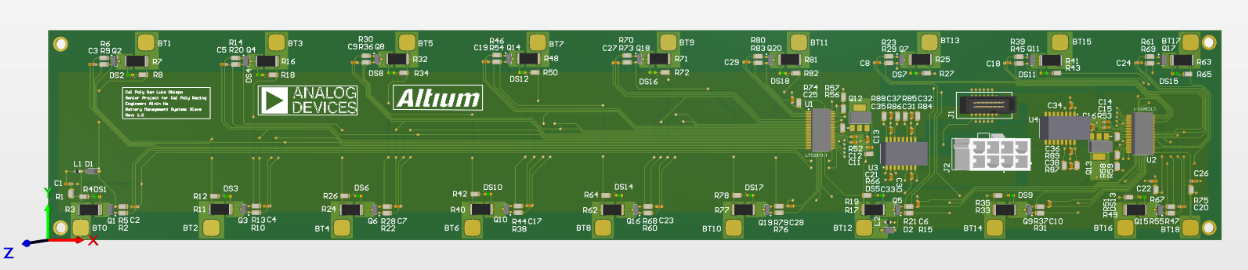


Figure 40: BMS Slave 3-D Layout

6.0 Manufacturing and Integration

This senior project used Bay Area Circuits to manufacture all the PCBs according to Gerber files generated in Altium Designer. The team populated the board by using a reflow machine and solder iron and purchased parts from various vendors including Digikey, Mouser, and Linear Technology.

The team built a miniature version of a single battery module which only used 36 batteries (18 series 2 parallel). A full-sized module is infeasible to test because of the required power rating for testing equipment and the time to charge/discharge.

Figure 41 below shows the BMS Slave board integrated into the test module. Figure 42 below shows the completed master board.

Figure 41: BMS Slave Test Module

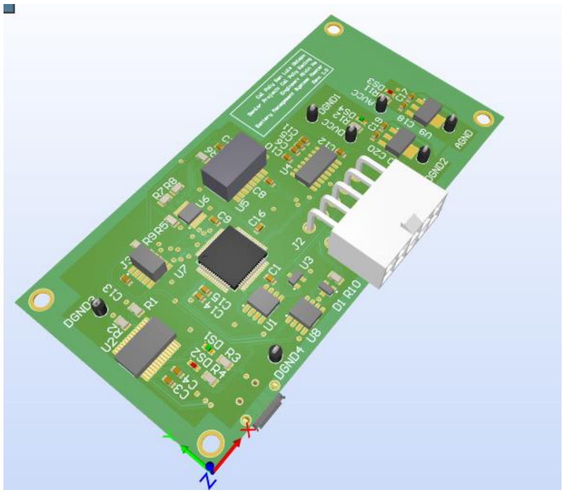


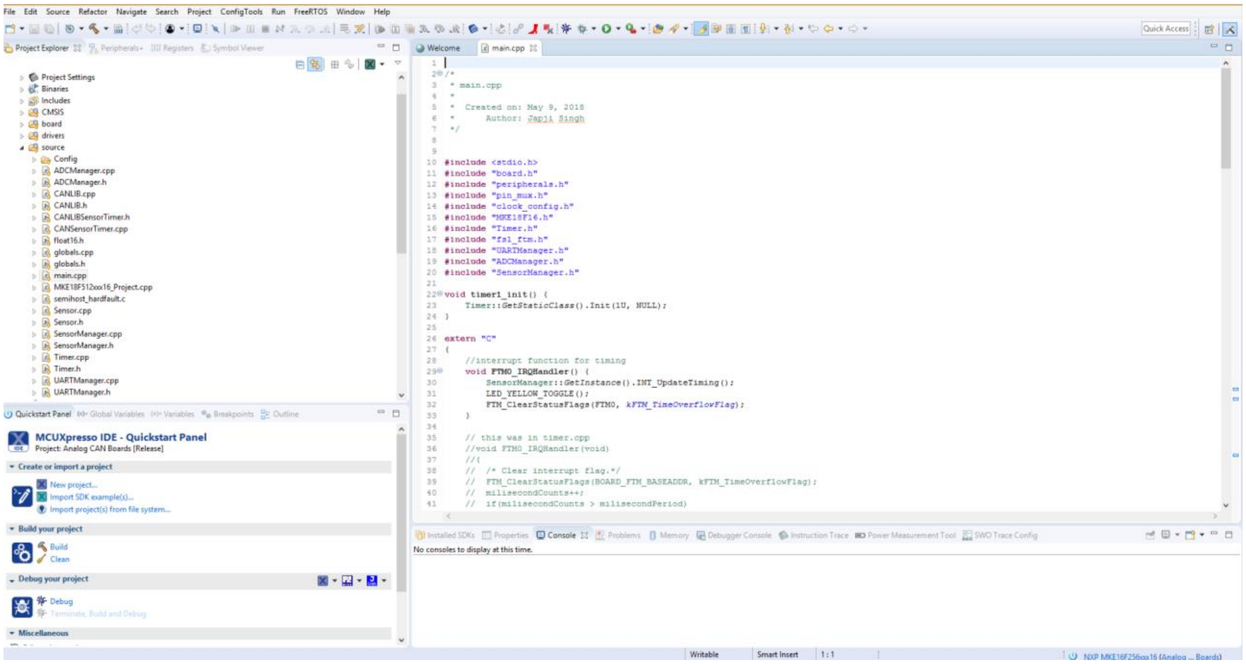
Figure 42: BMS Master Board

7.0 Testing

Overall, the team was only able to test the basic functionality of the battery management system. Testing was limited by two factors: time constraints and lack of a fully developed codebase. However, Cal Poly Racing will be continuing this senior project, which has formed a good foundation, throughout the next year. Thus, this section will also include guidelines for future comprehensive testing.

BMS Master

The BMS Master was most impacted by the lack of fully developed code. However, the team was able to flash the microcontroller using the Kinetis IDE software and the P&E UMultilink seen in Figure 43 and 44 below. For a full description of the microcontroller software, see reference 15.



```

/*
 * main.cpp
 *
 *  Created on: May 9, 2018
 *      Author: Japji Singh
 */


#include <stdio.h>
#include "board.h"
#include "peripherals.h"
#include "pin_mux.h"
#include "clock_config.h"
#include "MKE18F16.h"
#include "Timer.h"
#include "fsl_ftm.h"
#include "UARTManager.h"
#include "ADCManager.h"
#include "SensorManager.h"

void timer1_init() {
    Timer::GetStaticClass().Init(1U, NULL);
}

extern "C"
{
    //interrupt function for timing
    void FTM0_IRQHandler() {
        SensorManager::GetInstance().INT_UpdateTiming();
        LED_YELLOW_TOGGLE();
        FTM_ClearStatusFlags(FTM0, kFTM_TimeOverflowFlag);
    }

    // this was in timer.cpp
    //void FTM0_IRQHandler(void)
    //{
    //  /* Clear interrupt flag.*/
    //  FTM_ClearStatusFlags(BOARD_FTM_BASEADDR, kFTM_TimeOverflowFlag);
    //  milisecondCounts++;
    //  if(milisecondCounts > milisecondPeriod)
```

No consoles to display at this time.

Figure 43: Kinetis MCUXpresso

Figure 44: P&E Universal Multilink Debugger

A comprehensive list of desired BMS Master tests and their engineering specifications is found in table 10 below.

Table 10: BMS Master Tests

Test Name	Engineering Specification
General Electrical Conductivity	
Flashing the Microcontroller	The system must be able to be programmed and debugged by Cal Poly Racing members.
Microcontroller Functions	System must calculate common battery characteristics including state-of-charge, state-of-health, and power limits and report them to the main controller.
CAN Communication	Each distributed system module must communicate with the centralized controller with RS232 or CAN.
Slave SPI Communication	Each slave module must communicate with the master board using a serial communication protocol.
USB Communication	The system must be able to be programmed and debugged by Cal Poly Racing members.
UART Communication	Each distributed system module must communicate with the centralized controller with RS232 or CAN.
Relay Driver	System must provide a relay driver for an Accumulator Isolation Relay for hardware shutdown.

BMS Slave

The team combined three development boards from Linear Technology to emulate the BMS Master for the slave board, since the slave board cannot be tested alone. The DC2259A provided a LTC6811 with daisy chained isoSPI communication. The DC2026C provided an Arduino and QuikEval code development platform like the NXP microcontroller on the master board. Lastly, the DC1941D provided the isoSPI transceiver using the LTC6820. Figure 45 below shows the testing setup for the LTC6811.

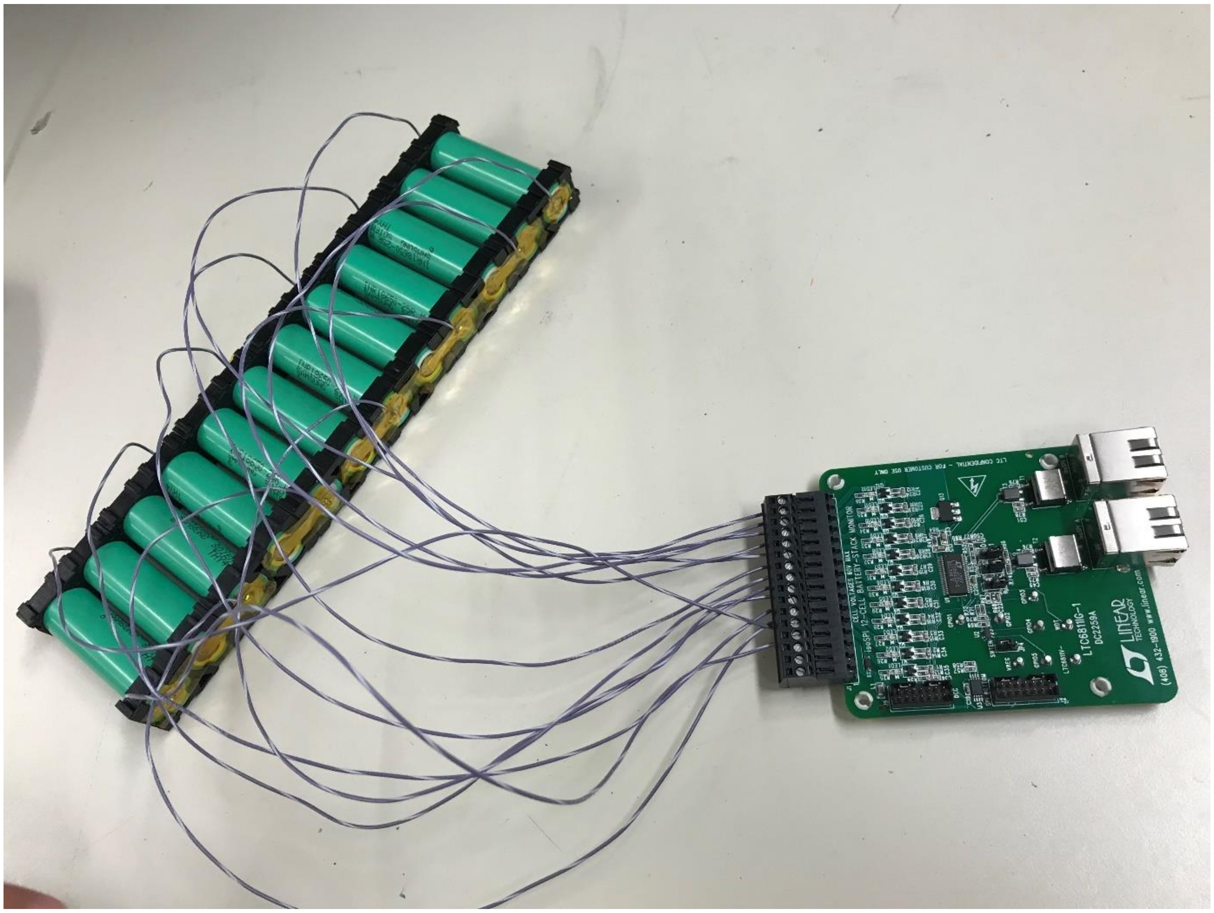
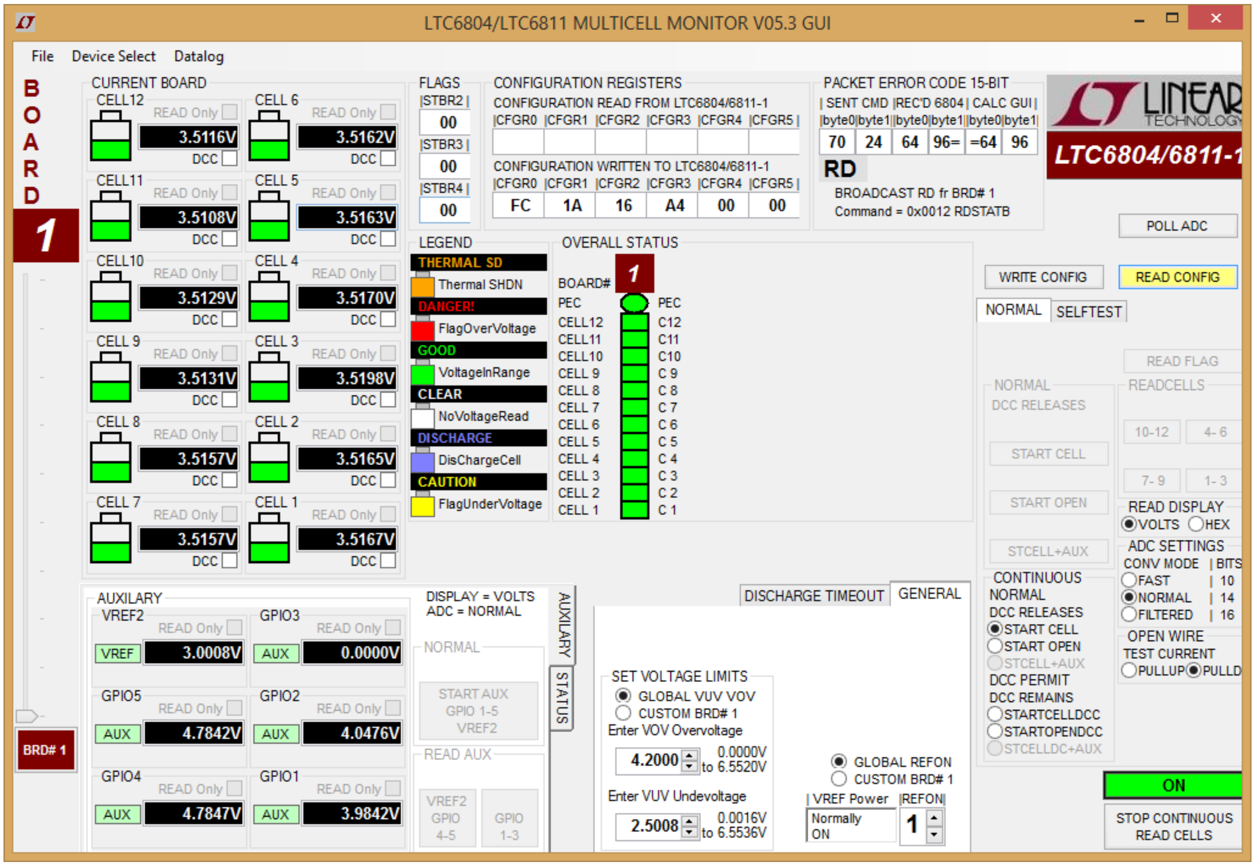


