

SMART HYBRID DRONE BATTERY

By

Namin Shah

Nicolas Nkiere

Raj Lulla

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TA: Uma Lath

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Abstract

Our senior design project was to build a smart hybrid battery system, leveraging the strengths of different battery chemistries to cancel out the weaknesses of others. The goal is for the battery to dynamically switch between the different chemistries depending on what the drone is doing at the time. In order to achieve this, the battery records and stores data from the flight to be used to create and tune the switching algorithm. Over the course of the project, we attempted multiple approaches to different aspects of the project and had to adapt to issues we encountered. Our attempts and solutions are documented in the following report.

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1. Introduction

1.1 Project Overview

Entering this semester, our team has been working on a startup, Haylon Technologies, with the goal of creating a longer-lasting battery. Our plan was to leverage the technology and support from senior design to create our first prototype of this battery.

In order to achieve longer-lasting batteries, we are combining multiple, different, battery chemistries in a single battery pack, leveraging the strengths of one to cancel out the weaknesses of others. Batteries vary greatly in areas like energy density by weight, volumetric energy density, discharge rate, and cyclic stability. Generally, batteries that excel in energy density and cyclic stability lack in discharge rate - we will call these high-capacity or high-stability batteries. Similarly, batteries that excel in discharge rate lack energy density and cyclic stability - we will refer to these as high-energy or high-power batteries. We plan to combine one high-energy battery with a high-capacity battery, and dynamically switch between the two to extend battery life.

We have found drone batteries to be the best market for us to launch our technology, as these users tend to have the biggest need for longer-lasting batteries and a markedly lower concern about cost. Drone batteries are limited to Lithium Iron Phosphate (LFP) batteries, as drones draw significant current during tasks like takeoff and acceleration, and these batteries excel in discharge rate. This significantly limits the battery life of drones, leaving most drones with a ~20-minute battery life, which only drops when a payload is added. In this project, we are combining these LFP batteries with lithium nickel cobalt aluminum oxide (NCA) batteries, which will be used for flight operations like hovering.

A major aspect of the battery is the ability to record and report data during flights. Ultimately, when this technology is applied to new, experimental chemistries, we want to be able to intelligently predict when the battery should switch between chemistries. In the long run, intelligently predicting when to switch will be able to prolong the cycle lives of the high-capacity batteries.

In our project, we worked to implement three main aspects of this battery: the switching/charging circuit, the data collection, and the algorithm.

1.2 Block Diagram

Our initial block diagrams are displayed below, in Figure 1 and Figure 2.

