LOW-COST DISTRIBUTED BATTERY MANAGEMENT SYSTEM

ECE445 Final Report - Fall 2018

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Abstract

This paper documents the design and testing process of a low-cost distributed battery management system (BMS) for UIUC's EV Concept RSO. The BMS uses a distributed design where additional battery modules can be daisy chained and hot swapped at the touch of a button. The BMS monitors the battery health based on voltage, temperature and current specifications of the cells and balances them to the target voltage, if unbalanced. This is intended to make the use of Li-ion batteries safe by preventing battery degradation and fires. The BMS was designed to give university car team a low cost and simple way to experiment with different battery configurations for electric vehicles. This was accomplished by using low cost microcontrollers, custom designed isolation, limited high precision components and clever design to deliver a system that delivers both accuracy and flexibility on a budget.

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1 Introduction

1.1 Purpose

While lithium batteries are incredible for their energy density and longevity, they also bring with them many downsides. Lithium ion (Li-ion) batteries are often found to be out of their temperature, current or voltage specification. Violating these specifications can often lead to battery pack degradation and the pack catching fire. Additionally, many applications that use lithium batteries require much higher voltages than their cell average of 3.6/3.7V such as electric cars. This demand for higher voltages has forced manufacturers to place batteries in series to create desired voltages without the need of expensive and relatively inefficient DC/DC converters. Even if the batteries placed in series initially have the same charge, over time the battery cells' charges will begin to drift away from one another and must be brought back together through balancing to prevent damage to the battery and to maintain battery capacity.

To tackle this problem, we plan to take advantage of low-cost microcontroller units (MCUs) and a variety of peripherals to make a low cost distributed BMS. Our goal is to make the LEGOs of BMSs in terms of easiness to assemble and operate. To accomplish this, we will utilize a stackable PCB design with a master that can easily adjust to the addition and removal of modules with the touch of a button.

1.2 Background

In the market today exist many Battery Management Systems (BMSs) that keep batteries balanced and operating in spec, however they are either centralized approaches that offer little flexibility on changes in system configuration, require many wires, and large amounts of effort to implement or distributed systems that can cost over $600 for a 16S battery [1]. This causes many people who are looking to create one-off projects or prototypes with lithium batteries in series to either face large unneeded complexity and messy wiring or face the exorbitant cost of current distributed BMSs.

These hurdles can keep many from making the jump to lithium ion batteries or worse lead to battery packs being made without proper protection. Such battery packs can be very detrimental as they can cause a lot of damage by catching fire, which in turn, can burn down entire buildings and take lives. A common example of this are the fires caused by e-bikes that often utilize cut-rate BMSs or none at all [2].

1.3 Functionality

The functionality of the project is defined by the master and slave's ability to have bidirectional communication, monitor cell voltages and protect cells from entering states that violate their specifications. The ability to communicate bidirectionally allows the system to centralize its data to be processed and then send out commands based on said data. The ability to monitor voltages allows the BMS to model the state of the battery and act to optimize the pack's lifetime and functionality. Lastly, the ability to for the BMS to protect its cells from spec violations allow it to prevent permanent damage to the battery and or even fire.

1.4 Subsystem Overview

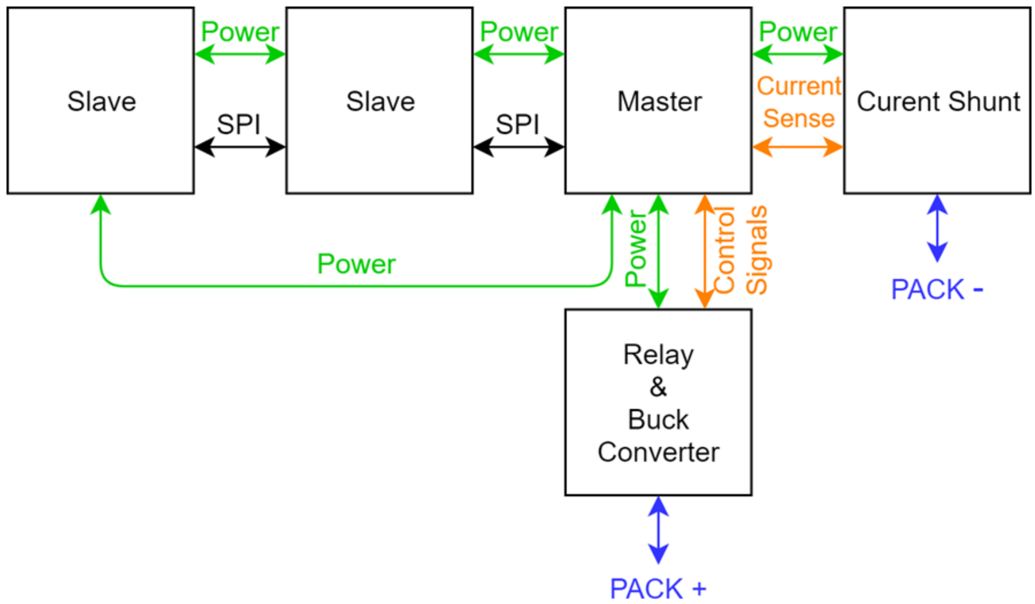

Figure 1.1: Slave Module Block Diagram

The BMS system is broken up into 3 primary components: Slave Module, Master Module, and Power Electronics. The slave modules collect voltage and temperature data. They then pass that data to one another to the master. Additionally, the slaves relay master commands to one another and discharge their cells to the target voltage in the master's commands. The master processes slave data and user input and changes the relay states or sends a balance command if necessary. Power component subsystem is made up of the current shunt and relays. The relays allow the BMS to isolate the battery from the charger or load to prevent battery damage. The current shunt is used by the master to measure current in and out of the battery by measuring the voltage across it.

2 Design

2.1 Slave Module

The slave module collects the cell data, sends/receives messages, and balance the battery pack. The slave can be broken up into 4 core components: analog data collection, digital communication, discharge circuit, and software.

