INTEGRATED LI-ION BATTERY SENSORS

By

James Wyeth

Karl Mulnik

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TA: Evan Widloski

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Abstract

Electric vehicles require large battery packs in order to contain the energy required to operate for long distances. These batteries can be dangerous if used incorrectly and cause serious harm to the end user. Our project is a step in the process of ensuring this doesn't happen. We developed a compact sensor board that measures the temperature and voltage of a small part of the battery pack. They were designed such that many can be daisy-chained together to measure the important data across the entire pack. Because of this daisy-chained nature, each board is only affected by the batteries above and below it in the chain. This reduces the maximum voltages they see, reducing part sizing and cost. The only boards that may see a high voltage are the ones on the upper and lower ends of the pack, requiring a different isolation mechanism. The data from these boards is collected at the end and a central Battery Management System processes it and keeps the batteries in a safe state.

Contents

1. Introduction

This project is a redesign of some of the sensing devices in an electric vehicle battery pack. The design is modular sensing circuitry to send data to a central Battery Management System (BMS). For each module, six temperatures and two voltages are to be measured. The system needs to use minimal wiring.

To do this we created a Printed Circuit Board (PCB) with voltage sensing and temperature sensing modules with a microcontroller for processing and communication. The data is sent using single-wire serial down a daisy chain to minimize wiring and isolation requirements.

The voltage sensing is done via voltage divider and the temperature is sensed via thermistors. To isolate the modules a capacitor is used on the communication lines. The block diagram can be seen in Figure 1.