Figure 45: Battery Monitor Test Setup

The Linear Technology development boards also feature a graphical user interface (GUI), used to test the functionality of the LTC6811. Using the GUI, the team was able to test the voltage measurement accuracy, protection against over charge, protection against over discharge, and balancing. Figure 46 on the next page shows the DC2259A GUI.



CELL	Voltage	CELL	Voltage
CELL12	3.5116V	CELL 6	3.5162V
CELL11	3.5108V	CELL 5	3.5163V
CELL10	3.5129V	CELL 4	3.5170V
CELL 9	3.5131V	CELL 3	3.5198V
CELL 8	3.5157V	CELL 2	3.5165V
CELL 7	3.5157V	CELL 1	3.5167V

AUXILARY	Voltage		Voltage
VREF2 (VREF)	3.0008V	GPIO3 (AUX)	0.0000V
GPIO5 (AUX)	4.7842V	GPIO2 (AUX)	4.0476V
GPIO4 (AUX)	4.7847V	GPIO1 (AUX)	3.9842V

|STBR2| 00
|STBR3| 00
|STBR4| 00

CONFIGURATION READ FROM LTC6804/6811-1

CFGR0	CFGR1	CFGR2	CFGR3	CFGR4	CFGR5

CONFIGURATION WRITTEN TO LTC6804/6811-1

CFGR0	CFGR1	CFGR2	CFGR3	CFGR4	CFGR5
FC	1A	16	A4	00	00

SENT CMD		REC'D 6804		CALC GUI	
byte0	byte1	byte0	byte1	byte0	byte1
70	24	64	96=	=64	96

RD
BROADCAST RD fr BRD# 1
Command = 0x0012 RDSTATB

OVERALL STATUS: BOARD# 1; PEC; CELL12 … CELL 1 (C12 … C 1)

DISPLAY = VOLTS
ADC = NORMAL

● GLOBAL VUV VOV ○ CUSTOM BRD# 1
Enter VOV Overvoltage 4.2000 (0.0000V to 6.5520V)
Enter VUV Undevoltage 2.5008 (0.0016V to 6.5536V)
● GLOBAL REFON ○ CUSTOM BRD# 1
|VREF Power |REFON| Normally ON 1

CONTINUOUS
NORMAL
DCC RELEASES
● START CELL
○ START OPEN
○ STCELL+AUX
DCC PERMIT
DCC REMAINS
○ STARTCELLDCC
○ STARTOPENDCC
○ STCELLDC+AUX

READ DISPLAY ● VOLTS ○ HEX
ADC SETTINGS
CONV MODE | BITS
○ FAST | 10
● NORMAL | 14
○ FILTERED | 16
OPEN WIRE TEST CURRENT ○ PULLUP ● PULLD

Figure 46: DC2259A GUI

A comprehensive list of desired BMS Slave tests and their engineering specifications is found in table 11 below.

Table 11: BMS Slave Tests

Test Name	**Engineering Specification**
General Electrical Conductivity	
Voltage Accuracy	System must measure DC voltage ranging from 2.5V to 4.2V with an accuracy of 20 mV.
Voltage Measurement Interval	The system must measure cell voltages every 30ms, keeping the cells inside the allowed minimum and maximum cell voltage levels stated in the cell data sheet.

Balancing	System must monitor and balance cell charge using a balancing method.
Temperature Regulation	The system must maintain pack temperature within range of 45°C to 55°C.
Temperature Measurement Interval	The system must measure battery temperature every 30ms and keep cells below the limit stated in the data sheet or below 60°C.
Electrical Isolation	High voltage system must remain galvanically isolated from low voltage components

8.0 Conclusion

Overall, this project experienced mixed success. While much more testing and integration is required, this senior project created a solid foundation for a fully functional battery management system. The hardware design successfully touched on all the engineering specifications for the master and slave board. Since the ARM Replatform senior project provides a solid general code base to work with, Cal Poly Racing is well poised to create BMS-specific code. The future BMS team should consider adding a third LTC6811, which adds enough GPIO pins to implement temperature monitoring using multiplexers. This senior project was a fantastic learning experience in the realm of batteries and battery management systems. With further revisions and testing, the battery management system can be fully functional system for Cal Poly Racing's Formula SAE electric vehicle.

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Appendix A: Senior Project Analysis

Table 12: Senior Project Design Analysis

Project Title: Passive Balancing Battery Management System for Cal Poly Racing's Formula SAE Electric Vehicle

Student's Name: Alvin Joseph Ha **Student's Signature:**

Advisor's Name: William Ahlgren **Advisor's Initials:** W. A. **Date:** 6/19/2018

• 1. Summary of Functional Requirements

The Passive Balancing Battery Management System for Cal Poly Racing's Formula SAE Electric Vehicle senior project provides comprehensive sensing and high voltage control, protection circuitry, interface capability, performance management, and diagnostic information. The system takes in individual cell voltages, input pack current, pack temperature, and input charging power. The system provides protection against over charge, over discharge, over current, thermal runway, shorts, ground faults, and misuse. The system measures each input in a digital signal sent to a microcontroller. The microcontroller analyzes battery characteristics to form diagnostic and performance management information. The system sends commands and data through a CAN bus to the main application controller.

• 2. Primary Constraints

Battery management systems, capable of multiple complex functions, have many different implementations each with their own benefits and drawbacks. Research proved a significant challenge due to the sheer amount of information required for understanding. While some projects facets were decided beforehand, like using lithium-ion batteries, the majority required detailed analysis on the best option. For example, battery management topologies include centralized, master-slave, modular, and distributed. Each topology considers measurement quality, noise immunity, versatility, safety, and cost. In addition, adherence to official Formula SAE Electric rules were huge limiting factors that impacted design. Several requirements and specifications specifically aimed at fulfilling competition guidelines.

• 3. Economic

Human Capital – What people do

Tesla, a large-scale automobile company, delivered 77,000 electric vehicles to consumers in 2016 [24]. Using Tesla as an example, each electric vehicle requires a BMS. From design to maintenance for just the BMS, the estimated number of employees required is 200, including engineers, technicians, sales, and manufacturers.

Financial Capital – Monetary instruments.

A single BMS unit costs approximately $ 64,364.93 according to the Table IV project budget. Materials including IC, wires, and electronic components cost approximately $ 1,323.44. Manufacturing and test equipment cost approximately $ 237.82. Other costs including labor and software cost $ 64,364.93.

Manufactured or Real Capital – Made by people and their tools.

Battery management systems require extensive labs stocked with state-of-the-art equipment. Electronic test equipment includes oscilloscopes, power supplies, and digital multimeters. Simulation software include STAR CCM+, LTSpice, and PSpice. Manufacturing equipment include spot welders, holders, and hand tools.

Natural Capital – The Earth's resources and bio-capacity.

A large portion of natural capital relates to lithium-ion batteries. Each lithium-ion cell contains three major parts: the anode (graphite), electrolyte (lithium salts), and cathodes (varying chemistries). Many of these natural resources mined from the ground do not currently have adequate supporting infrastructure. Other natural capital include nickel, PCB semiconductor materials, and electricity generated from natural or renewable sources to power manufacturing and test facilities.

During the initial research, design, and simulation phase, only software and labor make up major costs. At this point, employee understanding of BMS theoretical information and functionality benefit the company. As the project moves toward its build and test phase, manufacturing, equipment, and labor costs occur. At this point, fully developed systems ready for product integration benefit the company. Finally, the operational maintenance and debugging phases require minimal labor costs.

Project inputs include component parts and labor. Component parts including ICs, transceivers, isolators, passive components, wires, connectors, terminals, holders, batteries, and microcontrollers originally estimated to cost $ 1,323.44. The entire project development over approximately 9 months costs about $ 65,000. Companies and project teams planning to make this project must allocate sufficient funds to cover estimated costs.

Equipment including solder, Kapton tape, spot welder leads, safety equipment, and test equipment estimated to cost $ 237.87.

A typical standalone BMS goes for approximately $ 1,110 [4]. However, this project aims for integration in an electric vehicle which costs anywhere from $ 23,000 to $ 150,000. Individual battery management solution sellers and electric vehicle companies profit from this project.

Product aims to emerge during the beginning of Cal Poly's 2018-2019 academic year, when Cal Poly Racing includes the BMS in a competition car. Previous Cal Poly Racing BMSs lasted for about three years; this senior project expects to last five. In broader applications such as electric vehicles, the BMS expects a lifetime of about seven years, when it retains only 70% total capacity. Battery modules with integrated BMS require yearly checks for degradation and abuse. Operation costs may include rising electric bills to cover the cost of charging battery modules.

The original estimated development timeline spans approximately 9 months beginning September 18th, 2017 and ending May 28th, 2018.

After the project ends, Cal Poly Racing plans to continue BMS iteration and develop four more fully functional battery modules. Ideally, these battery modules aim to provide power to the electric car for the next four years.

- **4. If manufactured on a commercial basis:**

An automotive company aims to manufactures and sell approximately 77,000 estimated devices per year. Each device costs approximately $ 300 to manufacture. According to the budget justification section in section 4.1, each BMS adds approximately $ 1,300 to electric vehicle price tags, with an estimated profit of $ 1000. Estimated user maintenance costs approximately $ 850 every three years for battery pack verification.

- **5. Environmental**

Facilities required to create battery management systems require both land, water, electricity, and raw materials to build a suitable environment. Engineers and other project members directly impact the environment via method of travel, amenities, and waste. Many raw materials used to build battery management systems come from the environment.

Lithium-ion batteries utilize many different natural resources such as graphite and lithium salts to provide power. Automotive manufacturers typically use Lithium-Nickel-Cobalt-Aluminum-Oxide battery chemistries. Materials such as lithium and graphite appear in select few countries. Gathering these materials via methods such as mining directly impact local ecosystems. Aside from batteries, materials used to make printed circuit boards (PCBs) such as silicon gathered from the Earth, affect each location's environment.

Indirectly, a BMS charges batteries with electricity often from industrial or home sources. As more electric vehicles and BMSs enter the market, municipal electric grids face added strain. While electricity gathered from renewable sources, like the sun, alleviate the strain, some energy still comes from conventional sources such as natural gas and oil.

