ECE 445: Senior Design

Automated Cell-Tester: Design Document

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1 Introduction

1.1 Problem and Solution Overview

Battery applications have been increasing in popularity and stories of terrible battery-related chemical fires along with them. Unfortunately, the causes of these fires is often not discovered until after the fact. The official reports filed after such an event often cite issues such as manufacturing defects in the separator, impurities introduced at production, thermal runaway, design flaws that cause unnecessary current drain, overworking the battery and improper use, and a few others [2]. Not only are these fires dangerous, but they are costly. Like in the case of an entire electric vehicle catching fire, not only is the car destroyed, but also the fire may take as much as 40 times the amount of water an internal combustion engine car fire would take to put out due to the nature of the battery's chemical fire [3]. This has increased some of the stigma in regards to working with batteries which slows the transition towards an electric future. A future that involves many forms of huge energy storage banks made up of lithium-ion batteries that help incorporate more solar and wind power into the grid as well as enable technologies like electric vehicles [1]. Therefore, using lithium-ion batteries can be quite dangerous therefore limiting entry into the industry of battery-powered applications or, at a worse extreme, causing major harm and damage to any individual or application. In many cases, the latter can be avoided by simply having more insight into the characteristics and expected behavior of the battery pack's individual cells. With the proper behavior defined for the battery, the user could theoretically know when a battery is acting out of line with the expected behavior and shut down the application before any fires break out. The reduction in lithium-ion related fires and accidents could possibly result in a broadening of the industries applications as well as ensure safe and efficient use in increasingly popular applications such as electric vehicle and power storage.

To achieve safer use of lithium-ion batteries we are going to provide the user with the necessary insights of an individual cell in any given pack to be able to know when to shutdown safely in order to avoid any destructive chemical fires or harmful battery behavior. To do this we are going to build a cell-tester that is specifically suited for testing the cell's characteristics through different tests and varying thermal conditions. In this way, we will be able to characterize a cell in its application's normal operating conditions and provide the baseline to which all the cells in the pack will be compared. Providing the information from the different tests to the management system responsible for the battery will allow the early shutdown desired. Another benefit of having all this information about the cells being used is that they can also be optimized for longevity and efficiency.