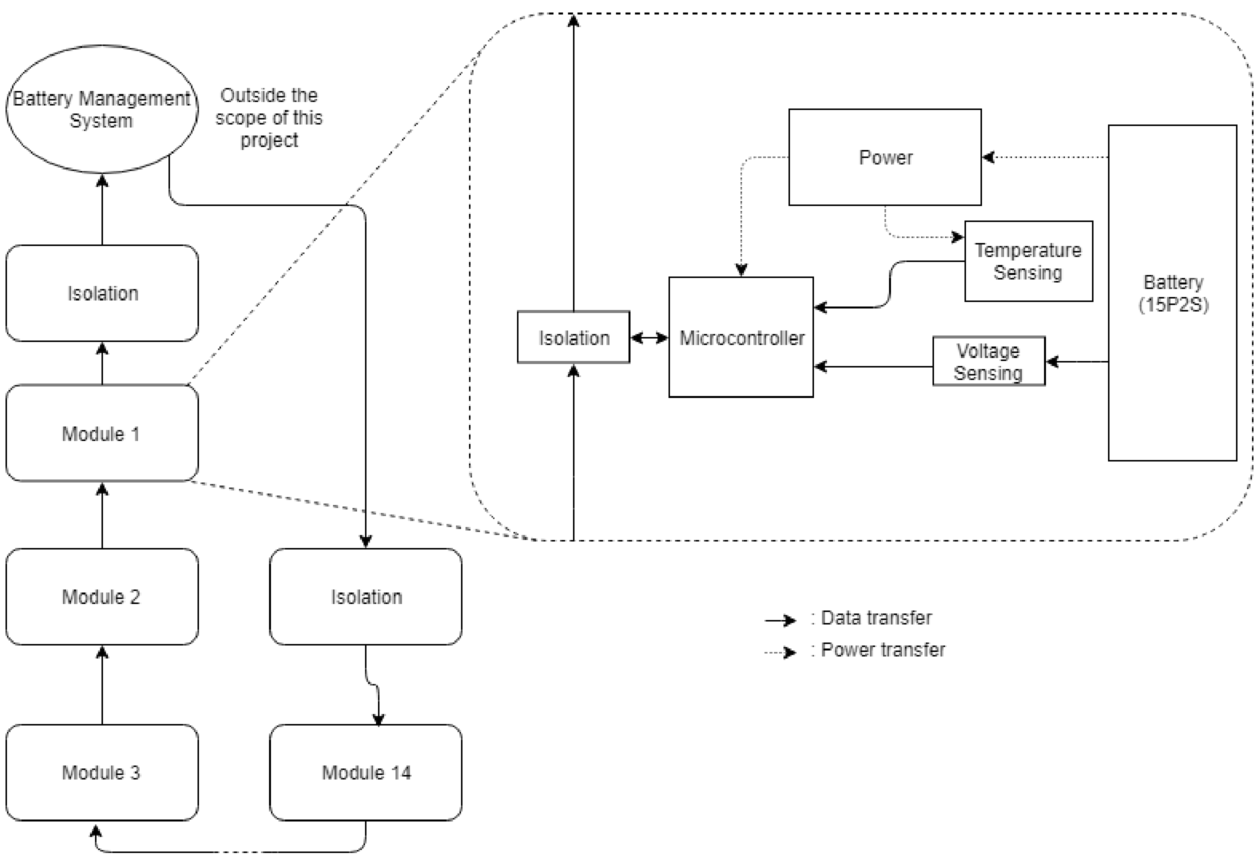

Figure 1: Block Diagram of System

2 Design

2.1 Equations and Simulations

2.1.1 Equations

The accuracy of the measurements is very important. It determines whether the battery pack will be operated safely. Inaccurate measurements could result in battery over-voltage or over-temperatur. Using (1.1), where x is the number of bits, we can find the least number of bits required for 10 mV accuracy. Here, that is ten bits. To meet this requirement, we will be using a 12-bit ADC as it is the next step up. Unfortunately, the values of the components used can vary. Even considering the tolerance of the resistors and voltage supply, the measured values should be within 10 mV. A critical part of this sensing is the voltage divider for the voltage sensing. If the resistors are out of range the voltage could

$$2^x = \frac{8.5}{.01} \tag{1.1}$$

exceed safe levels. To analyze the worst-case scenarios, (1.2) was used. With this information resistor values could be picked.

$$\frac{V_{meas}}{V_{exp}} = \frac{(R_1 \pm tol)}{(R_1 \pm tol) + (R_2 \pm tol)} V_{bat} \tag{1.2}$$

2.1.2 Simulation

A simulation was used to ensure that data would be able to pass through the isolation capacitors. Figure 2 shows the simulation made in LTSpice. The left side of C1 is a model of the inside of the microcontroller as seen in the data sheet from NXP [1]. The right side models the data being sent at a higher voltage. As can be seen in Figure 3, the data passes through perfectly. Since simulations aren't perfect, precautionary measures were taken and a pull up resistor was added to the board.