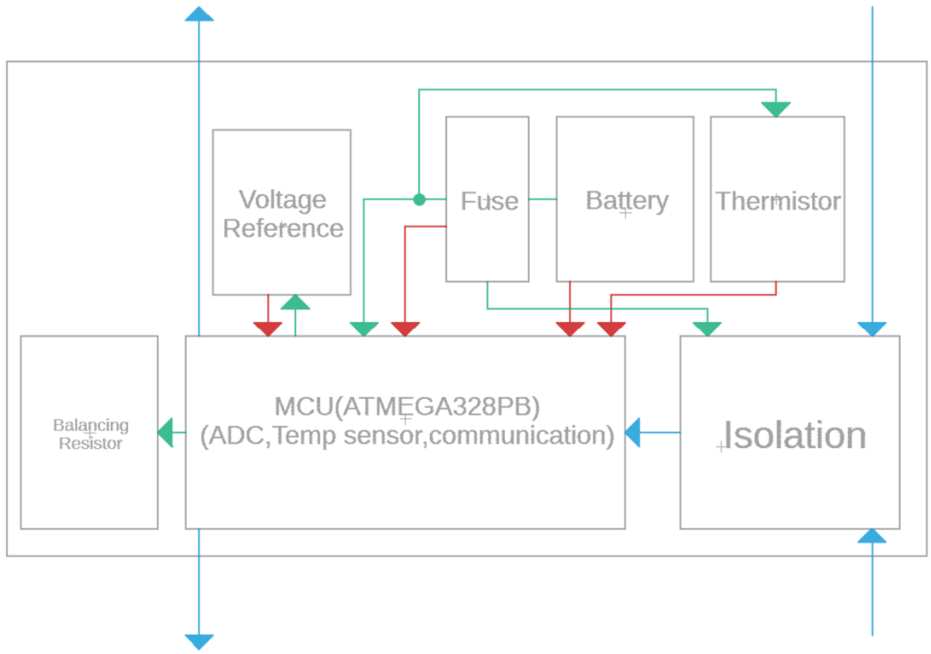

Figure 2.1: Slave Module Block Diagram

That analog end first collects the data and stores it in the MCU. The data is then sent to the digital communication for external analysis. The slave will then receive a message instructing it what its target voltage is. By using its analog data collection, the slave can tell if its voltage is over the target and use the discharge circuit to reach its target.

2.1.1 Analog Data Collection

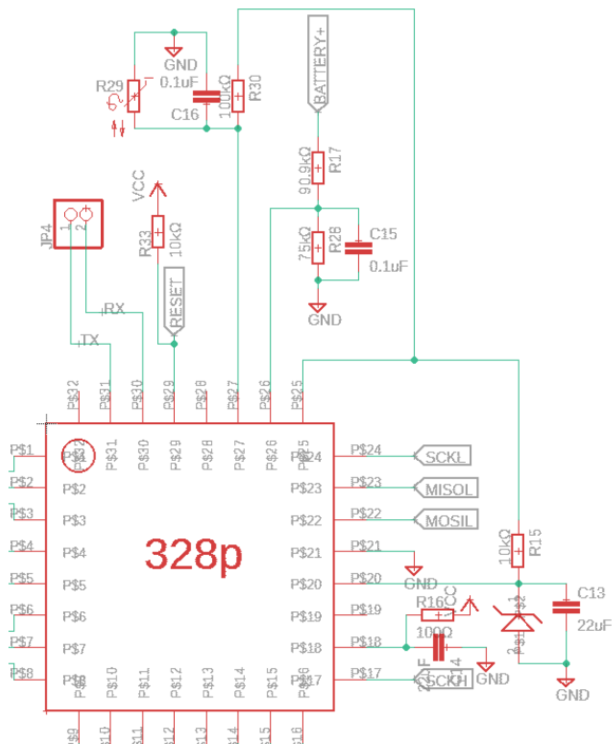

Figure 2.2: Analog Circuitry

The analog data collection sub-module above all else is designed to be as accurate as possible. At its core is the ATMEGA328PB's ADC. The ADC has 10 bits of resolution and error is dominated by its reference voltage and voltage divider. The internal voltage reference for the MCU has 100 mV error, which is far too large to meet our 50mV spec. To mitigate the error on the voltage reference external one with 0.1% tolerance was added. The LM4040 reference chosen for the task comes in many variants out voltages. Since ADC can only measure between ground and their reference voltage, we opted to choose the highest reference that could be used over the entire voltage range of lithium battery voltages. The resistor that goes in series with the LM4040 shunt reference was chosen to be 10k by finding the highest resistance that would allow the 60 µA quiescent current to power the reference while the battery was at its minimum of 2.5 V. By maximizing the input voltage range, we can minimize our voltage divider, this is critical for accuracy since all reference error will be multiplied by the divisor shown in equation (1). The thermistor circuit required much less tolerance since the constants on it are very relaxed, to cut cost 1% tolerance components were used for the voltage divider.

E_{total}: Total error in reading, E_{REF}: Internal ADC Error, D: Voltage divider, $E_{divider}$: Voltage Divider Error

$$E_{total} = E_{REF} * D + E_{divider} \qquad (1)$$

For the divider 0.1% tolerance resistors were used since they provided the accuracy need for the divider without breaking the bank. The ratio of the resistors needed to divide the max input voltage of 4.2V to below the voltage reference of 2.048V. To choose the actual values a divider with a resistance of