1.2 Visual Aid

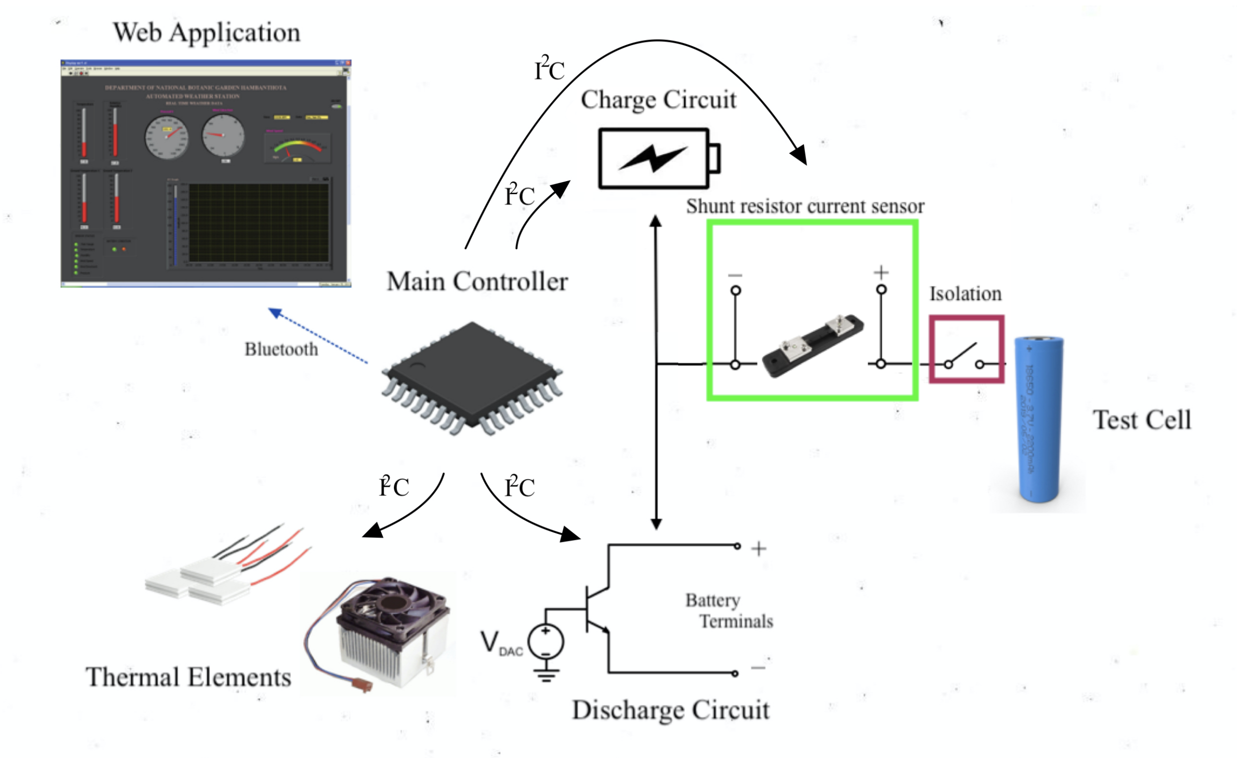

Figure 1: Visual aid for representing the system and its components such as thermal and current control, as well as the interface with the web application and isolation from the battery.

1.3 High-Level Requirements List

- The device will perform the three necessary tests (see section 2.5.2) to accurately characterize a lithium-ion cell's capacity, charge/discharge curve, and RC polarization characteristics which provide a great deal of insight into battery performance.
- The web application will receive results from tests of specific cells and use those results to display the current battery characteristics as well as the cell's performance over time.

- The device will control a thermal unit that will to maintain a constant temperature from 15°C-35°C to within 5°C throughout any given test allowing for characterization of the cell over a range of thermal conditions.

2 Design

2.1 Block Diagram

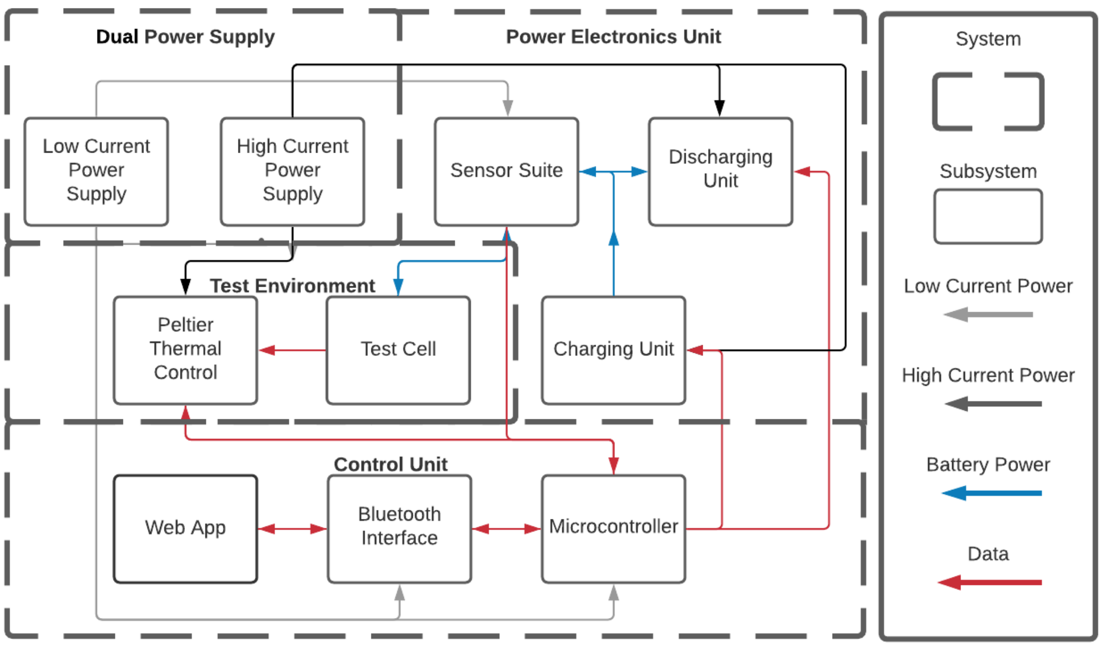

Figure 2: Block diagram representing the various systems and subsystems of the device, including thermal unit, power unit, and control unit.

The design of the device calls for three major systems, each addressing one of the three high level requirements, and a fourth power supply system to power the device. Performance and measurements of the characterization tests will be performed by the Power Electronics Unit. This system will be capable of charging and discharging the test cell as well as monitoring the cell's voltage and current. The Test Environment system composes the thermal unit and will be capable of changing the temperature of the cell. The Control Unit system provides control to the other major systems. It will be capable of collecting and sending the data gathered in the Power Electronics Unit to the web application.