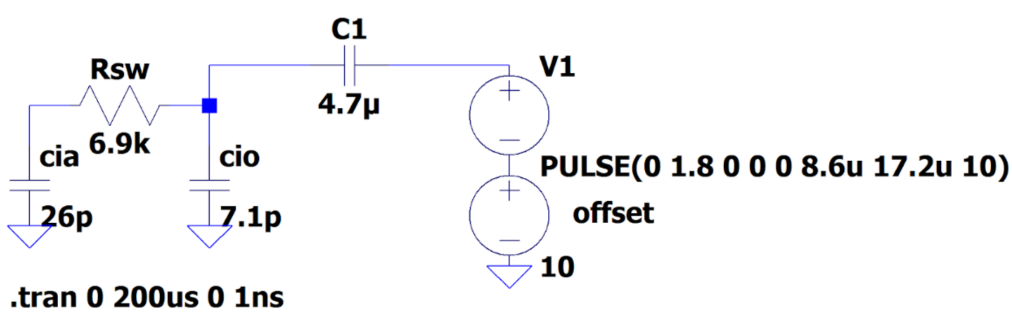

Figure 2: Communication Simulation

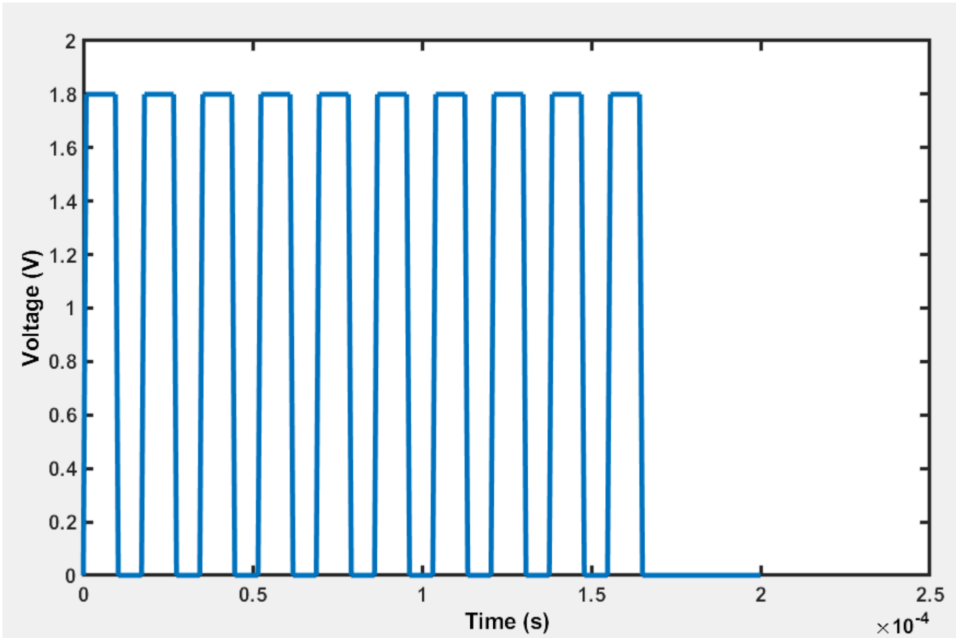

Figure 3: Plot of the Voltage Across cio (microcontroller input).

2.2 Design Alternatives

There was concern that the isolation capacitors would not pass readable data, therefore pull-up resistors and were added to the board design. To hold the voltage steady when not sending data a 10 kΩ pull-up resistor was added. This is because 10 kΩ is a standard pull-up resistor. Another corrective action taken was changing the resistor configuration. We made an error in board design and the resistor divider was upside-down. Therefore, the actual population of the board is different from the schematic. R9 and R9 were flipped, as were R10 and R11. R12 was shorted. Also, the program files took up more memory than expected. The board did not have enough memory to store the C++ libraries. Therefore, the code had to be rewritten in C with skeleton libraries. The only issue that still needs a resolution is the accuracy of the measurements.

2.3 Subsystem Diagrams and Schematics

2.3.1 Voltage Sensing

A resistor divider (seen in Figure 4) was used to step down the voltage to below 1.024 V for measurement by the ADC on the microcontroller. As previously mentioned, there was an error in board design. Therefore, the actual population of the board is different from the schematic. R9 and R9 were flipped, as were R10 and R11. Also, the 69.8 kΩ resistor was replaced with a 75 kΩ. R12 was shorted.

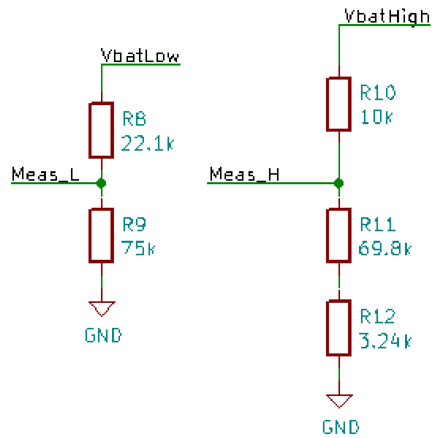

Figure 4: Schematic of voltage sensing circuitry

2.3.2 Temperature Sensing

The circuit in figure 5 shows a column of 10 kΩ resistors. Each is part of its own resistor divider and connected to a negative temperature coefficient (NTC) thermistor. The graphs form Vishay show a parabolic curve for the graph of resistance in relation to temperature [2]. The temperature can be modeled using the Steinhart-Hart equation using the B values given or using a parabolic fit of measured resistances. Thermistors are directly on the battery modules for better temperature measurement, so they are not shown here. This circuit measures the temperature of the batteries and will be powered by the voltage reference. This will in turn go into an ADC, which also needs to be 10 bits to satisfy accuracy requirements. There are six temperature sensors per module. This gives more accurate temperature readings as different parts of the battery module may be at different temperatures.