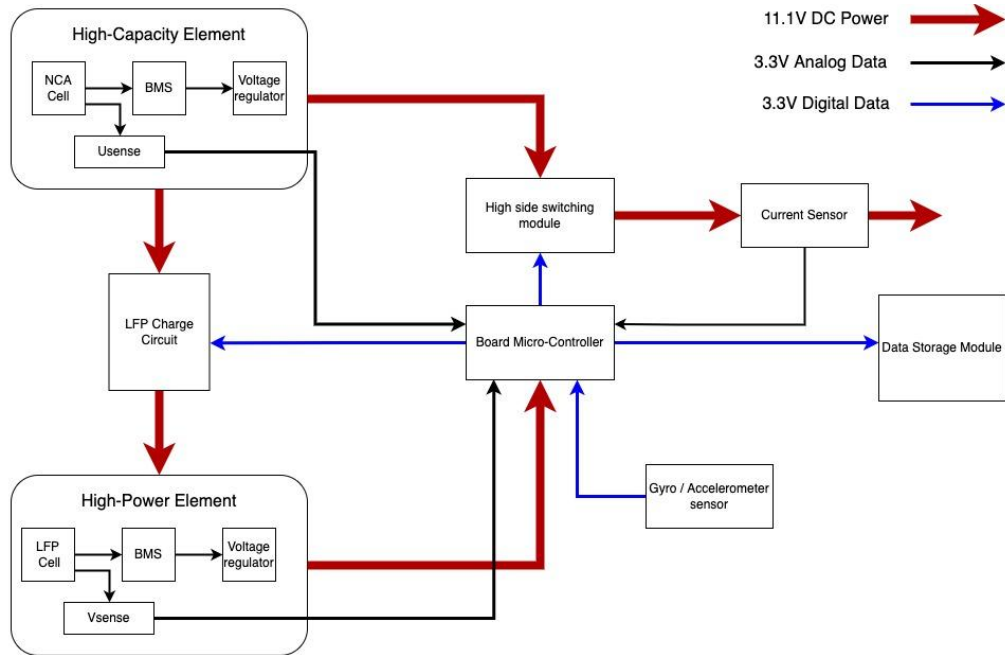


Figure 1: Block diagram of switching and charging circuit

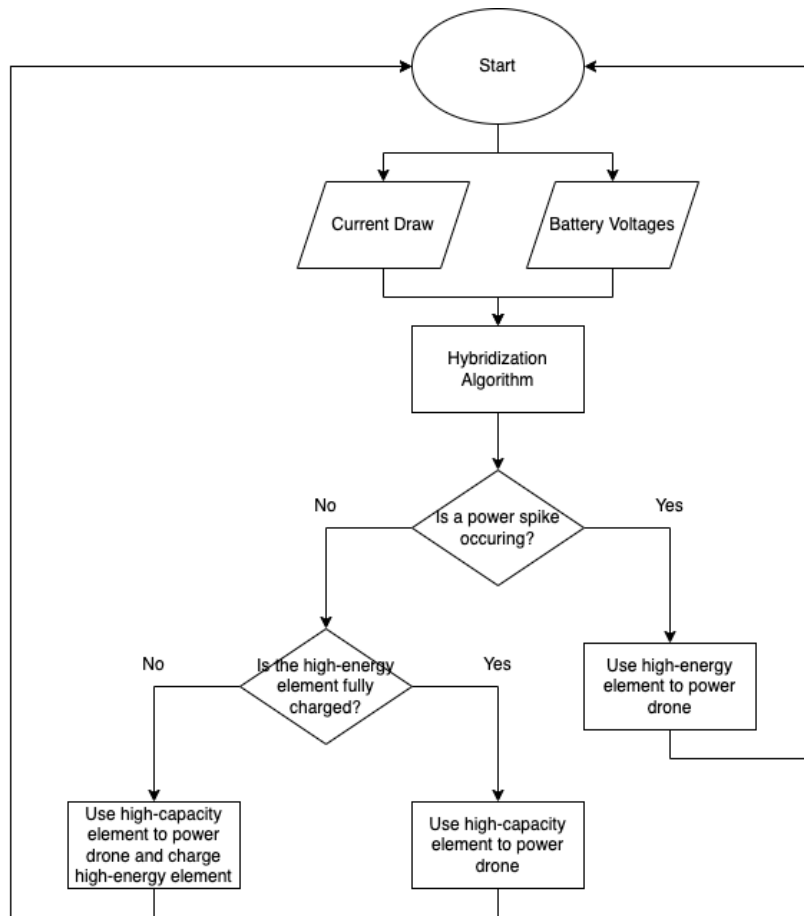


Figure 2: Block diagram of switching algorithm

Changes were made between our initial plan and final product. Most notably, the LFP charging circuit was too dangerous for us to continue to build given our time constraints and knowledge. In addition to removing that block from Figure 1, the charging flow from Figure 2 had to be removed.

1.3 High Level Requirements

Our high level requirements set from the beginning of the semester are as follows:

- Successful high side switching circuits that allow the microcontroller to alternate between energy buffers that supply to the load at will. This switching should occur seamlessly, within a few clock cycles.
- A successful version of the switching algorithm that visually improves the shape of the discharge curve of our Li-NCA cell, when compared to the discharge curve from typical use.
- Our battery provides 11.1 volts, maintains a 20A max output, similar to a standard drone battery, and holds 50% more energy than a standard drone battery at the same weight.

2. Design

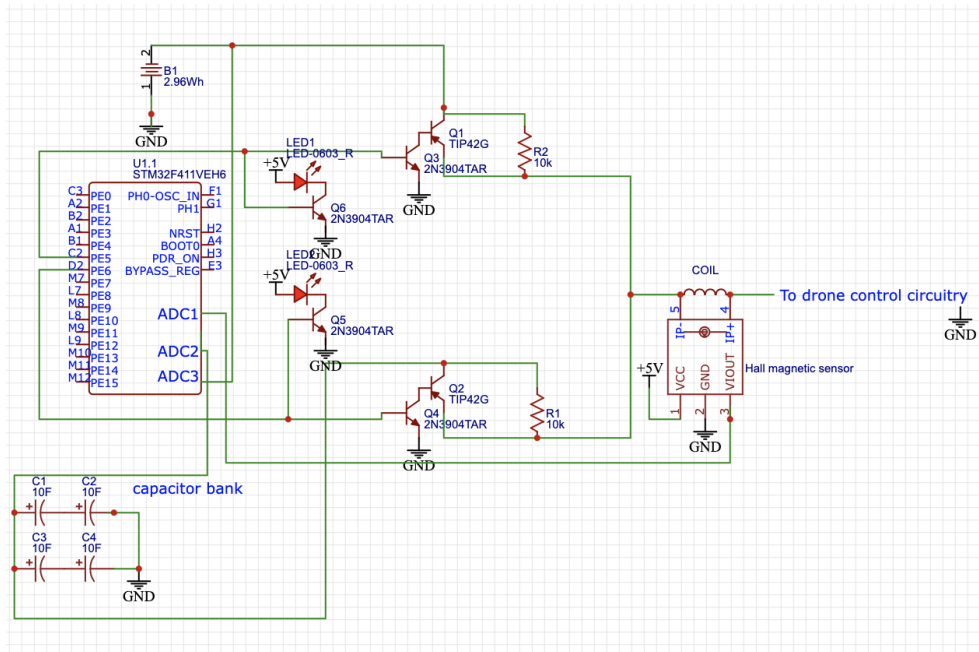
As mentioned prior, our design evolved to be split into three main components: the switching circuit, the data collection, and the algorithm.