2.2 Physical Design

The physical design, figure 3 below, features mostly the thermal chamber that will be thermally insulating so that the environment inside can be easily manipulated as well as maintained at maximum efficiency. This chamber will be about a cubic on the inside to accommodate almost any form factor of cell. Not featured in this design is the lid that will inevitably be placed on top of the module while testing to optimize efficiency. It also shows the potential location of the thermistor we will be using to determine the cell's temperature during a test.

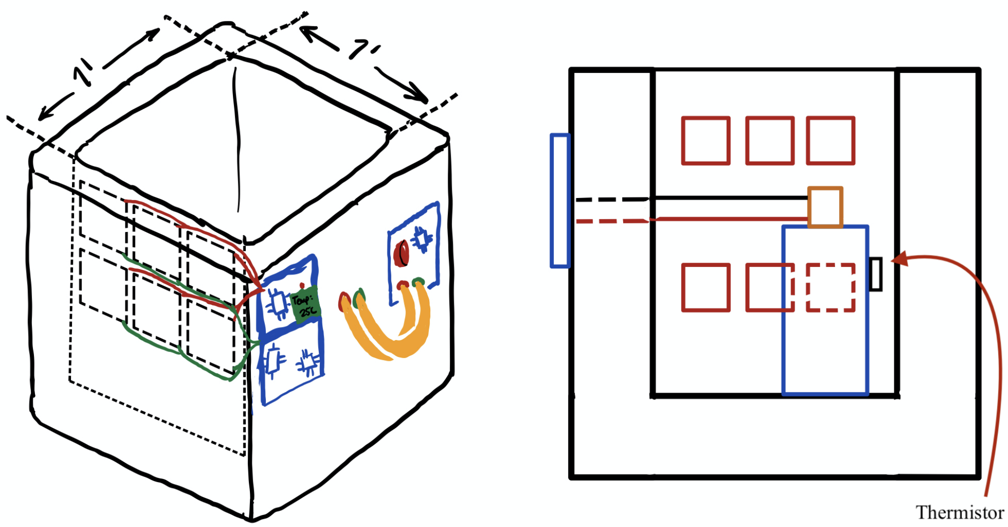

Figure 3: The physical design, most notably the thermal chamber and its components.

2.3 Power Electronics Unit

The device will require power electronics for ensuring safe operation of any cell placed under load, including IC chargers, power resistors, BJTs, fuses, and whatever circuitry as well as decoupling necessary to isolate the battery completely from the parts of the system not required for managing power such as the chip. The BJTs and power resistors are what the controller will use to control current flow while the IC will perform solely the charging under control of the main controller. This unit will also contain all the necessary sensors such as ADCs as inputs to the main control unit. We will need other external DACs as well for controlling inputs to specific ICs.

2.3.1 Discharging Unit

This subsystem is responsible for discharging a cell at a fixed current. This is primarily accomplished via a power switching BJT rated up to 250W. The current through this BJT is controlled via an op amp buffered I^2C DAC. Given that both precisely controlled small and large currents are of interest, the discharging circuit can be configured for high or low current via a single control signal. The current from the buffer to the base of the BJT can pass through either a larger 1000 ohm resistor or small 20 ohm resistor, determined by a pair of complementary FETs. This increases the current resolution of the DAC controlled BJT at smaller currents.

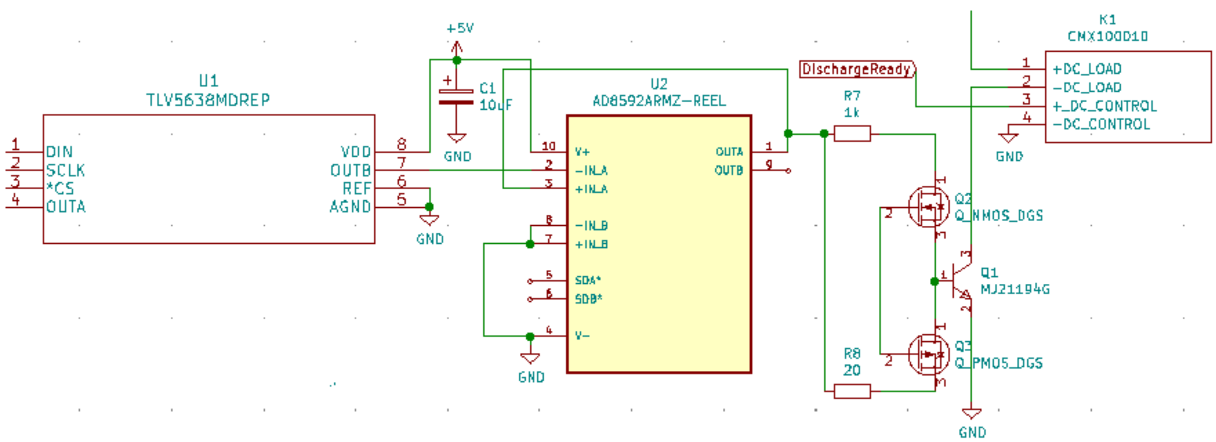

Figure 4: Schematic of the discharge circuit, including isolating solid state relay.