However, battery management systems are an integral part of transitioning the world to sustainable energy. As more consumers shift towards electric cars, less people rely on fossil fuels. Increasing the supply of renewable energy allows us to replace carbon-intensive energy sources and significantly reduce global warming emissions [7]. Improved public health and environmental quality not only benefits humanity, but all other species sharing this planet.

• 6. Manufacturability

The biggest challenge associated with manufacturing is safety. Large scale lithium-ion packs, often rated at more than 300V and 30A, pose a serious safety risk. The utmost care in design, manufacturing and testing an integrated BMS must be taken to avoid loss of life. Storage consistently poses an issue, since engineers must consider temperature, insulation, chance of fire, and possible shorting. Another challenge, integrating a BMS into a pack, requires careful and precise engineering. Each module must meet stringent safety standards due to user risk.

• 7. Sustainability

Once a complete battery module with integrated BMS enters the market, maintaining the system requires yearly checks. While the BMS sends useful diagnostic information, some issues pose a greater challenge than others. For example, if a BMS detects a battery has become defective, the entire module requires removal because of its welded connections. BMS checks should occur annually and undergo rigorous validation testing to ensure user safety.

As noted in section 5, battery management systems directly impact sustainable uses of electricity. Fossil fuel and other conventional energy sources, finite resources, eventually run out. Their byproducts, such as air pollution, negatively impact the atmosphere. Efficiency, the biggest reason for advanced battery management systems, allow for more energy efficient storage and use of electricity. Some battery management systems utilize pure clean energy such as wind and solar to energize their packs.

• 8. Ethical

Under the IEEE Code of Ethics, engineers and users must recognize the importance of technology affecting the quality of life throughout the world. This senior project must pay attention to the first ethic, accepting responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment. Battery management systems try to mitigate safety risks posed by lithium-ion solutions. Each design decision must receive strict consideration to prevent possible accidents or misuse of its technology. The senior project team must validate functionality under a variety of environments and situations to ensure device operates predictably.

Project teams may encounter a significant ethical dilemma if considering advancing BMS technology. Teams must consider if time spent building more advance battery management systems could be used better on other systems. For example, Cal Poly Racing aims to boost competition electric car performance. However, other systems, such as the drive train, could provide more performance gains with equivalent improvement time. Teams may address this dilemma by conducting research, creating design matrices, and analyzing opportunity costs.

Using the “I CARE” method, this senior project analyzes several different ethical frameworks.

Advancing battery management technology fuels humans’ self-interest (psychological egoism). By advancing renewable energy technology, the environment becomes cleaner which has less adverse effects on health. Similarly, as energy efficiency rates continue to improve, overall energy costs may decrease as dependence on fossil fuels decreases. Alternatively, humans may choose to advance other forms of clean energy such as nuclear and solar. However, lithium-ion batteries and battery management systems, continue to see increasing growth in several different market sectors. Lithium-ion batteries provide one of the largest energy densities per weight, which allows use in a variety of applications. Thus, a focus on battery management system technology advancement becomes justified.

Renewable energy technology also provides the greatest good for the greater number of people (utilitarianism). By transitioning the world to sustainable energy, everybody benefits from the environment. Battery management system design creates jobs in engineering, manufacturing, and maintenance. Unfortunately, some people do not believe or understand the need for sustainability and prefer to use funds elsewhere. Likewise, BMS design may remove jobs in traditional industries such as fossil fuels, as these companies may see a loss in revenue. Fortunately, several studies have shown nearly every aspect of human life improves with a healthier environment [25]. Also, proper government incentives and education may mitigate the impact of advancing BMS technology on traditional non-renewable energy companies. Thus, BMS design supports the greatest good for the greatest number of people.

• 9. Health and Safety

Engineers must follow stringent standards during BMS design. Protection circuitry must work under a variety of different environments due its high risk. Manufacturers must use proper safety equipment to guard against accidents and failures. Battery modules may leak, catch fire, or explode without proper care. Certain tools, such as capacitive spot welders, require adequate training to prevent injuries. The most important safety concern regards consumers and their use of battery management systems in their vehicles. BMS must have extensive protection and safeguards to prevent accidental discharges, destruction of property, and loss of life.

- **10. Social and Political**

Battery management systems play an integral role in the global transition to sustainable energy. As more people transition to renewable energy transportation, governments begin to subsidize energy technology. Although electric vehicles represent a small percentage of global car sales, they have seen exponential growth and interest in the past years.

One of the biggest concerns affecting sales of pure electric vehicles includes range limitation. Consumers assume (erroneously) worst-cases scenarios regarding range estimation. As BMS technology becomes more advanced, more efficient pack energy usage and greater pack lifetime become possible to placate consumers.

Lithium-ion disposal, another issue regarding lithium-ion technology, has significant impacts in the environmental community. As lithium-ion applications grow, more space allocated to their disposal becomes necessary. Many consumers choose to recycle battery cells instead of depositing them in landfills. Advanced battery management systems extend cell lifetime significantly which prevents more harmful cells from entering the environment.

The stakeholders in this project include Dr. William Ahlgren, Alvin Ha, Nick Mah, Jason Zhou, Andrew Ferguson, Oliver Ousterman, Japsimran Singh, Max Wu, Cal Poly Racing, and Cal Poly. Additionally, companies who implement lithium-ion batteries in their applications may consider themselves a stakeholder.

The designers gain substantial technical knowledge and learning on batteries and battery management system. This project explores weighing different aspects such as topology, functionality, and topology and choosing the most applicable options. This project may inspire Dr. Ahlgren who currently researches energy storage. This project primarily impacts the Cal Poly Racing team. By having a more advanced BMS, Cal Poly Racing spends less time replacing and changing their battery cells and focus on areas with more performance gains. This project secondarily impacts companies who may use this project in a product.

Initially, stakeholders in natural gas applications may suffer while stakeholders in renewable energy applications may benefit. As the world transitions to sustainable energy, more companies may shift their focus where all stakeholders benefit from BMS growth.

Project completion results in a fully-functional BMS integrated into a single battery module. The project team aims to present during the Cal Poly Electrical Engineering senior project expo, along with project plans and acquired data. During the Cal Poly academic year 2018-2019, future teams aim to improve and implement the system into the Cal Poly Racing Electric car for the Formula SAE electric competition. At the competition, the Cal Poly Racing team presents the entire electric car, including this senior project, to a panel of industry professionals who assign points to each university by reviewing each vehicle subsystem in depth. During the presentation, team members defend their design choices before a wide-ranging audience consisting of other universities, companies, and engineers.

• 11. Development

During this project, team members performed extensive research on battery management systems, gaining large amounts of energy storage knowledge. From the literature search, team members explored concepts such as battery management system functionality, battery dynamics, and vehicle integration. Members refined skills using simulation software such as PSpice and new programs such as Altium Designer. Manufacturing members learned how to use capacitive spot welders to build lithium-ion test packs. Overall, members gained experience designing, building, and testing a complete project from start to end.

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Appendix B: Initial Project Cost Estimation

Table 13: Initial Cost Breakdown

Project: Passive Balancing Battery Management System for Cal Poly Racing's Formula SAE Electric Vehicle	**Estimated Cost**	**Justification**
MATERIALS subtotal	**$ 1,323.44**	
Battery Balancer IC	**$ 23.53**	Example chip (LTC3300) costs \$9.57. Three units purchased in case of damage. $Cost_a = \$20.00$ $Cost_m = \$28.71$ $Cost_b = \$35.00$
Battery Charger IC	**$ 43.75**	Example chip (LTC4103) costs \$14.79. Three units purchased in case of damage. $Cost_a = \$35.00$ $Cost_m = \$44.37$ $Cost_b = \$50.00$
Battery Monitor IC	**$ 26.06**	Example chip (LTC6804) costs \$8.86. Three units purchased in case of damage. $Cost_a = \$20.00$ $Cost_m = \$26.58$ $Cost_b = \$30.00$
CAN Transceiver	**$ 7.97**	Example chip (MAX485CPA) costs \$2.65. Three units purchased in case of damage. $Cost_a = \$6.00$ $Cost_m = \$7.95$ $Cost_b = \$10.00$
Opto-Isolator	**$ 1.80**	Example chip (6N137S) costs \$0.30. Three units needed with additional three sets purchased in case of

		damage. Cost_a = \$1.50 Cost_m= \$1.80 Cost_b = \$2.10
Passive Components	**\$ 35**	Approx. total cost of various resistors, capacitors, and inductors Cost_a = \$20 Cost_m= \$30 Cost_b = \$70
Wires	**\$ 45**	Approx. total cost of different gauges of wire Cost_a = \$30.00 Cost_m= \$40.00 Cost_b = \$80.00
Wire Connectors	**\$ 50**	Approx. total cost of different types of wire connectors Cost_a = \$40 Cost_m= \$50 Cost_b = \$60
Nickel Strips	**\$ 73.33**	One single module costs approx \$70 according to Cal Poly Racing information Cost_a = \$60.00 Cost_m= \$70.00 Cost_b = \$100.00
Wire Terminals	**\$ 40**	Approx. total cost of different wire terminals Cost_a = \$30 Cost_m= \$40 Cost_b = \$50
Plastic Holders	**\$ 60**	Two plastic holders cost approx. \$30 each according to Cal Poly Racing information Cost_a = \$30 Cost_m= \$30

		$\text{Cost}_b = \$30$
Batteries	**$ 897**	Wholesale retail price of Samsung lithium-ion ifr 25R batteries at $5 apiece. 180 batteries make up one module $\text{Cost}_a = \$810$ $\text{Cost}_m = \$900$ $\text{Cost}_b = \$975$
Microcontroller	**$ 20**	Automotive 32-bit microcontroller chips typically within $15-25 $\text{Cost}_a = \$15$ $\text{Cost}_m = \$20$ $\text{Cost}_b = \$25$
MANUFACTURING subtotal	**$ 237.82**	
Kapton Tape	**$ 23.87**	Example 1 Mil Kapton Tape ½’’ x 36 Yds costs $8.55 for one unit. Three units purchased to ensure adequate stock. $\text{Cost}_a = \$20.00$ $\text{Cost}_m = \$26.55$ $\text{Cost}_b = \$35.00$
Solder	**$ 23.95**	Example Kester Solder 60/40 “44”,1.5” costs $23.42. $\text{Cost}_a = \$20$ $\text{Cost}_m = \$23.42$ $\text{Cost}_b = \$30$
Spot Welder Leads	**$ 150**	Dual Sunstone Welder leads cost $150 according to product support salesman. $\text{Cost}_a = \$150$ $\text{Cost}_m = \$150$ $\text{Cost}_b = \$150$
Safety Equipment	**$ 20**	Approx. total cost of safety equipment including safety glasses, gloves, and protective clothing.