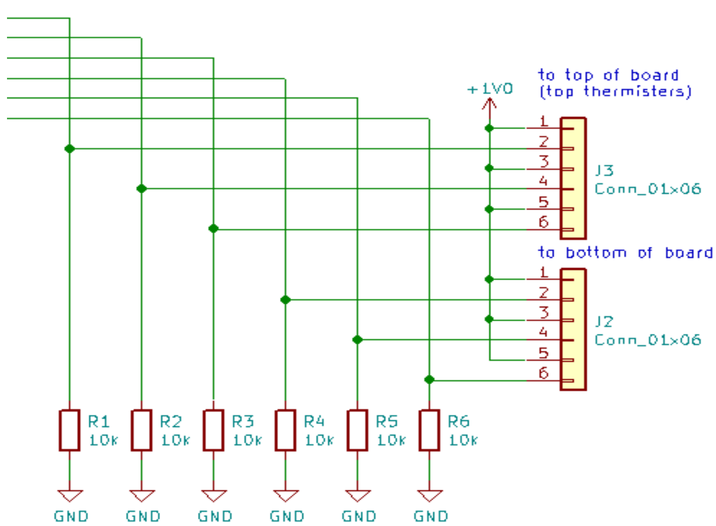

Figure 5: Schematic of temperature sensing

2.3.3 Microcontroller

This portion of the design takes the measurements from the measurement circuitry and translates them into data that can be sent to the next module. It uses UART for communication and eight 12-bit ADCs for voltage measurements [3]. In Figure 6 the microcontroller is shown with a JTAG header for programing as well as the signals for transmitting, receiving and measuring.

On the microcontroller a state machine was created to control data retrieval and transmission. The process can be seen in Figure 7.