Requirements	Verification
1. Isolate the battery and avoid any inrushes of current to the board or power supply. 2. Successfully control current out of the battery to within 1%.	1. Perform exhaustive startup conditions and measure current on oscilloscope over time. 2. Demand constant current at 0A to 5A in 1A increments from the battery and use an oscilloscope to measure current at each step, compare results with expected value. 100%→0%).

2.3.2 Charging Unit

This subsystem is responsible for charging a cell at a fixed current. Due to the relative danger involved in the charging of lithium-ion cells, an existing IC solution will be utilized along with supporting hardware. The IC is rated up to 5A with a 10mA current resolution. This is a perfect match to the required maximum charging current of 5A. Additionally, this IC contains safety features such as thermal regulation and emergency shutdown signals that would prove difficult to implement conventionally.

Requirements	Verification
1. Isolate the battery and avoid any inrushes of current to the chip, board, or power supply. 2. Successfully control current flowing into the battery to within 1%.	1. Perform exhaustive startup conditions and measure current on oscilloscope over time. 2. Supply current to the battery at 0A to 5A in 1A increments and use an oscilloscope to measure current at each step, compare results with expected value.

2.3.3 Sensor Suite

This subsystem is responsible for measuring the voltage and current of the cell. This is accomplished via voltages tapped into on either side of a small quarter ohm resistor. This resistance was chosen such that at a maximum planned discharge of 5A, the BJT from the discharging circuit will not enter saturation until the test cell is below 2V, allowing for ample discharge of the cell at constant current for characterization. To protect the sensitive ADCs from the battery, these tapped voltages are buffered via op amp before inputting to the ADCs. While the voltage of the cell can be read by directly comparing the upper buffer voltage against ground, current measurements require the differential between the upper and lower buffers. To leverage the full dynamic range of the ADC, the differential voltage is multiplied by 4 via op amp such that a 5A current would produce a 5V differential at the ADC. From the ADCs data is conveyed to the control unit via I2C.

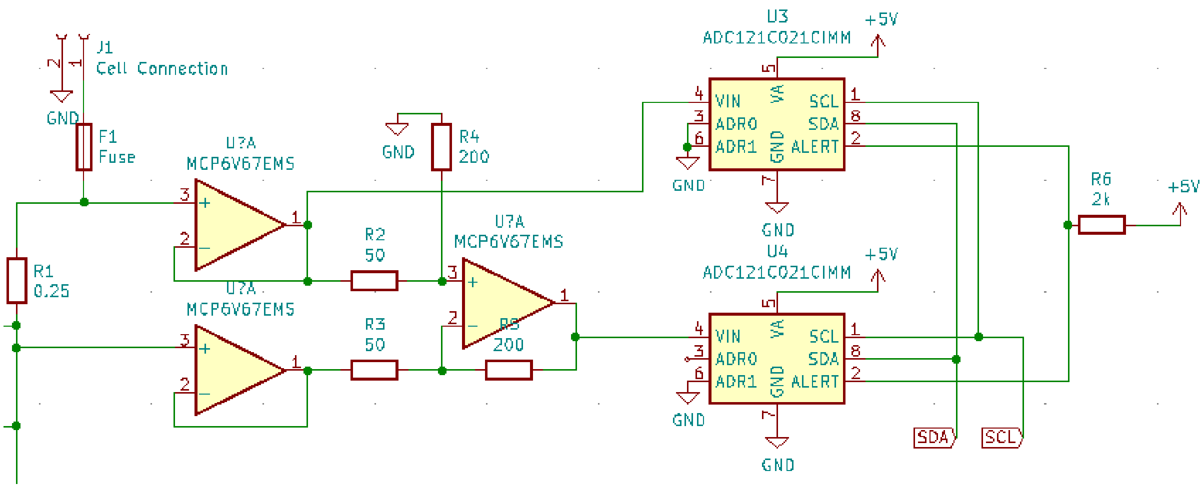

Figure 5: Schematic of the sensor suite, including the cell connection to the system and safety 10A fuse.