~150kΩ was used to strike a balance between low power draw and parasitic. Using equation (1) and (2) we can see that our analog data collection subsystem has a resolution of 4.44 mV with an error of ±8.74 mV

$$LSB = (2.048\ V/2^{10})\ D = 4.44\ mV \tag{2}$$

2.1.2 Digital Communication

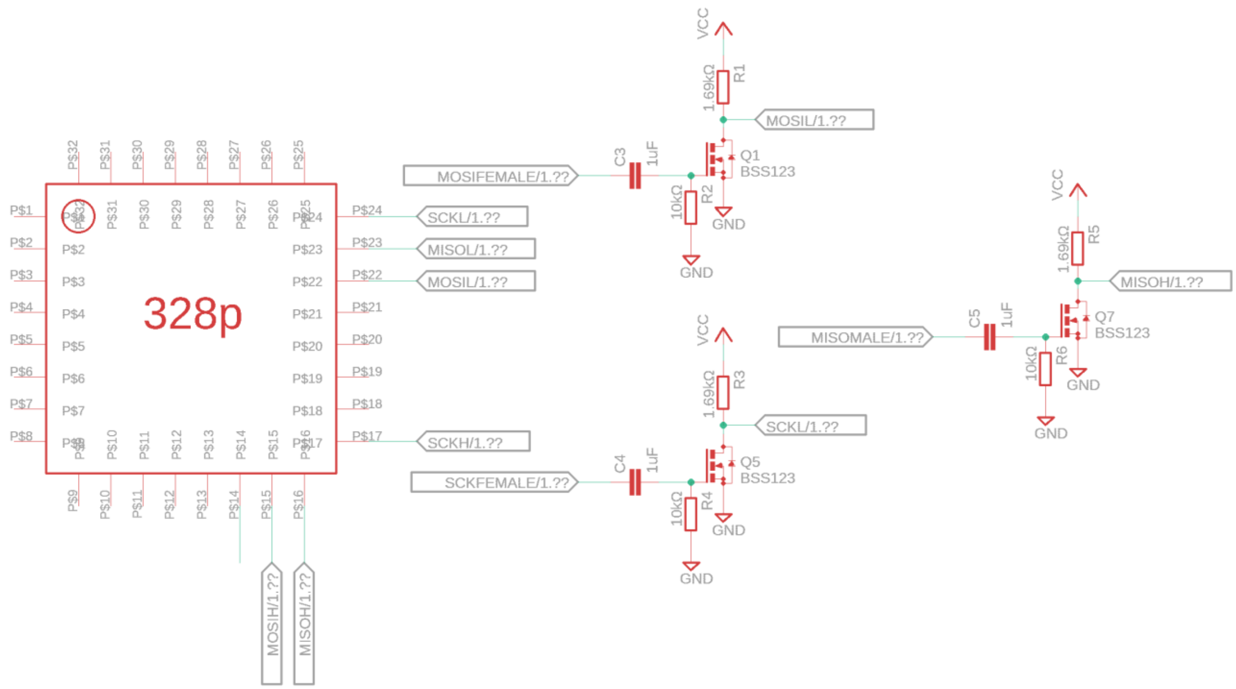

Figure 2.3: MCU and Digital Isolation

For the digital communication all incoming signals are ran through isolation shown on the right of figure 2.3. Isolation is used since all MCUs are powered by their local cell pack, this creates a DC voltage offset between each slave. The capacitor in the isolation blocks the DC offset while the remaining circuitry protects from startup transients and as a level shifter. The DC offset must be blocked because it will cause the MCU to receive a voltage on its GPIO pins that violates their input range. The level shifter is used to allow for communication between MCU that have large differences in voltages such as the master and a slave running off a near empty battery at 2.5V. A 1uF capacitor was used for its price to size and a corresponding pull-down resistor was chosen to create a RC constant longer than the length of a message so that during a message no large change in voltage across the capacitor will occur due the signals sent.

$$\tau = RC \tag{3}$$

2.1.3 Discharge Circuit

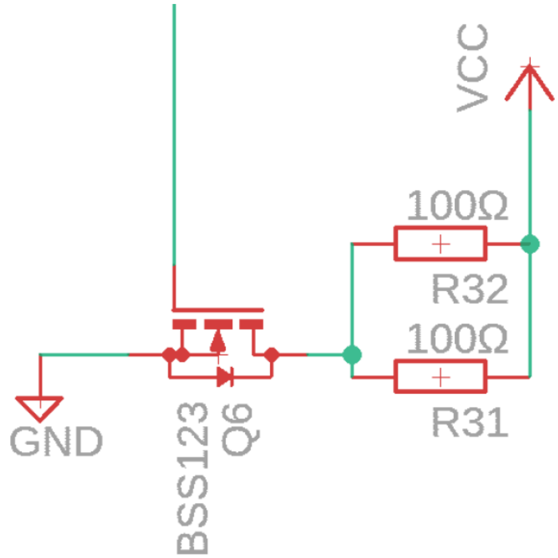

Figure 2.4: Discharge Circuit

Though the discharge circuit is simple it is a critical part of the slave. The discharge circuit allows the slave to "burn off" excess charge on its cells in a controlled manor. As a result, the slave has the ability to balance itself with the rest of the pack. For the circuit we choose to go with a 50Ω load so that the cells could be balanced in a timely manner without placing such a load on the cells that the voltages would drop from load. If we had placed larger loads on the cells during balancing the voltages across the cells would change even though the SOC had not, as a result the balancing preformed would have a much greater error than if we had used a smaller load. The MOSFET needed a V_{DS} that could handle the 4.2V across it in the off state, be able to handle the continuous 84 mA current through it and have a low R_{DS} so that the current would be only limited by the resistors in the on-state. The MOSFET was used on the low side so that no special gate driver would be required to operate the circuit and due to the MOSFET being on the high side providing no additional benefit.