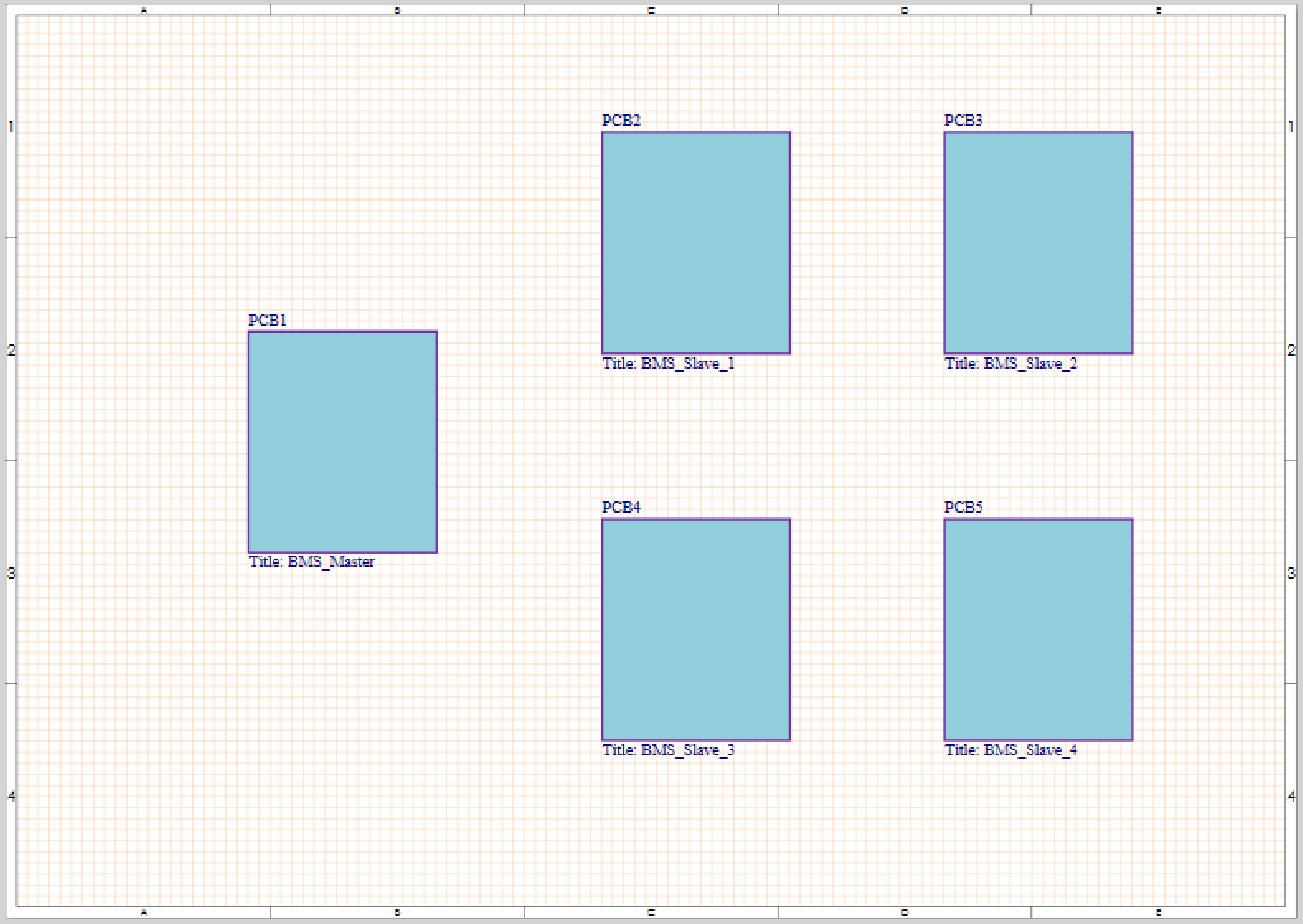
		$\text{Cost}_a = \$10$ $\text{Cost}_m = \$20$ $\text{Cost}_b = \$30$
Test Leads	**$ 20**	Approx. costs of different test lead parts $\text{Cost}_a = \$10$ $\text{Cost}_m = \$20$ $\text{Cost}_b = \$30$
OTHER: subtotal	**$ 62,803.67**	
Contractual Services	**$ 516.67**	Typical PCB manufacturing costs according to Cal Poly Racing information $\text{Cost}_a = \$400$ $\text{Cost}_m = \$500$ $\text{Cost}_b = \$700$
Labor	**$ 62,167**	40 hours per week for 31 weeks at $50/hr $\text{Cost}_a = \$55{,}000$ $\text{Cost}_m = \$62{,}000$ $\text{Cost}_b = \$70{,}000$
Software Licenses	**$ 120**	Altium Student Edition $\text{Cost}_a = \$120$ $\text{Cost}_m = \$120$ $\text{Cost}_b = \$120$
TOTAL	**$ 64,364.93**	

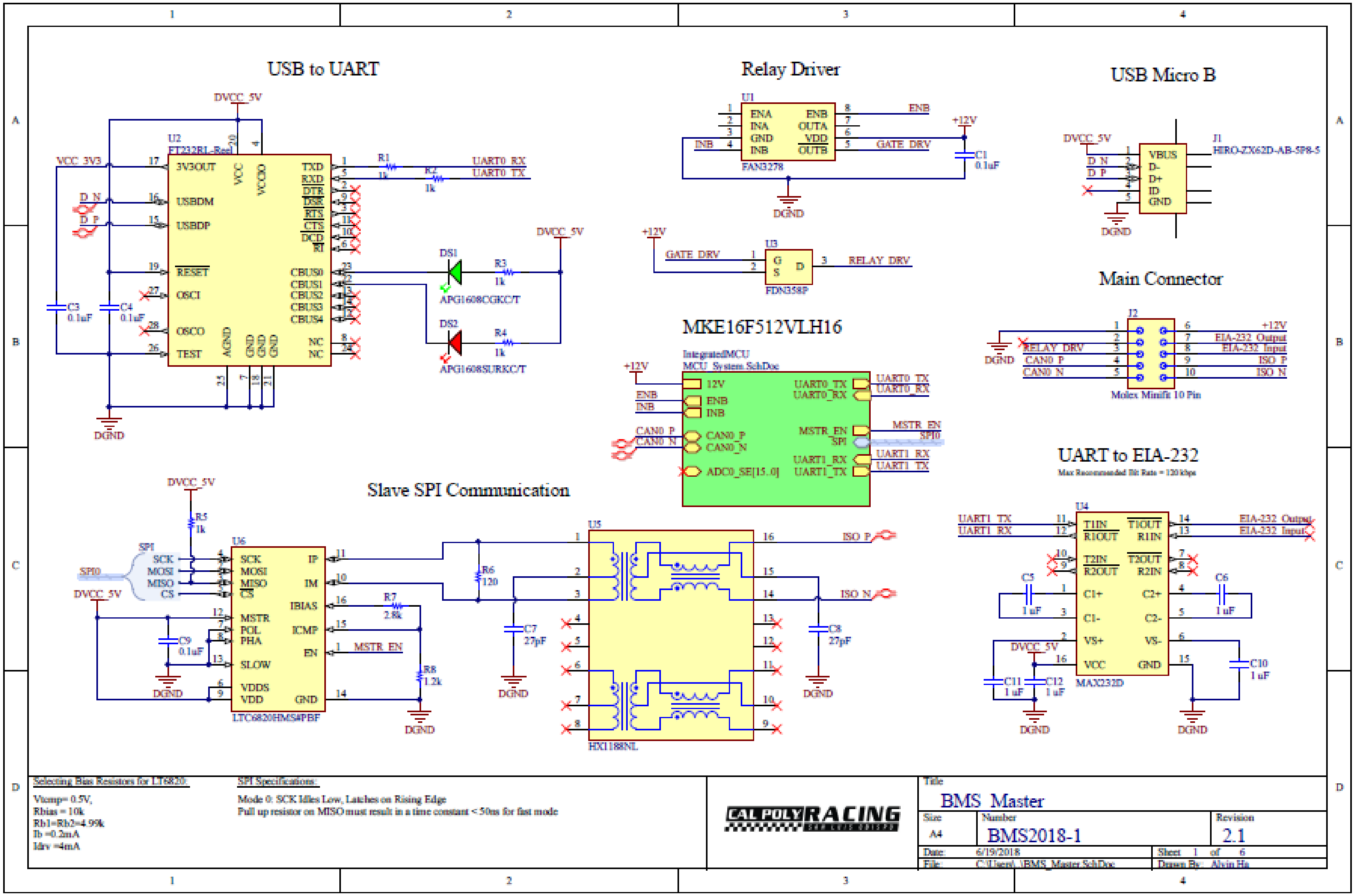
Appendix C: Final Project Cost Estimates

Table 14: Final Project Cost Estimates

Student Applicant(s): Lead: Alvin Joseph Ha Members: Nick Mah, Japsimran Singh, Max Wu, Oliver Ousterman, Jason Zhou, Andrew Ferguson	
CENG Faculty Advisor: Dr. William Ahlgren	
Project Title: Passive Balancing Battery Management System for Cal Poly Racing's Electric Vehicle	**Requested Funding**
Travel *subtotal*	**$0**
Travel: In-state	**$**
Travel: Out-of-state	**$**
Travel: International	**$**
Operating Expenses *subtotal*	**$3540**
Non-computer Supplies & Materials	**$3000**
Computer Supplies & Materials	**$20**
Software/Software Licenses	**$480**
Printing/Duplication	**$**
Postage/Shipping	**$**
Registration	**$**
Membership Dues & Subscriptions	**$40**
Multimedia Services	**$**
Advertising	**$**
Journal Publication Costs	**$**
Contractual Services *subtotal*	**$1460**
Contracted Services	**$1460**
Equipment Rental/Lease Agreements	**$**
Service/Maintenance Agreements	**$**
TOTAL	**$5000**

Appendix D: Hardware Schematics





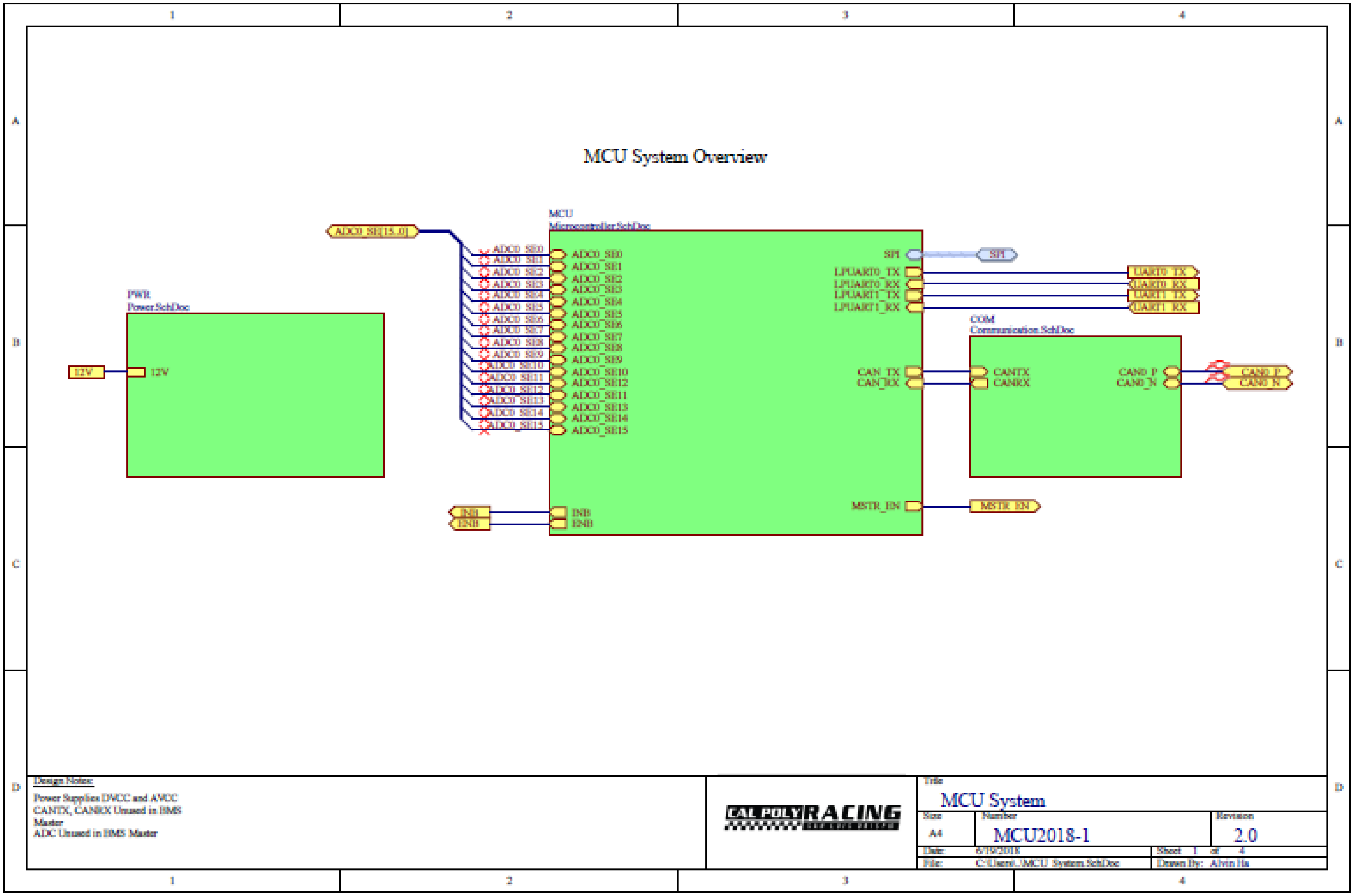
Selecting Bias Resistors for LT6820:

Vtemp= 0.5V,
Rbias = 10k
Rb1=Rb2=4.99k
Ib =0.2mA
Idrv =4mA

SPI Specifications:

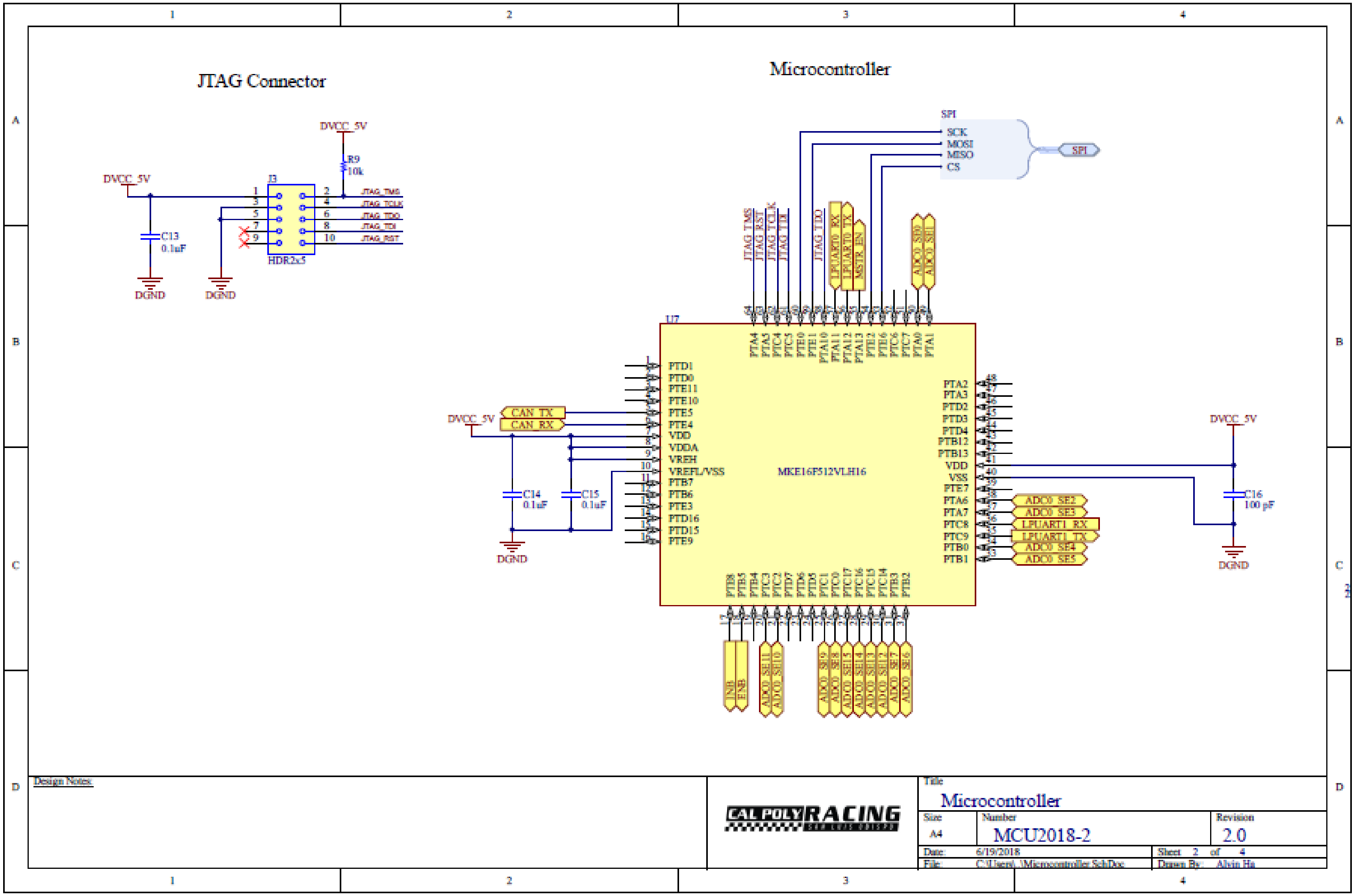
Mode 0: SCK Idles Low, Latches on Rising Edge
Pull up resistor on MISO must result in a time constant < 50ns for fast mode

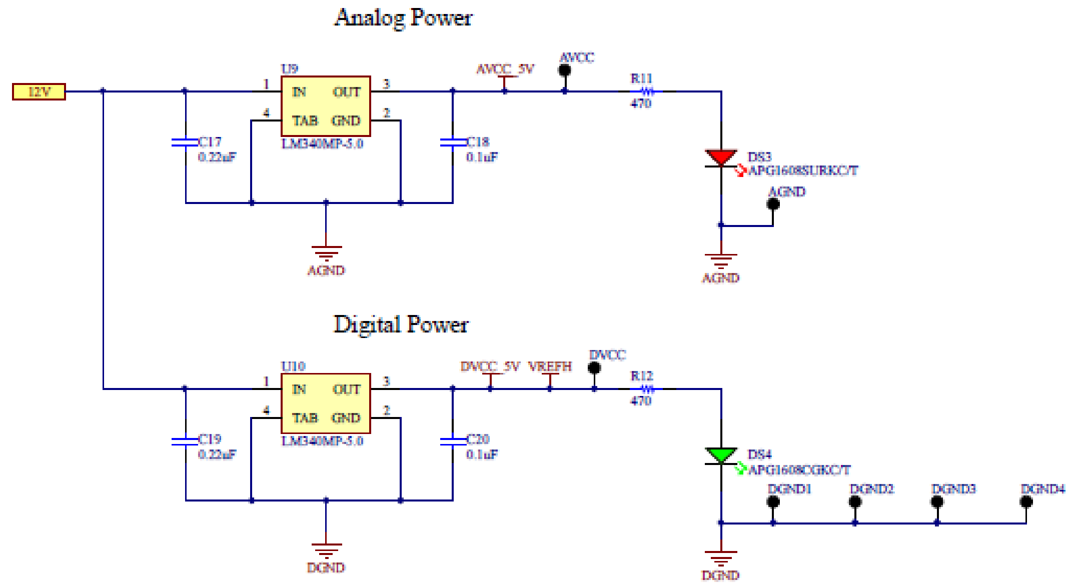
Title			
BMS_Master			
Size	Number		Revision
A4	BMS2018-1		2.1
Date:	6/19/2018	Sheet 1 of 6	
File:	C:\Users\..\BMS_Master.SchDoc	Drawn By: Alvin Ha	



Design Notes:
Power Supplies DVCC and AVCC
CANTX, CANRX Unused in BMS Master
ADC Unused in BMS Master

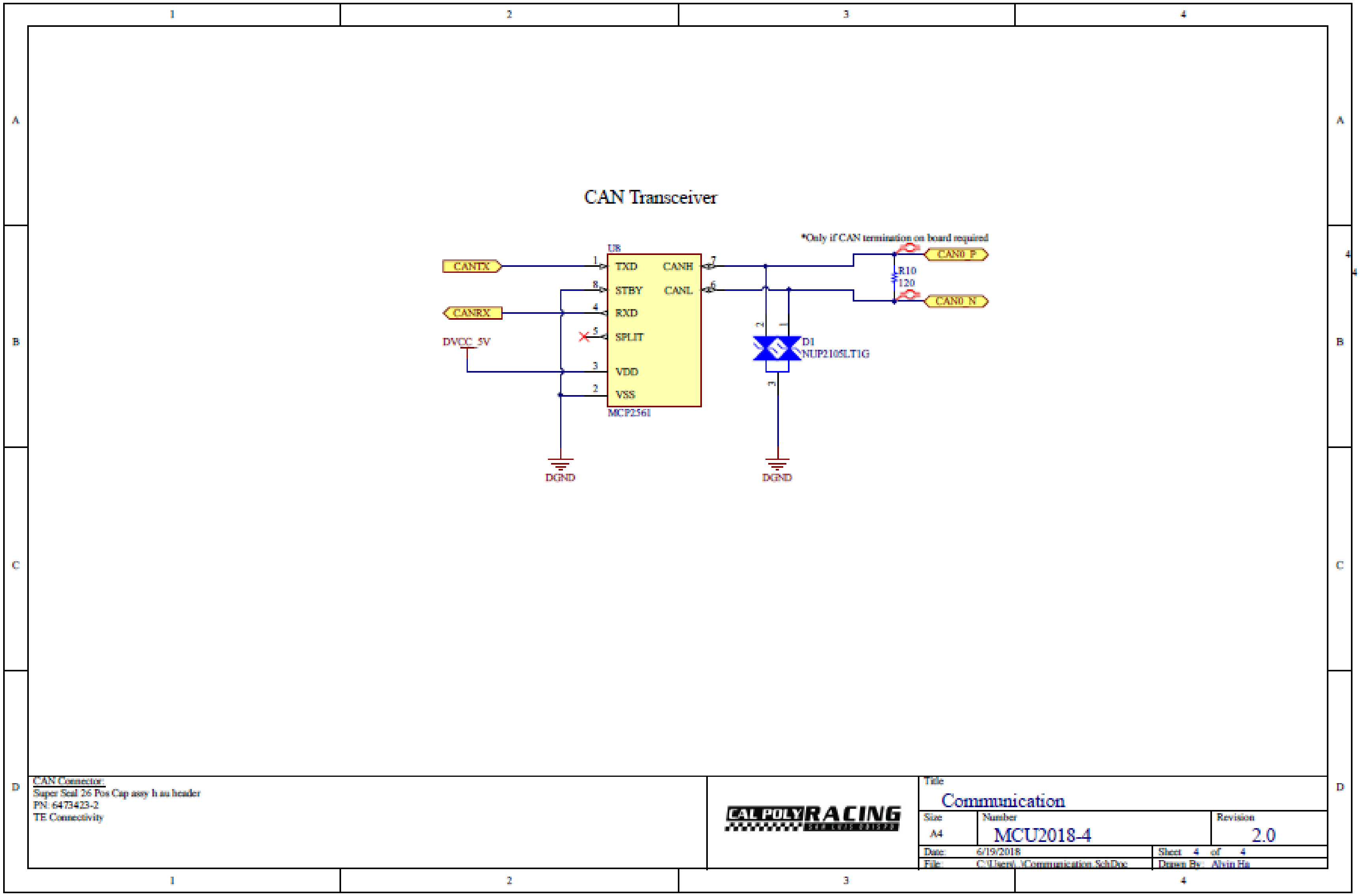
Title	MCU System	
Size A4	Number MCU2018-1	Revision 2.0
Date: 6/19/2018		Sheet 1 of 4
File: C:\Users\..\MCU System.SchDoc		Drawn By: Alvin Ha


JTAG Connector
Microcontroller
DVCC_5V
R9
10k
DVCC_5V
J3
HDR2x5
C13
0.1uF
DGND
DGND
JTAG_TMS
JTAG_TCLK
JTAG_TDO
JTAG_TDI
JTAG_RST
SPI
SCK
MOSI
MISO
CS
SPI
JTAG_TMS
JTAG_RST
JTAG_TCLK
JTAG_TDI
JTAG_TDO
LPUART0_RX
LPUART0_TX
MSTR_EN
ADC0_SE0
ADC0_SE1
U7
PTA4
PTA5
PTC4
PTC5
PTE0
PTE1
PTA10
PTA11
PTA12
PTA13
PTE2
PTE6
PTC6
PTC7
PTA0
PTA1
PTD1
PTD0
PTE11
PTE10
PTE5
PTE4
VDD
VDDA
VREH
VREFL/VSS
PTB7
PTB6
PTE3
PTD16
PTD15
PTE9
MKE16F512VLH16
PTA2
PTA3
PTD2
PTD3
PTD4
PTB12
PTB13
VDD
VSS
PTE7
PTA6
PTA7
PTC8
PTC9
PTB0
PTB1
CAN_TX
CAN_RX
DVCC_5V
C14
0.1uF
C15
0.1uF
DGND
DVCC_5V
C16
100 pF
DGND
ADC0_SE2
ADC0_SE3
LPUART1_RX
LPUART1_TX
ADC0_SE4
ADC0_SE5
PTB8
PTB5
PTB4
PTC3
PTC2
PTD7
PTD6
PTD5
PTC1
PTC0
PTC17
PTC16
PTC15
PTC14
PTB3
PTB2
INB
ENB
ADC0_SE11
ADC0_SE10
ADC0_SE9
ADC0_SE8
ADC0_SE15
ADC0_SE14
ADC0_SE13
ADC0_SE12
ADC0_SE7
ADC0_SE6
Design Notes
CAL POLY RACING
Title
Microcontroller
Size
A4
Number
MCU2018-2
Revision
2.0
Date:
6/19/2018
Sheet 2 of 4
File:
C:\Users\..\Microcontroller.SchDoc
Drawn By:
Alvin Ha
1
2
3
4
A
B
C
D



LM340MP-5.0 Info
Max DC Input = 35 V
Max Output Current = 1.5A
Output Voltage = 5V
Quiescent Current = 8 mA
Ripple Rejection 62 dB
Dropout Voltage = 2V

Title
Power
Size A4
Number MCU2018-3
Revision 2.0
Date: 6/19/2018
Sheet 3 of 4
File: C:\Users\..\Power.SchDoc
Drawn By: Alvin Ha