Requirements	**Verification**
1. Isolate the battery and avoid any inrushes of current to the chip, board, or power supply.	1. Perform exhaustive startup conditions and measure current on oscilloscope over time.
2. Measure voltage and current on the battery to within 1% of the true measurement.	2. Confirm that measurements read out from the main controller align to within 1% with those of a voltmeter/ampmeter etc. over the course of an entire capacity test (e.g. SoC goes 100%→0%).

2.4 Computer Interface

This subsystem will include the bluetooth connection from the device to the computer itself as well as the end-user web application. This will allow the product to be cross-platform and also allow us to store data from the device's tests on the local machine as well as use old data from previous tests to track performance over time.

Requirements: This includes a rather wide range of functions the device will perform, such as the web application and the bluetooth interface between the device and the users computer. As such this unit is required to do many things including the following

Requirements	**Verification**
1. Successfully relay information about the given test being performed or the start/end of a test to the users computer over bluetooth. 2. Web application should store data from tests on the users computer ("save data to file"). 3. Web application should convey information about a cell's history, as well as its current behavior. 4. Web application will have an option for viewing the current state of the cell and information on the test provided that it is currently performing one.	1. Perform at least one of each type of test while having Bluetooth keep alive message time signatures be $<$ 8ms apart. 2.A Save test results to computer. 2.B Read test results back to ensure they were saved in the proper format. 3. The user-end graphs and data are aesthetic, easy to understand, and encapsulate the data well. 4. The testing page of the web application updates at least every 500ms with all the data dumped to it since the last update, including current cell information.

2.5 Test Environment

In order to characterize a cell across a variety of conditions, control over the charging/discharging environment is required. As temperature is the most significant environmental factor which affects battery performance, this design focuses solely on controlling the temperature of the cell.

2.5.1 Peltier Thermal Control

The device includes a thermal chamber, about a cubic foot on the interior, which will control the internal temperature inside a $\pm 20°C$ range due to the drastically changing characteristics of these cells under extreme temperatures. This will include a somewhat large array of Peltier devices that separate thermal components in a system based on polarity. For this we will also need to include several accommodations to make the Peltier devices as efficient as possible, such as fans, ducts and ventilation of the exterior side of the devices.

Requirements: This is the most challenging part of the project. It must control a wide range of heating and cooling as well as isolate the system at a certain temperature. Therefore this unit must perform the following:

Requirements	Verification
1. Set the internal temperature of the thermal chamber by causing a change in the polarity or power consumed by the Peltier devices. 2. Maintain a given temperature over long stretches of time (e.g. ∼10 hours) by controlling the output of fans and Peltier devices to ensure optimal efficiency and minimize needless power consumption. 3. Identify a valid range of testing temperatures in given environment (e.g. outdoors vs. in a refrigerator).	1.A Generate voltage difference to Peltier devices. 1.B Use a thermal camera for ensuring there is a difference. 2.A Using some form of thermistor, ensure that the temperature of the two sides of the Peltier device do not tend towards the average temperature. 2.B Ensure that fans and heatsinks perform the necessary functions well enough by examining Peltier device behavior through a thermal camera over time. 3. Use a thermometer to analyze the exact temperature ranges available to the system.

2.5.2 Test Cell

The test cell is, by its very nature, an interchangeable part of the device. The design of the device is such that a variety of test cells will be accepted. This focus of this subsystem is, therefore, not on the cell itself, but on the monitoring of the cell, particularly, its temperature by means of a thermistor.

Requirements	Verification
1. Measure the current temperature of the cell to within 5°C	1. Use a thermometer to verify the accuracy of the temperature readings over the range of the thermal chamber's operating temperature.

2.6 Dual Power Supply

This design calls for a dual approach to the power supply, as the device must provide extremely consistent low current power to the microcontroller and ICs but also provide pulses of high current to the charging circuit. As such, the power supply has been separated into low and high current subsystems.

2.6.1 Low Current Power Supply

The Low Current Power Supply is intended to supply an extremely consistent 5v to sensitive components operating at low power. This includes the microcontroller and DACs as well as the subset of op-amp which will operate at lows currents. This requires a voltage regulator with a modest current rating of 1A.

Requirements	**Verification**
1. The power supply must be completely stable for the correct operation of the microcontoller and ICs.	1 Tax the power supply by drawing its full load (1A). Record and note any voltage differences in our ground compared to the lab's common ground.

2.6.2 High Current Power Supply

The High Current Power Supply is intended to supply the power electronics in the device. These include the Charging Unit, Discharging Unit, and the Peltier Thermal Control. As such it will utilize a 5v voltage regulator with a higher rating of 7.5 A to supply the Charging Unit and Discharging Unit. The Peltier Thermal Control, on the other hand, will receive an unadulterated 12v.