2.1.4 Software

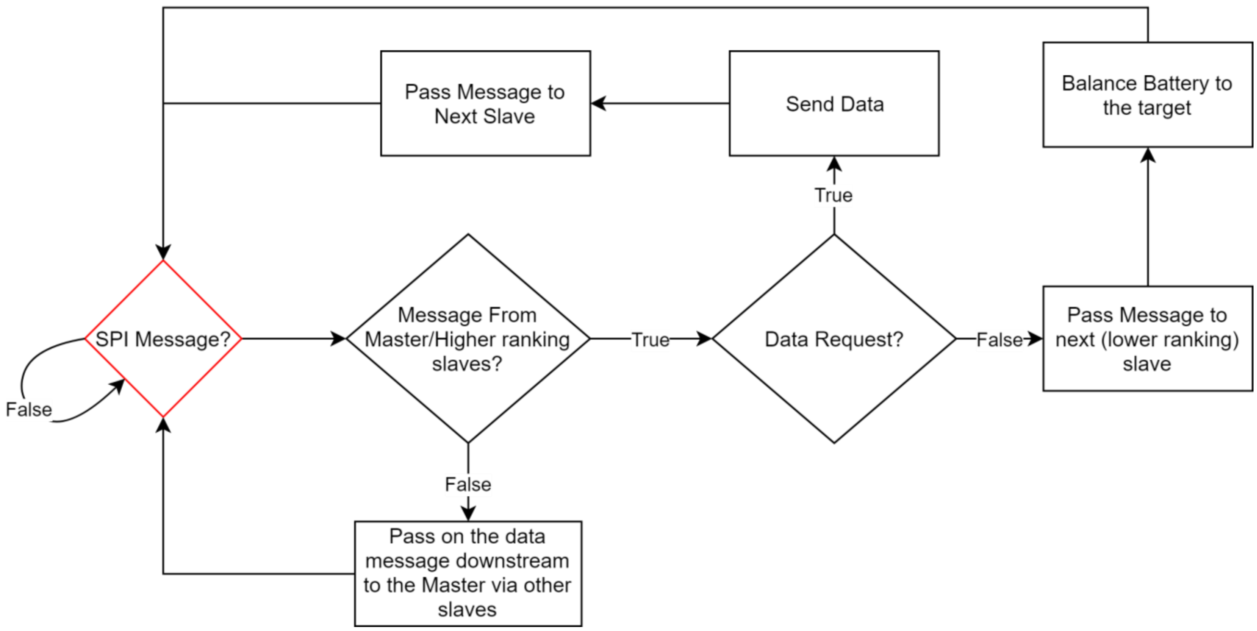

Figure 2.5: Slave Software flowchart

The Slave modules sleep until they receive a SPI message from the Master. The slaves can generally receive two kinds of signals:

1. From the Master/higher ranking slaves. The signals can be either be for data request or it can be a balancing signal instructing the slaves to get balanced.
2. From low ranking slaves. These signals can be data signals the lower ranking slave wants to send the master, but due to the sequential nature of the design the low-ranking slave must route the signal via the higher-ranking slave.

If the signal is of Type 1, then the slave is woken up. If the signal is for a data request, the slave passes the data downstream to either the Master or higher-ranking slaves and passes the SPI signal upstream to the lower level slaves. On the other hand, if the signal is for balancing, the slave first passes on the signal upstream to the lower level slaves and then starts balancing the battery to the target specification. After this, it goes back to sleep. If the signal is of Type 2, then the slave merely transfers the data downstream towards the master and goes back to sleep.

2.1 Master Module

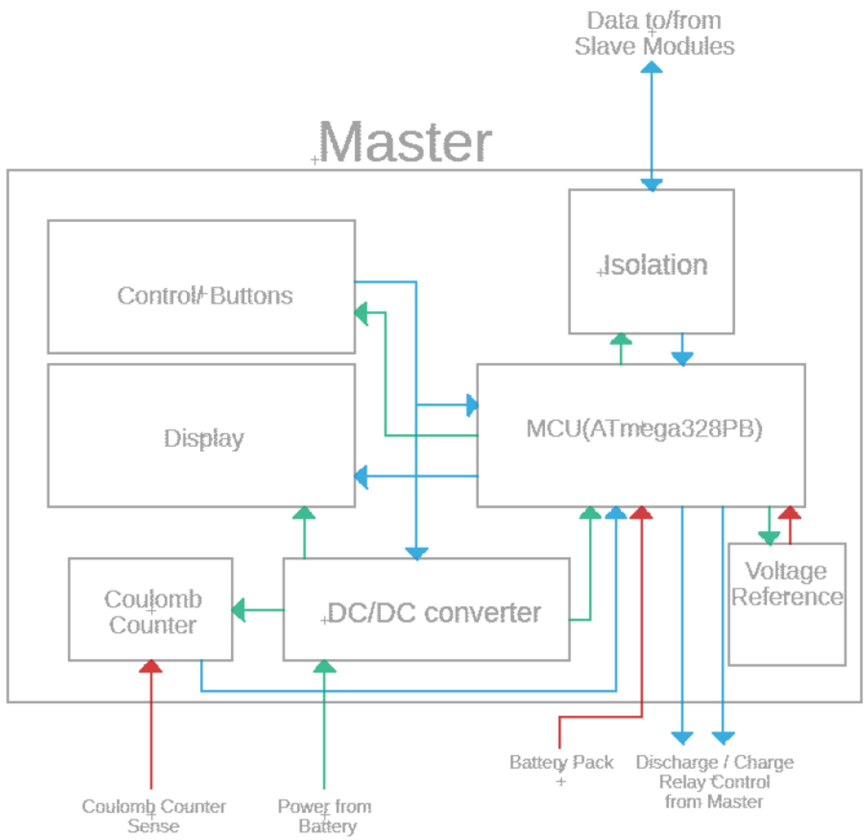

Figure 2.6: Slave Module Block Diagram

2.1.1 Digital Communication

The digital communication for the master works the same as the slave with the exception on only one SPI interface rather than 2. Please see 2.1.2 for more information on the digital communication submodule.

2.1.2 LCD Display and Buttons

The LCD and buttons were added to the master so that a human could easily interface with the BMS without the need for special hardware. We wanted to use as few of components as possible for this since the master's cost was quite high and many of its pins were in use. For the LCD we opted to use an I2C controller so that we only needed two wires to control it, additionally the ATMEGA328PB already has hardware support to I2C.

2.1.3 DC/DC converter

A DC/DC converter was used so that the master to run off the battery as a whole since the MCU cannot handle the high voltage of the battery. This functionality is vital because it ensures that the load across the slaves is that same, reducing the rate at which the batteries need to be rebalanced when compared to running the master off just one of the slaves. To ensure the reliability of the DC/DC converter we went with a leader in power conversion TI. Next, we selected a buck converter that supported as wide of range as possible while supporting a 0.5A load to power the master. This led us to the LM5017 which can support anywhere from 2 to 24 slaves in series. Additionally, the LM5017 is a synchronous converter which offers much higher efficiency especially at lower duty ratios vs asynchronous. For passive selection we took TI's reference design and increased both the inductor and capacitor size to reduce voltage ripple. TI offered several different feedback options to control the output voltage, to ensure a clean power rail we went with the "ramp generator" option that feeds voltage ripple into the error calculations so that they can be counteracted.