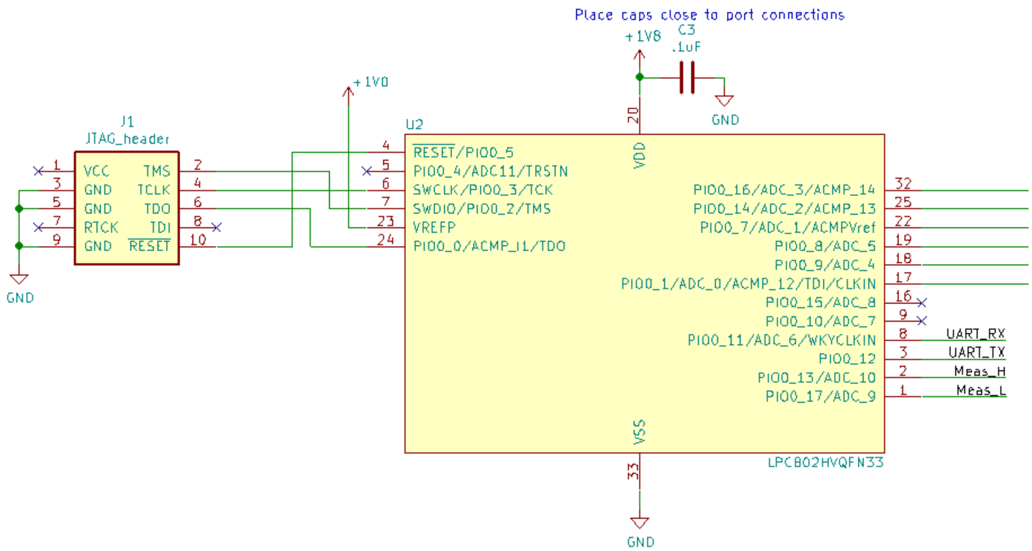

Figure 6: Schematic of Microcontroller system

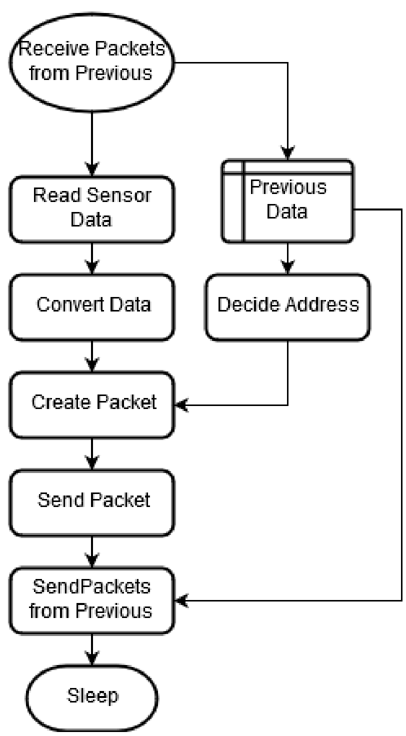

Figure 7: Code Flowchart

2.3.4 Isolation

Between each module is an isolation capacitor to galvanically isolate the data line. These need isolation of at least 10 V. The capacitor value was chosen as it was shown in KEMET to have the lowest impedance at the chosen baud rate [4]. This is C5 in Figure 8. This is because each board has a different ground reference. R7 and R6 were placed in case they were needed for capacitor voltage to be held steady when not transferring data. Only R7 was needed and was populated with a 10kΩ resistor.

There is a second population option for this board for isolation between the highest voltage module and the central BMS. This extra isolation was needed as the voltage difference here may be greater than 100 V. In this second population the digital isolator (MAX12931) is populated instead of the isolation capacitor.

A third option was included for the case where a completely isolated transmission line is required. This option requires only the isolation circuitry be populated, namely U5, U4, and R14. In this case the boards act only as an isolator and pass the signals through unchanged.

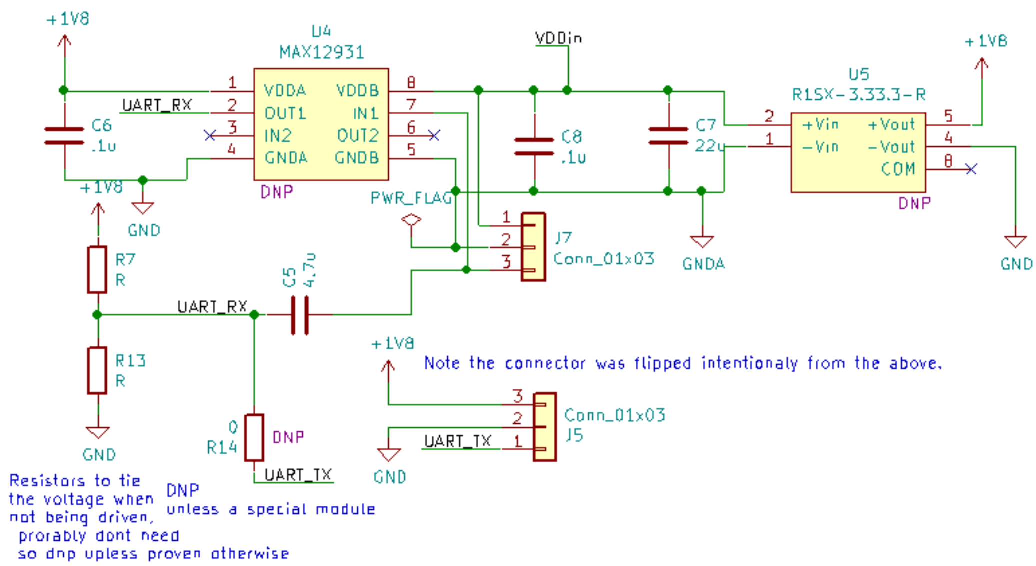

Figure 8: Schematic of Isolation

2.3.5 Power

A linear regulator was used to step down the voltage of the battery to a level usable by the microcontroller. Also, a voltage reference is needed for the ADCs of the microcontroller. These can be seen in Figure 9. The left shows the regulator and the right shows the voltage reference.