Requirements	Verification
1. The power supply must be completely stable as it is our reference and if something were wrong with the supply, we would likely not be able to detect an issue with the battery. 2. The supply will likely need to supply the necessary current to charge the battery so it should be rated for probably about 100 W to accommodate both the charging and the power consumption of the Peltier devices.	1.A Tax the power supply by drawing as much a load as we can (e.g. 5A discharge and 0°C). Record and note any voltage differences in our ground compared to the lab's common ground. 1.B Demand a 5A switching load from the battery and supply 1A switching current to the Peltier devices. Record and note any voltage differences in our ground compared to the lab's common ground. 2. Tax the power supply by drawing as much of a load as we can. Ensure there are no overcurrents in the ratings of the power supply.

2.7 Software

The main controller will handle the specific structure of the testing routines, the bluetooth communications with the web application, the control over the thermal module, and finally reading all the sensors. The web application will handle the data from the main controller as well as any data the user provides from previous tests and determine the characteristics of the cell.

2.7.1 Testing Algorithms

The main function when the device is on is to run the testing loop which is generalized in figure 6 below. Each test will require its own tracking variables and test command structure to ensure the proper current is being demanded for the given test. Each test is outlined below:

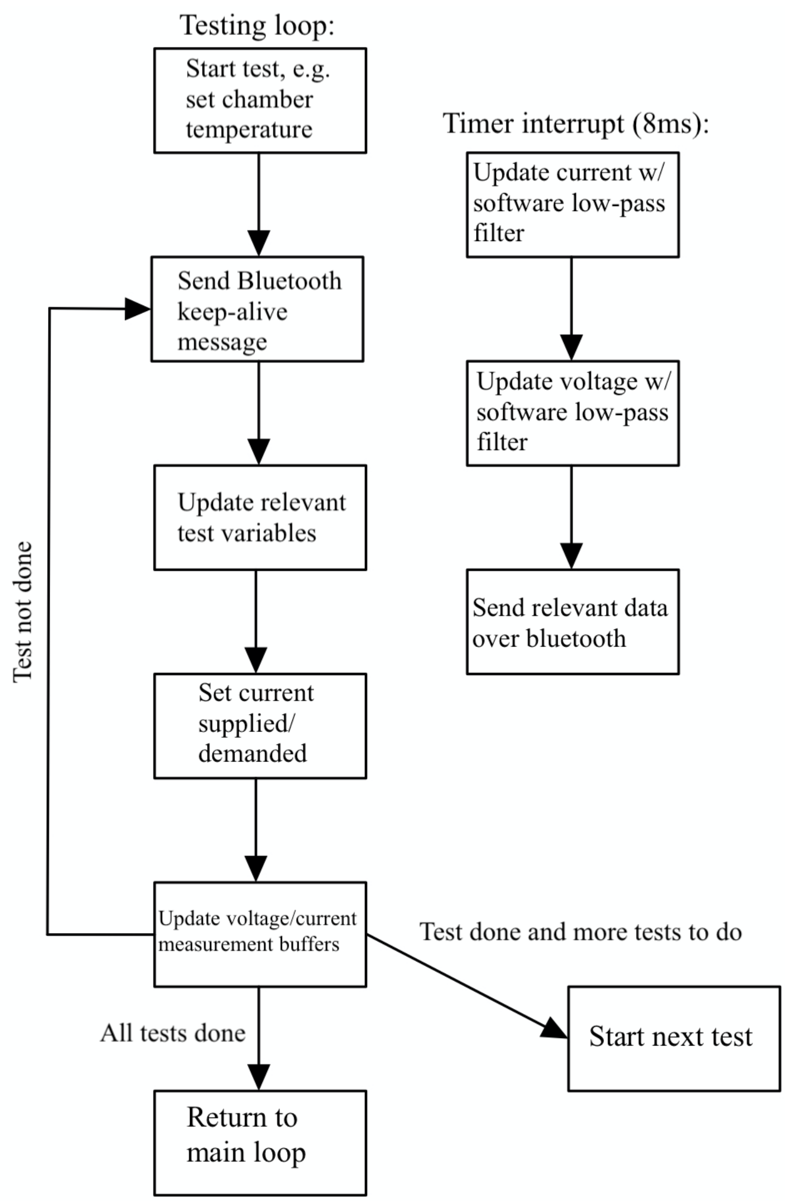

Figure 6: General testing routine.

Capacity Test

1. Ensure the battery is fully charged by either 1) charging it fully or 2) indicating the full charge open-circuit voltage (OCV) to the web application and let the device handle charging.