2.1.4 Coulomb Counter

In order to properly track the batteries state of charge (SOC) a coulomb counter was used. The coulomb counter must be able to track the number of electrons that are currently stored in the battery. Since current is just electrons per time, we can integrate the current flow from the battery to properly measure the charge left in the battery. We chose to this method of SOC tracking due to its simplicity and accuracy. The other common method to track SOC is to measure the pack voltage however this method provides little data unless the pack is fully charged or near empty since under load the battery takes its nominal voltage for most of the discharge and charge cycle as shown in figure 2.7. The in selecting a coulomb counter we choose on based on cost while still being able to read the range of currents from the car idling to driving, thus ensuring accuracy SOC tracking.

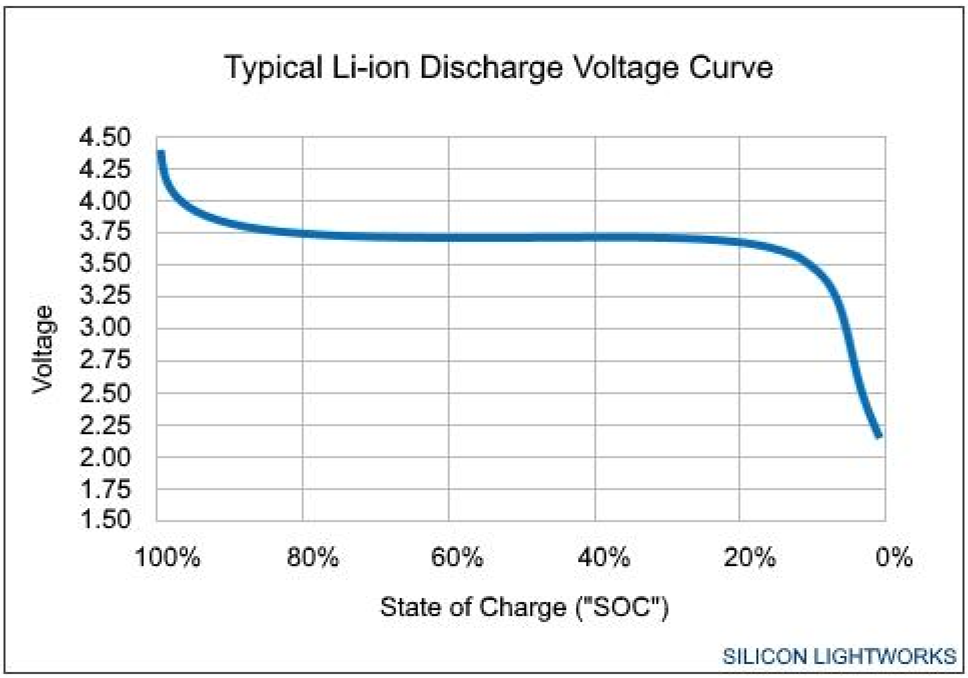

Figure 2.7: Master Software flowchart [3]

2.1.5 Software

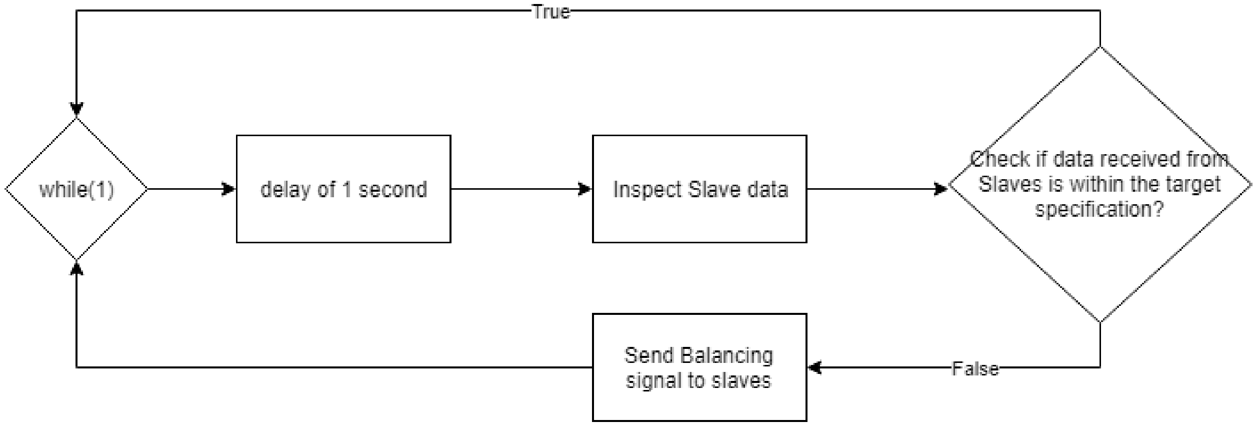

Figure 2.8: Master Software flowchart

The Master module, as seen above on Figure 2.8 on the flowchart is responsible for polling the slaves for data. This is done every 10 seconds to conserve power. While the master is waiting 10 seconds to poll the slaves again, the slaves go to sleep to enter a low power state to conserve power. The Master on receiving the data from the slaves checks if each slave is within its temperature, voltage and current specifications. If yes, then it will poll the slaves again after a delay of 10 seconds. On the other hand, if the slaves become out of balance, the Master will send a balancing signal to the slaves instructing them to perform certain operations to get balanced.

3. Design Verification

3.1 Communication

In order for the distributed system to function all nodes must be able to have bidirectional communication. Additionally, in order to be able to support many nodes and process data in a timely fashion a minimum baud requirement of 9600 is required. To confirm we met this standard we send data in both direction and serial printed the received message. After confirming the 32-bit test message was correct we then analyzed the speed of the SCK line to confirm it was over 9600 Hz. The SCK line indicates at which time to read and write for SPI, therefore if the SCK line is 9600Hz the baud is also 9600.