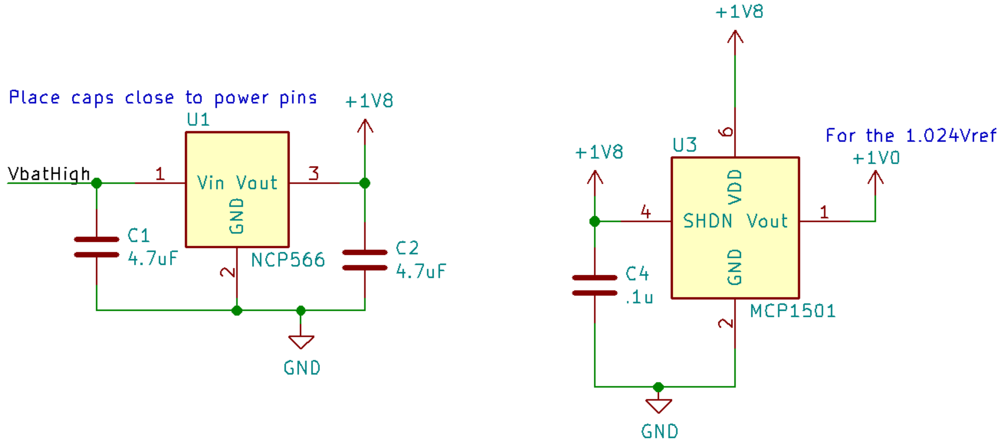

Figure 9: Power Schematic.

3. Design Verification

To test the current leakage of the voltage sensing, a board was populated with only the voltage dividers. Then, the expected battery voltage was applied to each circuit and the input current was measured.

For the temperature sensing, a board was populated with only the temperature voltage dividers populated and then the expected voltage reference was applied across the divider while the input current was measured.

The range testing required a thermal chamber. Since one could not be found, the temperature operating range went untested.

For power testing, resistors were applied to the outputs of the voltage reference and regulator. The values picked were 200 Ω and 18 Ω respectively. This set the output current to the testing limits.

For the rest of the testing a system loop was assembled. This includes three modules attached to a wood board using hot glue, level shifters, cells and a RedBoard. The three modules were assembled to communicate in a loop with the RedBoard acting as the BMS. Since the RedBoard operated at a higher voltage, level shifters were needed for the module to send signals to the RedBoard. The battery cells were used to power individual modules and arranged such that the modules were power at different ground voltages. The RedBoard was connected to a pc where the serial data it received was displayed on a terminal. The results can be seen in the appendix.

4. Costs

4.1 Parts

The total cost of a system including 14 measurement modules with extra isolation modules at the top and bottom is just under $40. The breakdown is shown in Table 1. The system it is designed to replace costs over $100. This is a significant cost reduction.

Table 1 Parts Costs

Part	Manufacturer	Retail Cost ($)	Cost @ 1000 ($)	Quantity per system	System Cost ($)
MAX12931BASA+-ND	Maxim Integrated	1.65	1.5284	2	3.06
568-13821-ND	NXP USA Inc.	1.49	.675	14	2.7
MCP1501T-10E/CHYCT-ND	Microchip Technology	.78	.5974	14	8.36
R1SX-3.33.3-R	Recom Power	3.03	2.6821	2	5.36
P22.1KHCT-ND	Panasonic Electronic Components	.10	.01273	14	.18
RMCF0603FT75K0CT-ND	Stackpole Electronics Inc.	.10	.00321	28	.09
311-10.0KHRCT-ND	Yageo	.10	.00476	98	.47
1276-2969-1-ND	Samsung Electro-Mechanics	.57	.16018	42	6.73
478-7018-1-ND	AVX Corporation	.17	.03391	70	2.37
S9015E-05-ND	Sullins Connector Solutions	.72	.39888	14	5.58

863-NCP566ST18T3G	ON Semiconductor	.82	.35	14	4.9
Total					**39.8**

4.2 Labor

A total of around 120 man-hours were invested in this project. The breakdown is shown in Table 2. At an hourly cost of $75, the engineering work for this project totaled $9000.