CAN Transceiver
*Only if CAN termination on board required
U8
MCP2561
1 TXD
8 STBY
4 RXD
5 SPLIT
3 VDD
2 VSS
CANH 7
CANL 6
CANTX
CANRX
DVCC_5V
DGND
DGND
D1
NUP2105LT1G
R10
120
CAN0_P
CAN0_N
CAN Connector:
Super Seal 26 Pos Cap assy h au header
PN: 6473423-2
TE Connectivity
CAL POLY RACING
Title
Communication
Size A4
Number MCU2018-4
Revision 2.0
Date: 6/19/2018
Sheet 4 of 4
File: C:\Users\..\Communication.SchDoc
Drawn By: Alvin Ha
1
2
3
4
A
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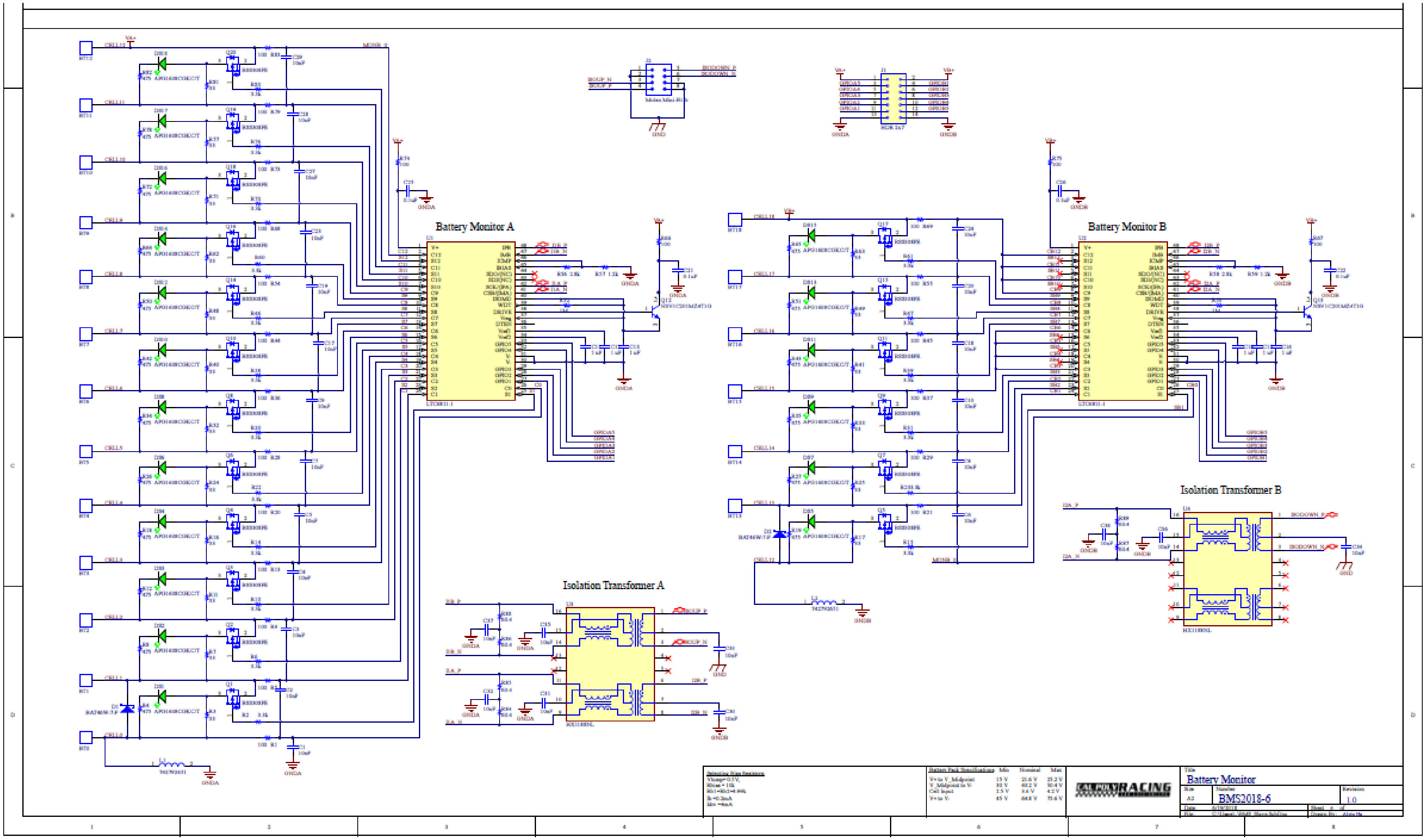

Battery Monitor A
Battery Monitor B
Isolation Transformer A
Isolation Transformer B
LTC6811-1
Molex Mini-Fit Jr
HDR 2x7
HX1188NL
Battery Pack Specifications
Min
Nominal
Max
V+ to V_Midpoint
15 V
21.6 V
25.2 V
V_Midpoint to V-
30 V
43.2 V
50.4 V
Cell Input
2.5 V
3.6 V
4.2 V
V+ to V-
45 V
64.8 V
75.6 V
RACING
Title
Battery Monitor
Size
A2
Number
BMS2018-6
Revision
1.0
1
2
3
4
5
6
7
8
B
C
D

Appendix E: Excerpts from Recommendation Report

Memo of Transmittal

TO: Nick Mah, Cal Poly Racing Electronics Director
FROM: Alvin Joseph Ha
DATE: 13 June 2018
SUBJECT: Proposal to Investigate the Benefits of Implementing a Passive vs. Active Balancing Battery Management System on Cal Poly Racing's Formula SAE Electric Car

Attached is my recommendation report that compares and analyzes two potential implementations of battery balancing for Cal Poly Racing's battery management system.

Solutions

My two proposed battery balancing implementations for Cal Poly Racing's electric car are the following:

- Passive balancing by dissipating excess energy through heat to regulate cell state of charge.
- Active balancing by evenly distributing charge between battery cells during charge and discharge cycles.

Research Methods

To develop a final recommendation for Cal Poly Racing, I have used extensive research from the following primary and secondary sources:

- Primary Sources
    - Interview with Nick Mah
    - Emails with Jon Munson
- Secondary Sources
    - "Battery Management Systems for Large Lithium Ion Battery Packs"
    - "Completely Decentralized Active Balancing Battery Management System"
    - "Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles"
    - "2017-2018 Formula SAE Rules"

Final Recommendation

My final recommendation is to implement passive balancing by using external resistors and transistors to dissipate energy from the most charged cells.

Thank you for taking the time to read this report. I hope this research and recommendation prove beneficial to your project. If you have any questions, please contact me at any time.

Introduction

Purpose

Cal Poly Racing, a student-led engineering team, competes in Formula SAE Electric, an international competition to design, build, and test a prototype electric vehicle against other universities. These prototype vehicles need extensive electronic power systems, often rechargeable battery packs, which power the **drivetrain** (Rahimi-Eichi et al.). The battery management system dictates the entire power system performance, optimization, and lifetime (Rahimi-Eichi et al.).

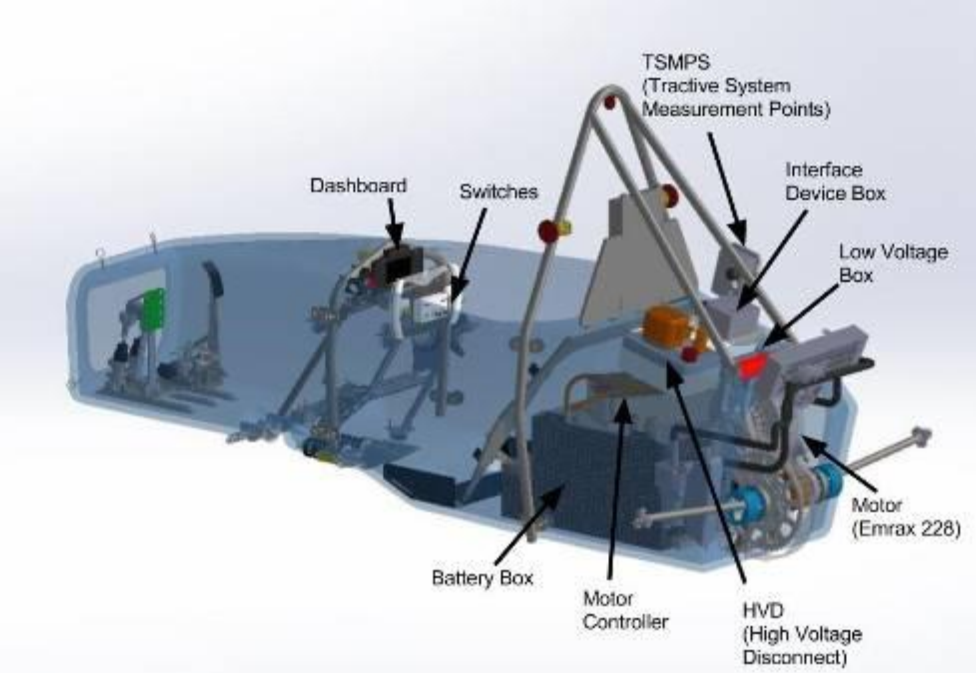


Figure 47: Cal Poly Racing's Electric Vehicle (Cal Poly Racing)

A battery management system, or BMS, manages a rechargeable battery by ensuring the device operator's safety, protecting battery cell integrity, prolonging battery lifetime, and reporting device characteristics (Andrea). One BMS function, balancing, aims to maximize capacity of a battery pack with multiple cells (Andrea).

Currently, my senior project group aims to design a custom BMS for Cal Poly Racing, who have struggled to find a commercial BMS that fulfills competition requirements and provides custom optimization (Mah). A proper balancing implementation gives the vehicle battery pack better performance and lifetime (Mah). By improving the vehicle's power system, the team can spend more time improving other areas of the car.

To narrow my research, I will focus on gathering data on the car's electrical system requirements. My client is Nick Mah, the Cal Poly Racing electronics director, who wants to implement balancing that minimizes battery charge time and accurately equalizes capacity (Mah). After discussing requirements and limitations, we concluded the most feasible way to implement balancing is either passive or active balancing, depending on several factors including complexity, cost, size, heat, and power. My research will recommend the better choice for the team to proceed with.

Background

A **battery** is a device that converts chemical energy into electrical energy and vice versa. A lithium-ion battery, a rechargeable battery where lithium ions move between the negative and positive electrodes, provides the highest energy density per weight, a low self-discharge, and low maintenance (Andrea). Common battery applications include consumer electronics, defense, automotive, and energy grids.

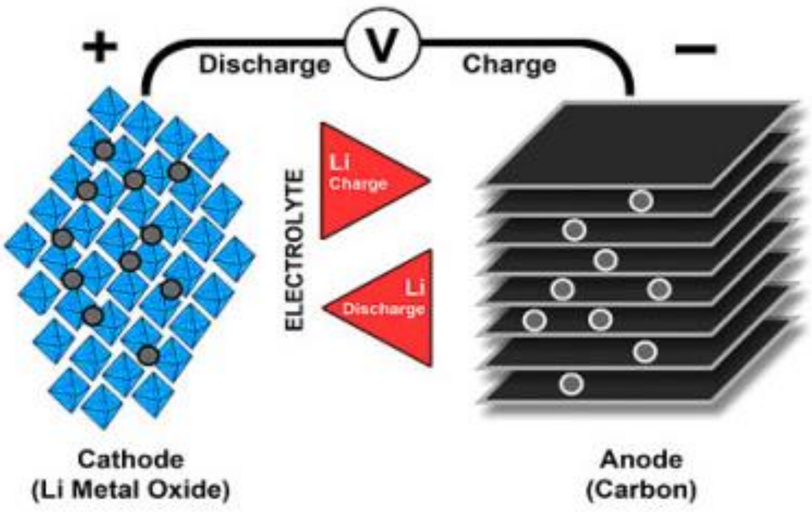


Figure 48: Ion Flow in Lithium Batteries (Battery University)

However, lithium-ion batteries need protection, their main disadvantage (Frost and Howey). They need protection from over charge, over discharge, thermal runaway, and damage (Andrea). Without adequate protection, lithium-ion batteries become a significant safety risk. Damage and abuse may result in thermal expansion, fire, or explosion, depending on the severity (Frost and Howey). Thus, engineers created battery management systems to combat these issues and give application specific optimization.

Capacity, a measure of the **charge** stored within a battery, directly relates to the amount of active material mass contained in the battery (Andrea). Capacity, measured in ampere-hours (Ah), represents the maximum amount of energy that a system can extract from a battery under certain conditions (Andrea 18). For example, measuring state of charge of a battery cell may result in 10 Ah, which indicates the cell can supply 10 amps of current for one hour.

Battery balancing maximizes a battery pack's capacity by regulating a cell's state of charge (Andrea 23). **State of charge**, or SoC, of a cell or battery at a given time is the proportion of the charge available at a given moment compared to the total charge available when fully charged (Andrea 18).