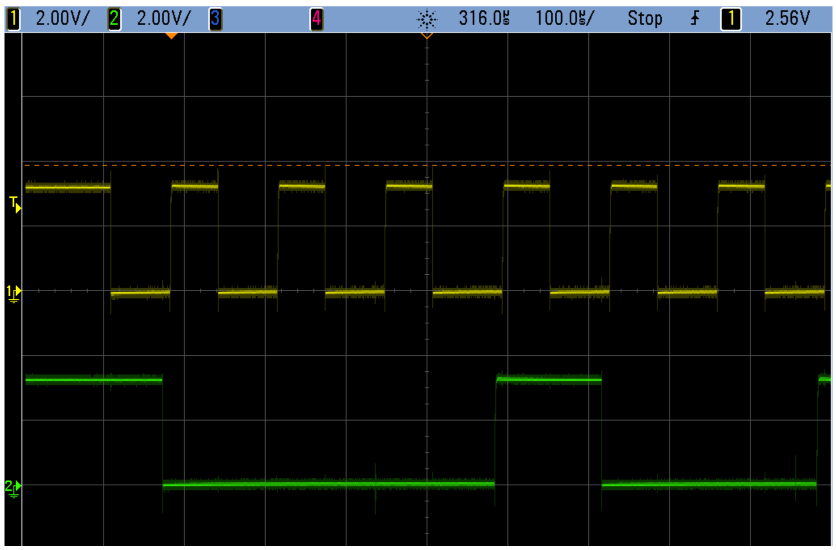

Figure 3.1: Master Slave Communication

3.2 Voltage Measurements

Our requirement promised the voltage measurements of cell voltages to be accurate within 50 mV, but we were able to achieve an accuracy within 5 mV. To verify the accuracy of our measurements we replaced one of the battery cells in the pack with a lab power supply. We then swept the voltage across the planned operating range of the cells. Table 3.1 summarizes the results of the voltage readings obtained below:

Table 1: Battery Voltage readings

Voltage Reading [V]	Actual Voltage [V]
4.20	4.20
4.10	4.10
3.90	3.90
3.78	3.80
3.70	3.70
3.60	3.60
3.50	3.50
3.40	3.40
3.29	3.30
3.20	3.20
3.10	3.10
2.99	3.00

3.3 SOC Measurement

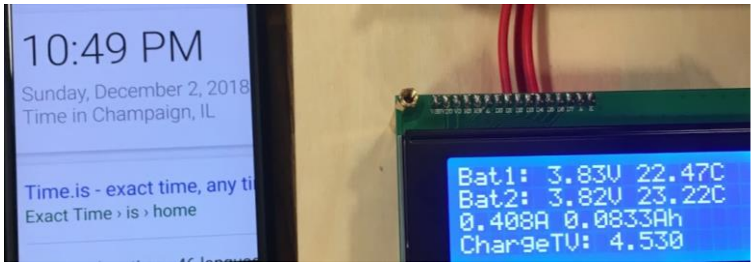

Figure 3.2: Initial SOC Reading

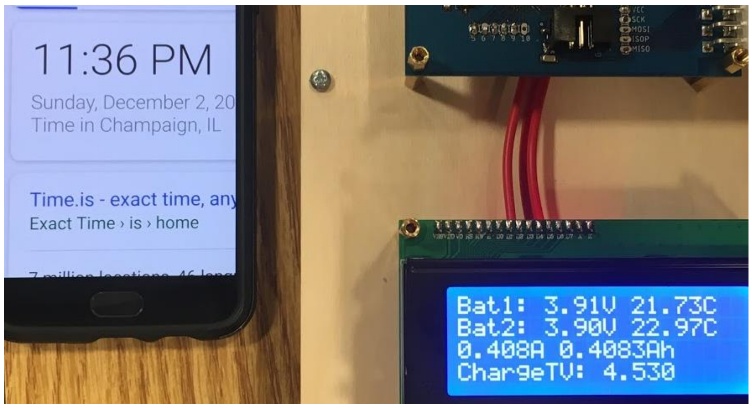

Figure 3.3: Final SOC Reading

To confirm that the SOC measurements are accurate we attached the battery pack to a lab supply. The supply then charged the pack at 0.40A for 47min. The theoretically SOC should had raised by 0.313 Ah, the master recorded a change of 0.325 Ah. This gives an error of 3% for SOC tracking. This result proves that over long periods of time the coulomb counter can accurately record the charge flow across the current shunt for system SOC within the required specification of 5%.

3.4 Balancing

The ability for the BMS to balance its cells is part of its core purpose. By bring cells to the same voltage the pack can be charge to a higher total voltage and discharge lower, as a result we unlock more of the packs capacity. Our goal was to be able to balance the pack within 50mV of one another. To verify these two cells that were unbalanced were placed into different slaves, following this the master send a balance command and any charger or load was disconnected. The slaves were then allowed ample time to burn down to the target voltage. The result was the two slaves at 3.86 and 3.81 both reached 3.79V. The first slave's voltage fell much faster due to its discharge circuit burning off extra power, while the other was only providing power to the master like the first. Since but batteries were brought within 10 mV of each other this proves the BMS can properly balance its cells within the 50mV target.

4. Costs

4.1 Parts

Table 2: Parts Costs Slave

Part	Quantity	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
ATMEGA328PB	1	Microchip Technology	1.46	1.14	1.20
Fuse 15A	4	Little Fuse	0.08	0.06	0.34
Thermistor	1	Generic	0.03	0.01	0.03
LM4040	1	TI	0.13	0.10	0.13
Passives	12	Generic	0.05	0.10	0.03
Precision Resistor	2	Bourns Inc.	0.14	0.68	0.14
Program port	1	Generic	0.12	0.10	0.12
Molex 5557	2	Molex	0.21	0.18	0.21
Molex 5559	2	Molex	0.33	0.25	0.30
Stand-off	4	Generic	0.09	0.07	0.09
PCB	1	PCB Way	0.80	0.30	0.80
Total					**3.46**

Table 3: Parts Costs Master and Power Components

Part	Quantity	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
ATMEGA328PB	1	Microchip Technology	1.46	1.14	1.27
LCD	1	Generic	2.98	2.00	2.98
Button	3	Generic	0.17	0.17	0.17
Current Shunt	1	Generic	3.75	1.00	3.75
Coulomb Counter	1	Maxim	4.78	1.91	0.00
LM5017	1	TI	4.00	1.83	0.00
PCB	1	PCB Way	0.80	0.30	0.80
Passives	10	Generic	0.05	0.10	0.03
Total					**9.00**