Table 2 Timeline

Week	**Task**	**Person**	Hours
10/15/2018	Schematic	Karl	3
10/15/2018	Communication Software	James	5
10/22/2018	Schematic	Karl	5
10/22/2018	Schematic/Layout Review	James	2
10/29/2018	Communication Software	James	5
10/29/2018	Layout	Karl	8
11/5/2018	Layout	James	1
11/5/2018	Layout	Karl	10
11/5/2018	Communication Software	James	4
11/5/2018	Measurement Software	James	1
11/12/2018	Communication Software	James	4
11/19/2018	Communication Software	James	2
11/19/2018	State Machine Development	James	4
11/26/2018	New Device Development	James	10

11/26/2018	Integration Test	James	8
11/26/2018	Integration Test	Karl	8
12/3/2018	Assembly	James	2
12/3/2018	Debugging	James	18
12/3/2018	Debugging	Karl	10
12/10/2018	Debugging	James	5
12/10/2018	Debugging	Karl	5
Total Hours			120

5. Conclusion

5.1 Accomplishments

This board can communicate data serially and reliably. None of the data was corrupted during sending. It is also able to measure voltage and temperature using very little current. The max current usage is less than 1 mA per sensing circuit.

5.2 Uncertainties

The measurements made by the ADCs on the microcontroller are inaccurate and inconsistent. The voltage measurements could be as much as 3 volts off and 1 volt different for each measurement. The conclusion is that the ADCs of the microcontroller are inaccurate Using the internal voltage reference may help, but the best solution appears to be getting an external ADC.

5.3 Ethical considerations

In carrying out this project, we did our best to follow the IEEE code of ethics [5].

1. When testing this project, we used external power supplies whenever possible. Since Li-ion batteries can be dangerous, we were careful about how, and when, we integrated them into our project. When connected, we monitored them carefully to ensure they were not going to an unsafe state. At one point, 2 of our batteries were depleted below their safe recharge voltage. Instead of attempting to revive them, we insulated them and marked them for safe disposal.
2. We did not run into any conflicts of interest when pursuing this project.
3. We documented our work and data as we collected it to ensure it was correct. We did not round our measurements to make them pass verification. We measured with more accuracy than we noted down, but noted down more accuracy than verification required.
4. We were not paid in any way for our work. Our parts were provided by the organization we were completing the project for.
5. This system does not have a direct societal impact. The larger system is an electric vehicle, for which the societal implications are well known.
6. Although we did not have all the experience required for this project, we had the background required to gain it while working on the project.
7. We regularly verified each other's work and changed it to reflect the criticism of the other.
8. In developing our project there was no opportunity to discriminate against others.
9. We were careful and courteous with the lab equipment we used, making sure to leave the workspace cleaner than we found it.
10. We held each other responsible for our actions and took advantage of every learning opportunity.

5.4 Future work

References

[1] NXP Semiconductors, "LPC802," 2018 April 2018. [Online]. Available: https://www.nxp.com/docs/en/data-sheet/LPC802.pdf. [Accessed 21 September 2018].

[2] Vishay Inc, [Online]. Available: https://www.vishay.com/docs/49498/ntcs-e3-smt_vmn-pt0283.pdf. [Accessed 16 September 2018].

[3] NXP Semiconductors, "UM11081," 6 December 2017. [Online]. Available: https://www.nxp.com/docs/en/user-guide/UM11081.pdf. [Accessed 13 October 2018].

[4] KEMET Corporation, "KEMET K-Sim," [Online]. Available: http://ksim.kemet.com/Ceramic/CeramicCapSelection.aspx. [Accessed 1 October 2018].