2. Determine the minimum OCV as well as desired thermal setting for the test.

3. Discharge the battery at 3A or 0.1 * capacity of the battery (whichever is smaller) until the

cell's OCV reaches the minimum allowed OCV.

4. During the discharge, perform the coulomb counting algorithm (detailed below) to determine the amount of Ah drained from the cell over the course of the test.

Note: If the battery has no predefined characteristics, the controller will have to assume no polarization voltage and consequently that the cell's capacity to be smaller than it truly is to avoid over-draining the cell. Assuming the battery has been tested before, the controller can load this information over bluetooth and accurately determine the safe conditions for operation, including any current limits unique to the cell as well as more accurate OCV and capacity tests.

Constant Charge/Discharge Test

1. Ensure the battery is fully charged by either 1) charging it fully or 2) indicating the full charge open-circuit voltage (OCV) to the web application and let the device handle charging.

2. Determine the maximum and minimum OCV as well as desired thermal setting for the test.

3. Set any current limits unique to the cell, this is necessary before starting any test.

4. Discharge the battery at 5±0.05 A or current limit until the battery is depleted.

5. Measure Amphours and voltage during entire test and communicate this data to the web application to store.

6. Charge the battery at 5±0.05 A or current limit until the battery is 70% full and thus can no longer sustain constant current charging.

Note: The charger can finish the test process by optionally finishing the charge at constant voltage or leave the cell in its current state. This data will be sufficient for extrapolation of the SoC-OCV curve.

HPPC Test

This test addresses the RC polarization characteristics of the cell. This voltage develops over long discharges. The RC characteristics of a cell can be calculated easily (detailed in section 2.7.3) with the data obtained from this test.

1. Ensure the battery is fully charged by either 1) charging it fully or 2) indicating the full charge open-circuit voltage (OCV) to the web application and let the device handle charging.
2. Determine the maximum and minimum OCV as well as desired thermal setting for the test.
3. Allow the cell to sit for an hour and come to equilibrium.
4. Discharge at 5±0.05 A or current limit until 10% capacity is drained from the cell.
5. Charge the cell at 5±0.05 A or current limit for 20 seconds.
6. Repeat steps 3-5 until the battery is depleted.

Note: The charge current acts as a regenerative pulse to remove some of the polarization voltage from the cell and allow it to come to equilibrium faster.

2.7.2 Sensors and Coulomb Counting Algorithm

The sensors consist entirely of a suite of ADCs that read various voltages produced by the IC. One particularly interesting sensor from a software perspective is the shunt resistor current sensor which enables the device to perform a Coulomb counting algorithm, which is shown in figure 6 above. The process consists of updating ampbuffers in the main loop to store the amount of current coming out of the cell in the ampbuffers until the next 8ms interrupt. The interrupt will then read the ampbuffers, average them and then update the current seen over the last 8ms through a software-based, low-pass filter. This way a we will be able to count the current coming out of the battery over time giving us Amphour integration or Coulomb counting.

2.8 Tolerance Analysis

The thermal aspect of the project is highly imprecise and as such deserves the most attention in a discussion on tolerance. We can calculate the temperature changes that our device can sustain by modeling the chamber as a calorimeter and use the following equation.

$$Q = mC\Delta T \tag{1}$$

where m is the mass of the air inside the chamber, C is the specific heat of air, and Q is the amount of energy that the Peltier devices will put into the system in 20 minutes. Assuming the Peltier devices are 5% efficient in converting electrical energy into thermal energy when cooling [4], we can define this energy to be

$$Q = \eta V I \Delta t \tag{2}$$

where η is the efficiency, and Δt is the change in time, 20 minutes. We will operate the devices at about 5V and 1.5A, thus we get $Q \approx 450$J and we can solve for the overall change in temperature. First, we note that the mass of a cubit foot of air is about 36.6 grams and the specific heat is 1.005 kJ/kgâK thus for the overall temperature change we have $\Delta T \approx 12$K. Which is sufficient to claim we are capable of about 10°C deviations from room temperature. In addition to this calculation, we also ran a simulation showing the normalized thermal effect of the Peltier devices spacially inside the thermal chamber. This illustrates the temperature differential that will be present inside the chamber which will contribute to inaccuracies in our estimations for temperature control.