For a battery pack with cells connected in **series**, each cell sees the same charging **current**. When a single cell becomes fully charged, the entire pack must stop charging otherwise it may push that one cell into an unsafe operating area. Thus, the most charged cell in a series connection limits the entire pack. The figures to the right show this effect. In figure 3, the two cells begin at the same initial state of charge and rise at the same rate. However, figure 4 shows what happens when the two cells begin with an unbalanced state of charge. The first cell is unable to charge to full because the second cell has already hit the limit.

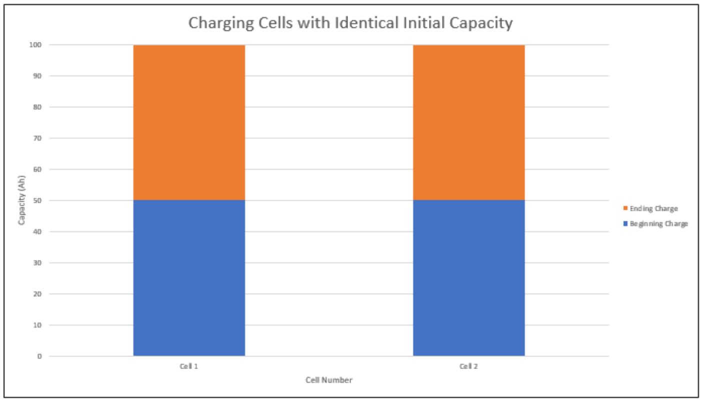


Figure 49: Charging Cells with Identical Initial State of Charge

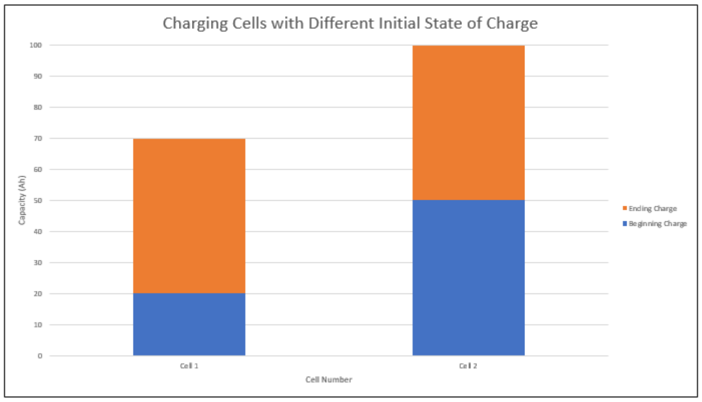


Figure 50: Charging Cells with Different Initial State of Charge

If only one cell is fully charged, it presents a problem for users of a battery pack; the pack cannot supply its nominal amount of energy. Balancing solves this problem by equalizing the capacity within a **string of batteries**. If all cells are the same capacity, a BMS can charge a pack to full. Figure 5 on the next page shows a comparison between an unbalanced and balanced pack. From looking at the graphs, the unbalanced pack cannot hold as much energy.

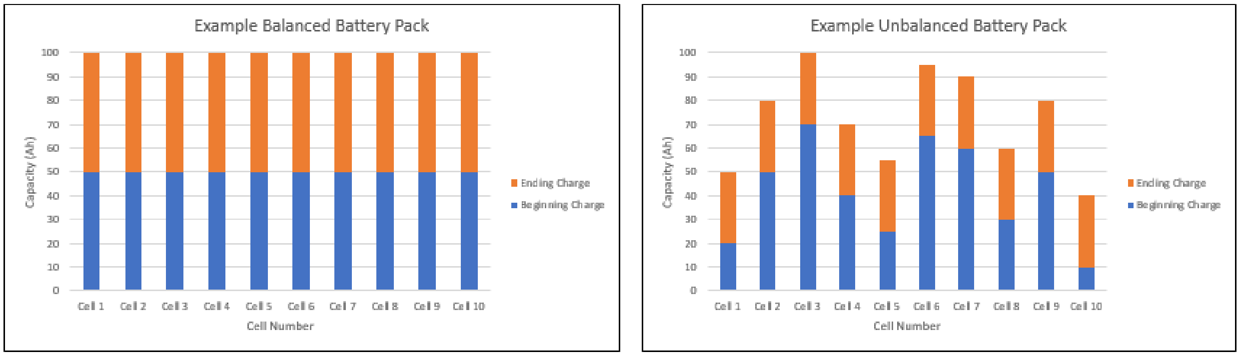


Figure 51: Comparison Between Balanced and Unbalanced Battery Packs

For this report, I am comparing passive and active balancing because Cal Poly Racing can feasibly implement either method. After the team decides, they will design the rest of the BMS around which balancing method we choose. The first solution, passive balancing, simply removes energy from the most charged cell and dissipates it as heat (Andrea 79). The second solution, active balancing, redistributes the excess charge between the battery cells (Andrea 80).

Solutions

I am proposing the following two solutions to implement battery balancing in Cal Poly Racing's battery management system:

- Passive balancing by dissipating excess energy through heat to regulate cell state of charge.
- Active balancing by evenly distributing charge between battery cells during charge and discharge cycles.

Criteria

I will be judging both solutions on the following five criteria in order of importance:

1. Balance Time
2. Complexity
3. Size
4. Heat Generation
5. Cost

Organization

The next sections of this report will describe research methods, conclusions from each source, a detailed analysis of each solution against the five criteria, and my final recommendation.

Methods

This section outlines the sources used to conduct my research for this report. I have divided this section into primary sources and secondary sources. Each source has a brief description.

Primary Sources

Interview: Nick Mah

This source is the interview with the client, Nick Mah, done on May 25, 2018. Nick is the current electronics director of Cal Poly Racing and has also been electronics lead in the past. Nick's electric car design expertise and familiarity with the Formula SAE Electric rules made him the best candidate to interview for the proposal requirements and constraints. Nick explained some basics and requirements about the electric car, what the current BMS lacks, and the constraints Formula SAE places on balancing. I used this source to find if either method is applicable for Cal Poly Racing. Below are the questions I asked him:

- What are the characteristics of your battery pack?
- How does your current BMS solve the balancing problem?
- What are your size constraints?
- Disregarding the grant, I received from CPConnect, what is your budget?
- What is your desired time to balance the pack?
- Do you currently have any excess thermal heating issues?
- What is the current imbalance developed over one charge cycle?
- What are the characteristics of your charger?
- What do you think of the first solution, passive balancing?
- What do you think of the second solution, active balancing?

Emails: Jon Munson

This source contains excerpts from emails sent to Jon Munson beginning on May 2nd, 2018. John Munson is a senior applications engineer for the Automotive Battery Management Products for Analog Devices. Analog Devices is a global leader in the design and manufacturing of analog, mixed signal, and DSP integrated circuits to help solve the toughest engineering challenges. John Munson works with engineering clients to find solutions that best fit with their systems. I sent these emails to gather information on certain BMS chips offered by Analog Devices. I used this source to confirm the solution I have chosen has the best possible fit for the electric car.

Secondary Sources

Book: "Battery Management Systems for Large Lithium Ion Battery Packs" by Davide Andrea

> This book, published in 2010, provides solid battery management system theoretical knowledge used specifically in lithium-ion packs like the one used by Cal Poly Racing. This book described technical challenges and solutions to the balancing methods being considered. I used this source to form the basis of my arguments in the final paper. Davide Andrea is the owner of Elithion LLC which sells large-scale battery management systems. He has more than 25 years of electronics industry experience and holds a B.S. in electrical engineering and computer science from the University of Colorado.

IEEE Journal Article: "Completely Decentralized Active Balancing Battery Management System" by Damien Frost and David Howey

> This IEEE journal article, published in 2018, gave an example of active balancing, energy reallocation by variable loading/charging. Variable loading/charging redistributes energy by dynamically changing the electronic loads in response to state of charge. Since this report discussed active versus passive balancing, literature on various implementations allowed informed decision-making on a best method forward. I used this source in my report to provide comparisons between the two methods. *IEEE*, a best-known electrical engineering professional organization, has a substantial peer-review process for journal articles.

IEEE Journal Article: "Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles" by H. Rahimi-Eichi, et al

> This IEEE magazine article, published in 2013, gave an overview of battery management system applications in energy grids and electric vehicles. Several sections in this article discussed automotive-specific characteristics such as deep charge/discharge protection and accurate state-of-health estimations, relevant to this report. Since this report is for an automotive application, this article provided relevant information that can support the method that most favors automotive characteristics in this report. *IEEE*, a best-known electrical engineering professional organization, has a substantial peer-review process for magazine articles.

Competition Rules: 2017-2018 Formula SAE Rules

The 2017-18 Formula SAE Rules, published in 2017, forms the backbone for many requirements and specifications for the competition vehicle. Rule adherence, an essential requirement, was the deciding factor between the two methods being considered in the proposal. I used this source as a final test to ensure the method chosen in this report fulfills all competition requirements. SAE International is a global association for more than 128,000 engineers and related technical experts which develops many industry standards and protocol for automotive and aerospace industries.

Results

This section outlines the information gathered from each source and how it will apply to my report.

Primary Sources

Interview: Nick Mah

Interview Transcript, May 25, 2018
(Transcript has been edited for conciseness)

Alvin: "What are the characteristics of your battery pack?"

Nick: "The accumulator pack consists of 720 Samsung INR18650-25R cells, 72 in series 10 in parallel. Cell terminals are connected using nickel bus bars. Parallel groups are connected in series using one nickel bus bar to connect ten cells in parallel groups. Modules are connected using custom-made quick disconnects and 600V rated 2-gauge wire, which are connect to the pack through a spot-welded copper busbar. The maximum voltage of our battery pack is around 300V with a maximum nominal current of 200A. The pack is charged with an 8A charging current and has a total capacity of about 6.48 kWh."

Alvin: "How does your current BMS solve the balancing problem?"

Nick: "Our current system, an Elektromotus BMS, uses up to 1.5A of passive balancing current. However, this system is obsolete because it was made for a previous generation of the Cal Poly Racing e-car, which means we've had to make it work with our system. We have had a hard time finding another commercial BMS that can do what we want. For your senior project and for your recommendation proposal, we would like your BMS to have a custom solution to balancing.

Alvin: “What are your size constraints?”
Nick: “The size of the battery management system is dependent on the restrictions placed by the battery box team. For example, there is a maximum headroom you have when designing the new BMS. Any solution you consider must fit into the dimensions which can be found in our electrical system form, or ESF.”

Alvin: “Disregarding the grant I received from CPConnect, what is your budget?”

Nick: “Not including whatever you are spending on your senior project, implementing the balancing system should take under $500 including design and test. This number isn’t concrete, I’m not sure what specific number to give. Just remember that we get most of our money from MESFAC, so any solution cannot be too expensive.”

Alvin: “What is your desired time to balance the pack?”

Nick: “Right now to charge and balance, it takes about three to four hours. Usually we let it sit for a couple of hours which is not ideal because that means we must allocate time where it just sits there instead of testing other systems. Honestly any time you save us would be great.”

Alvin: “Do you currently have any excess thermal heating issues?”

Nick: “No, it’s been fine. We use an air convection system to cool the pack. Any balancing circuitry you use shouldn’t have any issues with heat dissipation.”

Alvin: “What is the current imbalance developed over one charge cycle?”

Nick: “Unfortunately, we have not been able to take state of charge measurements because our old BMS does not allow us to do that without a pricey add-on. I don’t have a number for you, but maybe you can do research online on typical balance requirements.

Alvin: “What are the characteristics of your charger?”

Nick: “The pack is charged with an Elcon PFC2500+ charger that has a maximum charging power of 1.95kW at 115VAC. The max charging voltage is 389V at 6A charging current. The charger interfaces with the BMS through CAN.

Alvin: “What do you think of the first solution, passive balancing?”

Nick: “Passive balancing seems like a good choice. From what I know, passive balancing is the method used the most in battery management systems because it’s cheap, less complex, and isn’t too hard to debug. Our previous system used passive balancing.

Alvin: “What do you think of the second solution, active balancing?”

Nick: “Active balancing is interesting because I don’t know too much about it. I know that it can save power efficiency and charge time, but nothing beyond that. If it proves to be a good solution for Cal Poly Racing, we will consider it. “

Emails: Jon Munson

Email Transcript, Beginning May 2, 2018
(Transcript has been edited for conciseness)

Alvin: “Also, I would like to ask some questions whether active balancing is right for our system. Currently, our battery pack uses an off the shelf BMS that has a passive balancing current up to 1.5A. From what I understand, active balancing is the preferred method for EV batteries, particularly to minimize cell stress. Since we are designing a custom system, below are two reasons we were using to justify active balancing.

Our pack is a 300 V, 6.48kWh, 720 cell (72 series 10 parallel) that currently takes nearly four hours to charge and balance with our current system. Minimizing the amount of time waiting for the pack to fully charge improves our team efficiency and performance.