4.2 Labor

$$\$71{,}166/yr * 1yr/2087hrs = \$34.33/hr \quad (4)$$

Equation (4) shows the average amount of hourly salary that an ECE graduate from UIUC earns. Considering that we have 2 people for this project and we might work for 10 hours a week for 16 weeks; the total cost of labor can be shown using equation (5) below.

$$\$34.33/hr \times 2.5 \times 2 \times 160 \text{ hr} = \$ 27{,}464 \quad (5)$$

4.3 Schedule

Table 4: Schedule for the project

Week	Logan	Daksh
10/05/18	Design Document	Design Document
10/12/18	Master Module Schematic and Board Layout	Practice programming the ATTiny261a using test codes
10/19/18	Solder proto board, order parts	Hardware validation
10/26/18	Tolerance Testing	Begin testing Interrupts and SPI communication
11/02/18	Manufacture Slave boards	Programming the Slave
11/09/18	Manufacture Master boards	Implementing and fine-tuning SPI for a robust communication protocol
11/16/18	Testing and validation of slave	Programming the Master
11/23/18	Testing and validation of master	Debugging and Testing
11/30/18	Mounting	Preparing for Mock Presentation and Demonstration
12/07/18	Final Presentation	Final Presentation
12/14/18	Final Paper	Final Paper

5. Conclusion

5.1 Accomplishments

We were successfully meet all of our high-level requirements. The cells were able to balance themselves within 50 mV of the target voltage of the lowest cell. The bidirectional communication worked well and we could successfully communicate at a baud of 9600 with little to no glitches. The BMS was also able to monitor and rectify the batteries to their target specifications.

5.2 Uncertainties

The biggest uncertainty we faced was not including the Slave Select line for bidirectional communication. As a result, Hardware SPI was not possible, and we had to overcome this by bit banging the chips via software. We could achieve a maximum operating speed of 50 kHz which satisfies our requirement of bidirectional communication at 9600 baud. However, we could have achieved much faster rates of communication, even up to 100 kHz, if hardware SPI was implemented.

We are also not putting the slave modules to sleep when they are idle. In an active state, these modules consume a current of 3 mA which is still pretty low and provide a battery lifetime of 3 months, however, this could be considerably improved if we put the slaves to sleep as the current withdrawal then would drastically drop to 0.2 µA.

5.3 Ethical considerations

The biggest safety hazard with our project is the extensive use of batteries. We use lithium ion batteries which are extremely dangerous when they attain high temperatures which can be caused due to higher ambient temperature, overcharging or discharging. At high temperatures the lithium becomes more reactive and can catch fire or even blow up. The lithium ion batteries can also experience a thermal runaway where a positive feedback loop is created leading the batteries to overheat or even explode. A battery management system is precisely created to monitor battery health and eliminate such unforeseen circumstances; a thermistor is connected to the batteries whose resistance varies as a function of the temperature. Hence the battery temperature can be monitored and controlled by monitoring the thermistor's resistance value. In accordance to the IEEE code of ethics #1, through our project we strive to consider the safety and welfare of public in its highest regard, we ensure to disclose any factors that might endanger the public or environment [4]. A BMS is intended to ensure safe usage of lithium ion batteries. In addition to this, we also commit to be honest in stating claims based on the available data [5], IEEE code of ethics #3. According to ACM code of ethics 2.7, it is important to foster public awareness about new technologies and its tradeoffs [6]. A more efficient and cost-effective battery management system will be extremely important in the electric vehicles industry. Such a battery management system will greatly influence the advancement of the electric vehicles by making them more cost effective. Hence a technology like this will greatly benefit the environment and the earth by replacing cars fueled by polluting and non-renewable sources. Hence our project can serve to be a crucial step in making electric vehicles more widespread and universal.

5.4 Future work

Implementing hardware SPI by redesigning the Master and Slave PCB's and introducing a slave select line would considerably make the BMS more responsive and at least twice as fast as compared to now. It would also considerably reduce the software complexity and make the system more reliable and easier to modify.

We also intend to polish the UI by adding a D-PAD to allow the user to scroll through menu options. This will give users the ability to change the maximum and minimum voltages of the BMS without external hardware. The D-PAD will also allow the user to scroll through BMS data in a controlled manner rather than cycling through when many slaves are connected to the system.

References

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Appendix A - Requirement and Verification Table

Note: All requirements were met and verified for the project

Slave Module

The slave module sends battery data to master upon receiving a request and acts on master's command to balance battery.

Table 5: Slave Module High Level RV

Requirement	Verification
1. Can perform bidirectional communication with other slaves or the master at a baud of at least 9600 Hz 2. Can monitor its cells voltage within 50mV 3. Can monitor module temperature within 10°C 4. Can prevent any cell from discharging above it rate current continuously(20A) 5. Can run off 2.5-4.2V 6. Can dissipate battery charge at a rate of at least 40mA for balancing	1. Test that SPI communication with at least a 9600 Hz clock can be done through the isolation 2. Test that ADC can measure a 4.1V signal with less that 50mV error 3. Measure room temperature and compare against multimeter thermocouple 4. Short battery and confirm that fuse blows 5. Confirm that module operates off external power supply at 2.5V and 4.2V 6. Confirm that resistor value is low enough that V=IR will result in a <40mA current

Balancing Resistor

The balance resistor is used to burn off excess power on batteries during the balancing phase to bring them all down to the same voltage.

Table 6: Balance Resistor RV

Requirement	Verification
1. Balance resistor must be able to handle at least 50mA. 2. Balance resistor must draw > 40mA at 4.2V.	1. Run 50mA through resistor for 5min and confirm it does not break 2. Confirm that resistor value is low enough that V=IR will result in a <40mA current

Battery
Stores energy to power external devices as well as the BMS itself.