[5] IEEE, "IEEE Code of Ethics," [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed 17 September 2018].

Appendix A Requirement and Verification Table

Voltage Sense

Requirements	Verification	Pass Condition	Results
Leakage current less than 1 mA per measurement circuit	Apply maximum input voltage to isolated voltage measurement circuit.	DC current < 1 mA per measurement circuit.	99uA measured. PASS
Voltage sensing from 2.5 V to 4.2 V with 5 mV accuracy.	Power both cell inputs with 10 voltages spanning the range. Record cell voltage with DMM and software	Maximum difference between reference and measurement of 5mV.	ADC implementation inaccurate at low voltages. FAIL

Temp Sense

Requirements	Verification	Pass Condition	Results
Leakage current less than 1 mA per measurement circuit	Populate all temperature measurement circuits and short thermistor outputs. Apply 1.024V to reference pad.	Total DC current < 6 mA.	1.07 mA was measured. PASS
Temperature sensing with 1 degree accuracy at 40 C and 60 C	Apply heat to thermistors using heat gun. Record measurements at five temperatures spanning 30 C to 40 C. Do the same spanning 50 C to 60 C. Use a thermocouple for reference.	Maximum difference of 1 C between reference and measurement.	ADC implementation inaccurate at low voltages. FAIL

Temperature sensing from -20 to 60 degrees C	Use thermal chamber to bring ambient to -20 C and 60 C. Record temperature measured with firmware.	Any temperature is sensed at extreme ambients.	The range testing required a thermal chamber. Since one could not be found, this went untested.

Brain

Requirements	**Verification**	**Pass Condition**	**Results**
Communicates at 115200 kbaud	Send data to the module input and read the data at the output using a USB serial converter set to 115200 kbaud.	Data in is the same as data out.	Full packets were received. PASS
ADCs accurate to 1 count	Supply 10 voltages spanning 0 to 1.024 V. Measure value from ADC. Record voltage measured on a multimeter and multiply by 4000. Truncate.	Maximum difference of 1 count between reference and measurement.	ADC implementation inaccurate at low voltages. FAIL

Isolation

Requirements	**Verification**	**Pass Condition**	
10 V isolation between each module	Connect two modules in series. Apply 10V between the negative reference of each board. Send a message from the top board and monitor the second board.	The second board receives the packet sent by the first.	Message was sent down a line of 3 separately referenced boards. PASS

130 V Isolation between the top module and the BMS	Supply a message referenced 130V above the top board ground to the top board.	Top board receives the message.	High voltage isolated was not tested.

Power

Requirements	Verification	Pass Condition	Results
Average power usage within 1 mW across all modules	Assemble a 5-module system and measure average power over 10 seconds to each module while operating normally	The range of average powers is less than 1 mW	We never had 5 modules working at one time, so this went untested.
Can provide 100mA between 1.71 V and 1.85 V from 5 V-8.5 V source	Supply 5 V to system and connect a 18Ω resistor across the output. Supply 8.5V with no load.	Output voltage stays between 1.71 V and 1.85 V.	1.79 V was measured. PASS
Can provide 5 mA at 1.024 V ±1 mV from regulated voltage	Supply 1.71 V to reference and connect a 204Ω resistor across the output. Supply 1.85 V with no load	Output voltage stays between 1023 mV and 1025 mV.	1024 mV was measured. PASS

Communications

Requirements	Verification	Pass Condition	Results
No more than 1% of measurements corrupted	Run system under normal operation for 1 minute.	Maximum of 150 packets fail checksum.	While testing, no packet was corrupted

			PASS
100ms delay between request and receipt of message	Send a measurement request and time response 100 times.	No delay exceeds 100 ms.	

Measurement

Requirements	**Verification**	**Pass Condition**	**Results**
Memory usage does not exceed on board storage	Set up the system to communicate with the BMS. Apply test measurements for one hour.	All data is measured and is sent to the BMS.	All memory was allocated beforehand and never overflowed. PASS