Looking at the LTC6811 datasheet, the balance current is limited to 60 mA through the resistor network because of excessive die heating. Since we'd like to at least match our old balancing current of 1.5A (which seems large if we used external transistors), active balancing seems like a good choice to minimize waste heat that might otherwise affect the operation of the whole pack. Also, the LT8584 seems to have a small quiescent current even in switching mode, which means that waste heat isn't substantial.”

Jon: “The strategy and implementation of balancing will strongly influence your design. Normally cells will not develop significant imbalance in a rapid way, and in most cases, the imbalance is imparted by the BMS itself due to slightly differing current drain in the several monitored sections. If you are racing with a pack that is pre-balanced, then during usage you might experience a mAh of imbalance over an hour’s usage, which itself may not justify any balancing per se (just charger cutoff when the highest cell voltage reaches full charge).

Some BMS systems use the balancing feature to essentially perform charge termination to individual cells by simply “shunting” a current equal to the charger current, then cutting off the charger when the last cell reaches full charge. This brute-force method would certainly generate a lot of heat if done passively and would only be appropriate in a first usage scenario IMHO. Subsequent charging cycles should track well if the cells are reasonably matched.

A more sophisticated balancer will take operational data into account and program light discharging on the highest-voltage cells during a charge cycle that will trim imbalance and maintain it over the life of the pack without a lot of aggressiveness (so a reasonably well-balanced pack will stay that way but there is limited per-charge-cycle imbalance correction capacity).

Cells really don't know whether they are being actively or passively balanced, though there are claims that certain pulsed-current charge profiles will maximize longevity, but I think the time-scale is much slower than the PWM rate of any active balancer, so I don't think there is an inherent virtue to active balancing other than the efficiency and heat minimization."

Secondary Sources

Book: "Battery Management Systems for Large Lithium Ion Battery Packs" by Davide Andrea

This source gives a broad overview of the different types of balancing. The disadvantages of passive balancing include the costly waste of energy as well as generation of heat at high-balancing currents, which may affect the operation of the battery pack. The disadvantages of active balancing include more components and wasted power in standby. Andrea recommends active balancing in recommendations where low current passive balancing would take too long, or in applications where high heat generation poses a significant risk. In general, the significantly higher cost of active balancing offsets any energy saved during the balancing process. Applications requiring active balancing usually need to transfer large amounts of charge in a short time.

IEEE Journal Article: "Completely Decentralized Active Balancing Battery Management System" by Damien Frost and David Howey

This source gives a practical example of active balancing circuitry implementation. For certain cell chemistries, individual cell monitoring is necessary. To maximize the energy storage potential of several cells connected in a pack, a BMS must measure and balance the state of charge. Active balancing circuits fall within two main categories: energy reallocation and variable loading/charging. Active cell balancing is an expensive option, although future topologies will decrease in cost as efficiency rises.

IEEE Journal Article: "Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles" by H. Rahimi-Eichi, et al

> This source details how electric vehicles, like the one designed by Cal Poly Racing, require extensive battery management systems for their lithium-ion packs. Battery management systems must factor in cost, lifetime, power delivery, and environmental impact in its design. If there is a mismatch between the voltage and capacity of the connected battery cells, the entire pack cannot operate efficiently. Active balancing techniques are possible depending on how a BMS redistributes cell energy. Passive balancing circuitry is simple and cheap. On the other hand, it has zero efficiency and the resistors' power rating limits the maximum allowable dissipated power on board.

Competition Rules: 2017-2018 Formula SAE Rules

> The 2017-18 Formula SAE Rules detail some requirements to keep in mind when choosing a balancing implementation. These rules are design critical, the electric car will not pass inspection with rule violations. If the resistance from the BMS board to the cell is too high, cell balancing can affect the accuracy of the BMS voltage measurement. Cell balancing is not permitted when the accumulator isolation relays are open. While most BMS run autonomously, a balancing implementation needs a function that can pause during necessary times.

Conclusion

In this section, I will evaluate each solution using a decision matrix that follows my selected criteria. This decision matrix will provide insight into my final recommendation.

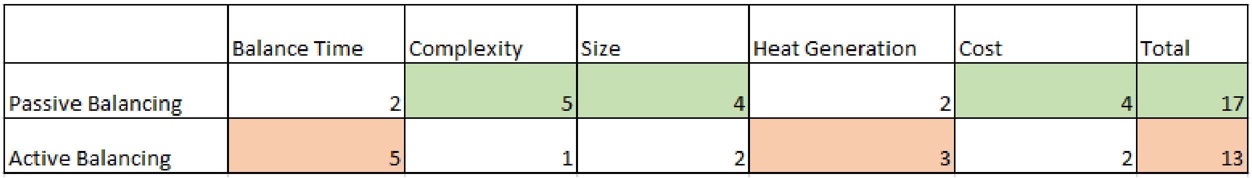
My two proposed balancing solutions are the following:

- Passive balancing by dissipating excess energy through heat to regulate cell state of charge.
- Active balancing by evenly distributing charge between battery cells during charge and discharge cycles.

I will be evaluating these solutions based on their balance time, complexity, size, heat generation, and cost. Table 1 below shows how the solutions rank according to each criterion.

I have ranked the criteria on a scale from 1 to 5. A score of 1 indicates the worst possible performance, while a score of five indicates the best possible performance. I marked the criteria that benefits passive balancing with a green color and I marked the criteria that benefits active balancing in red. I will recommend the solution with the highest score at the end of this report.

Table 15: Decision Matrix



	Balance Time	Complexity	Size	Heat Generation	Cost	Total
Passive Balancing	2	5	4	2	4	17
Active Balancing	5	1	2	3	2	13

I will now discuss the criteria scores for both solutions.

Balance Time

Balance time, the most important criterion, measure how long it takes the battery pack to completely equalize the cell charge (Andrea). The previous Cal Poly Racing BMS had a very slow charging and balancing time, approximately four hours (Mah). Any time saved improves system performance and team efficiency. In most small battery applications, it is reasonable for the balance circuitry to correct a 5% state of charge error within five hours of balancing (Linear Technology). This criterion is math-based with the following equation:

$$\text{Balance Current} = \frac{\text{\%SOC\_Imbalance} \bullet \text{Battery Capacity}}{\text{Number of Hours to Balance}}$$

Figure 52: Balance Time Calculations (Andrea)

Passive Balancing

Passive balancing uses resistor networks tied to external transistors to bleed charge from cells. However, passive balancing cannot correct large state of charge imbalances in a short time (Munson). The excessive heat created during balancing generally limits the current (Linear Technology). Large currents lead to large power dissipation on resistors limited by their power rating (Rahimi-Eichi et al.).

Using the equation in Figure 6 with a balance current of 100 mA, a battery capacity of 25 Ah, and a five percent imbalance leads to a total of 12.5 hours.

12.5 hours is a significant amount of time, especially in a competition setting where performance optimization is important (Mah). For this reason, passive balancing earns a score of 2.

Active Balancing

Active balancing methods typically transfer a significant amount of charge in a small amount of time (Andrea 82). Applications that require 1 A or greater of balancing current should consider active balancing (Linear Technology).
Using the equation in Figure 6 with a balance current of 2.5 A, a battery capacity of 25 Ah, and a five percent imbalance leads to a total of 0.5 hours.

After further discussion with Nick Mah, we determined 0.5 hours is a very acceptable amount of time both for competition and testing. For this reason, active balancing earns a score of 5.

Complexity

The second criterion, complexity, indicates how difficult a solution will be to design, implement and test. Since Cal Poly Racing is primarily composed of students, a solution that is too difficult will prove problematic to manufacture due to lack of knowledge and time. The amount and type of components used for each solution determines the complexity.

Passive Balancing

Passive balancing requires one bleeding resistor and switch per cell (Rahimi-Eichi et al.). Resistor networks are very simple to understand since every electrical engineering student learns the concept in their freshman year (Cal Poly State University).

Since each cell only requires a single switch and resistor, passive balancing earns a score of 5.

Active Balancing

Active balancing at the cell level is accomplished with power converters on each cell (Frost and Howey). Power converters fall under the class of **Power Electronics**, which is a specialty of electrical engineering typically taught to seniors and graduate students at Cal Poly (Taufik). Although active balancing saves energy, it uses more components than passive balancing (Andrea). More components lead to a lower reliability.

Since each cell requires many complex components, active balancing earns a score of 1.

Size

Size is an important factor when choosing a solution. Cal Poly Racing has very limited space in the battery box, the BMS location. This space cannot be exceeded due to design limitations set by the Formula Electric competition rules (Formula SAE). More components generally take up more space. More complex solutions may require larger circuits, like **transformers**. Figure 7 on the next page shows the amount of space available in the battery box. The BMS goes in the yellow section at the top with approximately 2.5’’x14’’x2’’ of space.

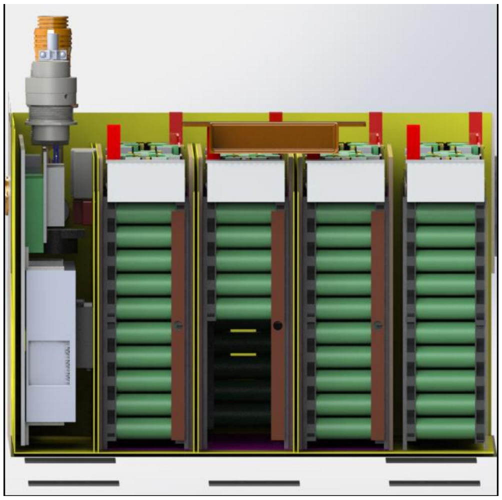


Figure 53: Cal Poly Racing Battery Box (Cal Poly Racing)

Passive Balancing

While passive balancing only requires switches and resistors, each cell needs its own set of components (Frost and Howey). Power resistors typically have wider dimensions to handle the power loss across each element (Cal Poly State University). Since Cal Poly Racing’s battery pack has 18 cells in series, many resistors will end up taking a significant amount of horizontal space.

Although passive balancing requires relatively small and flat components, the quantity required earns this solution a score of 4.

Active Balancing

Active balancing using **DC/DC conversion** to transfer charge from one cell to the next (Rahimi-Eichi et al.). One Formula SAE rule requires **galvanic isolation** (Formula SAE). DC/DC conversion typically accomplishes galvanic isolation through transformers, which are large and bulky components (Taufik). Similarly, many power electronics topologies use **inductors** which require space due to its **magnetics** (Taufik)**.**

Since active balancing requires components larger than simple resistors, this solution earns a score of 4.

Heat Generation

BMS design must consider heat generated when balancing (Andrea). Since the battery box is an enclosed space, Cal Poly Racing takes precautions to ensure temperature does not become a problem (Cal Poly Racing). Electronic components tend to function worse as temperature rises.

Passive Balancing

Passive balancing dissipates energy as heat (Andrea). When current passes through a resistor, the resistor converts electric power into heat energy. However, passive balancing does not use large balance currents (Rahimi-Eichi et al.). Assuming a balance current of 100 mA and a discharge resistor of 33 ohms, the power dissipated in a single resistor is 0.33 watts.

Although passive balancing has a high total power dissipation, proper electronic design can minimize the heat energy effects. This solution earns a score of 2.

Active Balancing

Although active balancing aims to conserve energy during the balancing process, it may still generate a significant amount of waste heat during standby (Andrea). The amount of standby power varies depending on the balancing method being chosen (Andrea). Several BMS circuits have a low **quiescent** current to mitigate this problem (Linear Technology).

Since active balancing theoretically should not generate that much heat, this solution earns a score of 3 (Andrea).

Cost

Cal Poly Racing has a limited funding supply (Cal Poly Racing). More complex solutions typically require more components, which leads to an increase in cost. However, CPConnect granted my senior project $5,000**.** I have allocated a large part of the budget to circuitry, so this category is not an immediate problem. Unfortunately, this grant is finite; future design and manufacturing costs should still be considered.

Passive Balancing

Passive balancing is included in many BMS chips, the only necessary external components are simple **passives:** resistors, capacitors, and inductors (Linear Technology).

Since many of these components are low-cost and easy to acquire, this solution earns a score of 4.

Active Balancing

Active balancing typically requires many more components that are often integrated on an external chip (Andrea). More components lead to a higher cost, which earns this solution a score of 2.

Final Analysis

After a thorough comparison using the five criteria, passive balancing received a score of 17 and active balancing received a score of 13. Passive balancing won in complexity, size, and cost. Active balancing won in balance time and heat generation.

Recommendation

After considering both solutions and performing a detailed analysis using balance time, complexity, size, heat generation and cost, I ultimately recommend passive balancing for Cal Poly Racing's electric car.

The next steps for Nick Mah and Alvin Ha's senior project group include choosing a BMS chip that supports passive balancing. The balancing implementation decision heavily affects the rest of the BMS design (Munson). This recommendation will hopefully enable the senior project group to successfully design a functional BMS for Cal Poly Racing.