Table 7: Battery RV

Requirement	Verification
1. Can handle voltages from 4.1-3.0V and continuous currents of 15A.	1. Discharge to 3.0V and charge up to 4.1V a. Use spec sheet to confirm safe voltage range

Fuse
Prevents internal shorts from taking down the whole battery and possibly causing a fire and prevents external shorts from over currenting batteries.

Table 8: Fuse RV

Requirement	Verification
1. Prevent continuous currents above battery rated value (20A) by opening the circuit.	1. Short battery and confirm that fuse blows

Isolation
Allows for communication between modules at different voltage level to allow for daisy chaining communication. This allows slaves to talk to one another, thus allowing for daisy chaining.

Table 9: Isolation RV

Requirement	Verification
1. Can support a baud of at least 9600b/s	1. Test that SPI communication with at least a 9600Hz clock can be done through the isolation

MCU
The MCU does most of the work on the module. The chip will take voltage measurements of the batteries and thermistor to ensure that all cells are within their operational area. Additionally, the MCU sends and receives communication through its communication busses. The IC must also manage power with its GPIO pins for the thermistor and the voltage reference.

Table 10: MCU RV

Requirement	Verification
1. Can support a baud rate of at least 9600 b/s on both busses (not simultaneously) 2. Measure battery voltages within 50mV 3. Manage power consumption	1. Test that SPI communication with at least a 9600 Hz clock can be done through the isolation 2. Test that ADC can measure a 4.1V signal with less that 50mV error 3. Can power all devices whose power it is to manage with GPIO pins

Thermistor

Used to convert temperature into an analog voltage by using thermistor in voltage divider.

Table 11: Thermistor RV

Requirement	Verification
1. Analog voltage must represent temperature within 10°C	1. Measure room temperature and compare against multimeter thermocouple

Voltage Reference

The MCU's internal analog reference has poor accuracy, to improve ADC readings a more accurate voltage reference must be used.

Table 12: Voltage Reference RV

Requirement	Verification
1. Voltage reference produces a 2.048 V ±1mV rail under ADC reference load.	1. Measure diode reverse voltage with multimeter

Master

Controls slaves and power components to ensure proper BMS functionality.

Table 13: Master Module High level RV

Requirement	Verification
1. Can display information to user without additional hardware 2. Can accept user inputs to adjust configuration / change state 3. Master must be able to track charge in and out of the battery with less than 5% error	1. Display battery data with LCD 2. Test button presses can be detected by MCU 3. Run current through shunt resistor and confirm that coulombs that the theoretical value of coulombs are within 5% of the theoretical

Control

Allows user to easily change basic parameters of the BMS and see battery status without need of changing and uploading code.

Table 14: Control RV

Requirement	Verification
1. Allows humans to interface with BMS without additional equipment	1. Test that buttons can be used to interact with master to display different data

Coulomb Counter

Allows for a simple way of tracking battery SOC with good accuracy by integrating current to track "how many electrons are left". Additionally, allows for an "battery odometer" which is useful for measuring energy consumption during use and battery lifetime ware.

Table 15: Coulomb Counter RV

Requirement	Verificatio
1. Track battery SOC within 5%	1. Run current through shunt resistor and confirm that coulombs that the theoretical value of coulombs are within 5% of the theoretical

DC/DC Converter

Converts battery output voltage (7.5-100V) to 5V for MCU, other master components, and relay power.

Table 16: DC/DC Converter RV

Requirement	Verification
1. Create 5V ±0.5V average voltage under 300mA load	1. Measure output of converter when powered by battery

Display

Let's BMS communicate battery information and fault conditions to users without need of extra equipment.

Table 17: Display RV

Requirement	Verification
1. Display data sent from master MCU	1. Create fault conditions and confirm that BMS detects them and displays the fault

Isolation

Isolation allows for communication between modules at different voltage level to allow for daisy chaining communication.

Table 18: Isolation RV

Requirement	Verification
1. Can support a baud rate of at least 9600b/s.	1. Test that SPI communication with at least a 9600 Hz clock can be done through the isolation

MCU:

The master MCU main job is to query the slave modules and coulomb counter for data and controls the charge and discharge relays to prevent the batteries from breaking their specified ratings. The master should also be able to take battery data and send out a command that specifies to the slaves which voltage to reduce themselves to. Additionally, the master should monitor for user inputs and respond accordingly.

Table 19: MCU RV

Requirement	**Verification**
1. Can support a baud of at least 9600b/s over SPI. 2. Can support a baud rate of at least 9600b/s over I2C. 3. Can support dallas one wire at standard speed 4. MCU has: >500B SRAM, >1KB Flash and >13GPIO pins without need of other ICs.	1. Test that SPI communication with at least a 9600Hz clock can be done through the isolation 2. Test that I2C communication with at least a 9600Hz clock can be done through the isolation 3. Read data from coulomb counter registers with one wire 4. Use spec sheet to confirm

Voltage Reference

The MCU's internal analog reference has poor accuracy, to improve ADC readings a more accurate voltage reference must be used.

Table 20: Voltage Reference RV

Requirement	**Verification**
1. Voltage reference produces a 2.048V ±1mV rail under ADC reference load.	1. Measure diode reverse voltage with multimeter

Power Components

Power components are off board components since there power rating it too high to be put on the master, additionally the master is agnostic to the exact components allowing for greater flexibility.

Shunt Resistor

The shunt resistor is a high current resistor whose voltage can be used to calculate current through it with I=V/R.

Table 21: Shunt Resistor RV

Requirement	Verification
1. Shunt must have a 60A continuous current rating 2. Shunt voltage must be below 50 mV at 60A.	1. Use spec sheet to confirm rating 2. Measure resistance and use V=IR to confirm the voltage across the resistor will be below 50mV at 60A

Discharge Relay

The relay is used to prevent load from over discharging battery and is controlled with a digital pin from MCU.

Table 22: Discharge Relay RV

Requirement	Verification
1. 60A continuous current rating, can be controlled with MCU.	1. Use spec sheet to confirm rating

Charge Relay

The relay is used to prevent charger from overcharging battery and is controlled with a digital pin from MCU.

Table 23: Charge Relay RV

Requirement	Verification
1. 16A continuous current rating, can be controlled with MCU	1. Use spec sheet to confirm rating