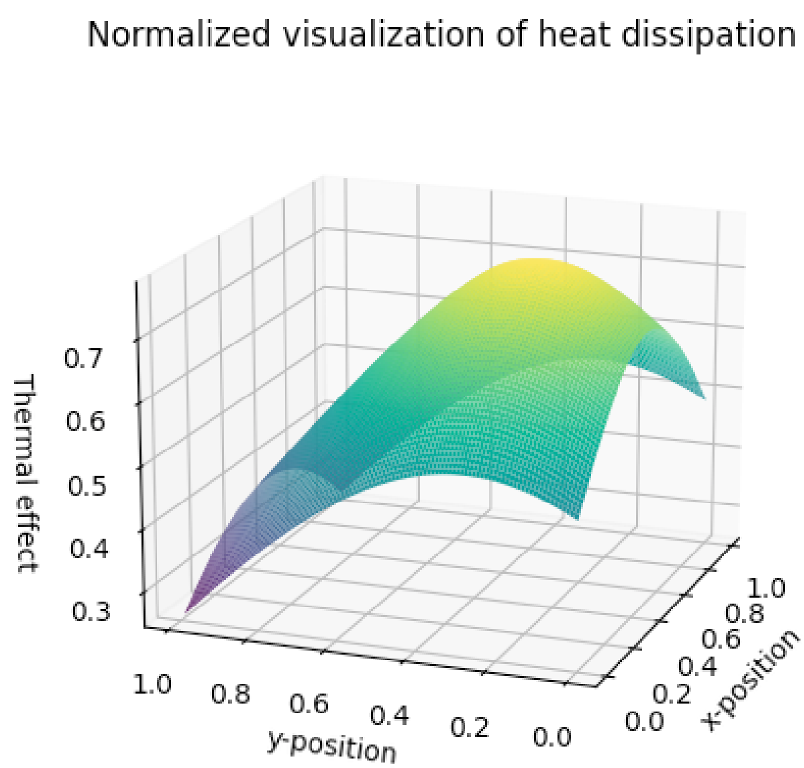

Figure 7: Spacial illustration of thermal effect of Peltier devices.

3 Cost and Schedule

3.1 Cost Analysis

In the current situation, we will conduct the experiment in wide ranges of temperatures, so we did not consider creating a very accurate and efficient thermal chamber, except for what is needed to ensure some form of thermal control inside the chamber. Thus our costs are estimated without the inclusion of highly-capable thermal insulation on the thermal chamber. We estimate our current costs to be:

Items	**Cost**
Bluetooth Module (Amazon; HC-05).	$ 10.89
Microcontroller (Digikey; ATmega32u4).	$ 5.28
Power Resistor (Digikey; RSB-500-50).	$ 26.16
2 x Digital to Analogue Converter (Digikey; TLV5618-EP).	$ 31.52
Battery Charger (Digikey; BQ24179).	$ 6.36
Analogue to Digital Converter (Digikey; ADC121C021).	$ 49
4 x Amplifier (Digikey; MCP6V69).	$ 10.12
Solid State Relays (Digikey; CMX60D10).	$ 41.55
2 x Diodes (Digikey; AZ1084C)	$ 0.74
Total	$ 181.62

3.2 Schedule

This is the schedule for the project that will be carried out during this semester.

Week	To do
Week 6 (9/27/21)	Check Design Document/PCB Review and Order.
Week 7 (10/04/21)	Determine main code constructs and finalize parts order form for PCB
Week 8 (10/11/21)	Implement a workable web application and discharge/charge circuit
Week 9 (10/17/21)	Finish majority of web application and run mock test
Week 10 (10/25/21)	Ensure all circuits are correct
Week 11 (11/01/21)	Finalize code and fine tune sensors
Week 12 (11/08/21)	Eliminate any possible bugs and prepare for mock demo
Week 13 (11/15/21)	Finish web application
Week 13 (11/22/21)	Remove any possible unsafe states
Week 13 (11/29/21)	Begin and finish final report

4 Discussion on Ethics and Safety

As with any lithium-ion battery application, our main concern is operating safely within the limits of any cell. This means even when the cell is broken or new, there must be some way for the device to determine this without actually demanding too much current to or from the cell. The device will need an emergency stop for isolating the battery mechanically from the circuit. In the case of a fire, there will be a mechanism for removing the lid at a safe distance and exposing the battery for extinguishing. The final safety concern will be huge rushes of current and any voltages present in the cell being tested. Therefore, we are implementing the proper isolation in order to avoid electric shock.

The ethical concern for this device will be money. Given that this device is supposed to allow anyone to work with batteries in a safe manner, we want to be able to market it to everyone. Another reason we call attention to the cost of the device is because batteries and systems involving batteries are expensive as is, it not likely that users will want to spend half their budget on testing equipment.

5 Appendix

References

[1] Hull, Dana, and Naureen S Malik. "Battery Fires Haunt the Electric Car and Clean Power Revolution." Bloomberg.com, Bloomberg, 24 Sept. 2021,

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