2.1 Switching Circuit

The most important subsystem of the circuit is the switching circuit, which actually performs the switching between the high-energy and high-capacity energy sources. For this aspect we tried FETs laying around the lab initially however we finally chose the durable and robust BUK7E8R3 N-Channel MOSFET. The reason we chose this was due to its high max current and low on-state resistance [1].

2.1.1 Initial Plan and Circuit Design

Initially, the circuit was designed to use two separate high-side switches, specifically P-channel MOSFETs for an active low configuration on the MCU side. These switches however did not support higher currents and so would not suffice going forward. The circuit diagram of this initial circuit is shown below, in Figure 3:



1.

Figure 3: Initial Circuit Schematic of Switching Circuit

After testing this circuit, we found that the Arduino failed to get to the correct VGS voltage of 13-16V to switch the FET. With battery voltages of 10.8-12.6 volts and a turn on voltage of 3 volts, the Arduino or any microcontroller was going to struggle to drive this voltage quickly. Below we briefly explain why.

For minimum on state resistance and optimal performance, saturation is needed on each switch.

In order to do so we need: $V_{gs} > V_{th}$ and $V_{ds} < V_{gs} - V_{th}$

Adding our numbers in we get:

(1)

$$V_{th} = 3 V, V_{ds} = 10.8 V - 12.6 V (11.1 \text{ nominal})$$

$$11.1 < V_{gs} - 3 V \text{ therefore } V_{gs} > 15.1 V$$

Arduino max output voltage: 5 V

The speed of switching is a tight requirement of this project so we opted for another solution. The steps we took to alleviate this problem are detailed next.

2.1.2 Low Side Switching

In order to achieve switching powered by the Arduino, we considered a few possible solutions. We attempted to use the IRS2183 gate driver IC from the Senior Design lab, shown below in Figure 4.

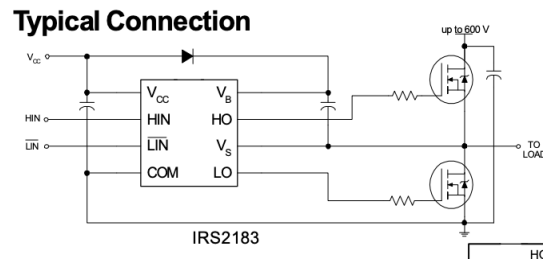


Figure 4: IRS2183 Gate Driver IC [2]

Similar problems arose, as the switches were not responding to the digital pin signals from the Arduino, and we were not able to fully debug why the driver setup did not work.

We then switched the MOSFETs from high-side switches to low-side switches. After testing, we found that the Arduino was able to drive these MOSFETs on their own at 5V. We decided to avoid the additional complexity and power consumption of a gate driver IC and opted to switch between each battery pack's ground and the ESC ground (low-side switching) instead.

2.1.3 Isolated Circuit

The second major change we made to the design was electrically isolating the switching circuit from the microcontroller. Our LFP battery is capable of sending more than 60A of current through the circuit, and sending this much current through our 3.3V microcontroller was not feasible. We learned this the hard way, as we fried two Arduino boards when the switching was connected and shared a common ground. Our best explanation for this was that there were high currents flowing through the inductive load that is our airplane propeller, and a voltage backspike fried our Arduinos internal regulator. Regardless, it became apparent that our MCU unit going forward would remain isolated and drive the MOSFET through an optocoupler. I chose to use the TCMT1100 optocoupler due to its compatibility with our MOSFET and a 5V MCU that we intend to use and also its availability and package size [3]. After testing in person the ideal resistance to pair with this device was 300 ohms. Further beyond that we added a 2.5

kOhm voltage divider on each side of the low side switching to create a more than sufficient voltage to turn on our MOSFET ($11.1\text{ V} \div 2 = 5.5\text{ V} > 3\text{ V}$). The final component was a simple diode in reverse bias across each battery terminal, to protect both the electronics and the batteries from that voltage back discharge. The diode provides a path for this energy to safely discharge.

2.1.4 Final Circuit Schematic

The final circuit schematic, incorporating the two changes detailed in sections 2.1.2 and 2.1.3, is shown below, in Figure 5:

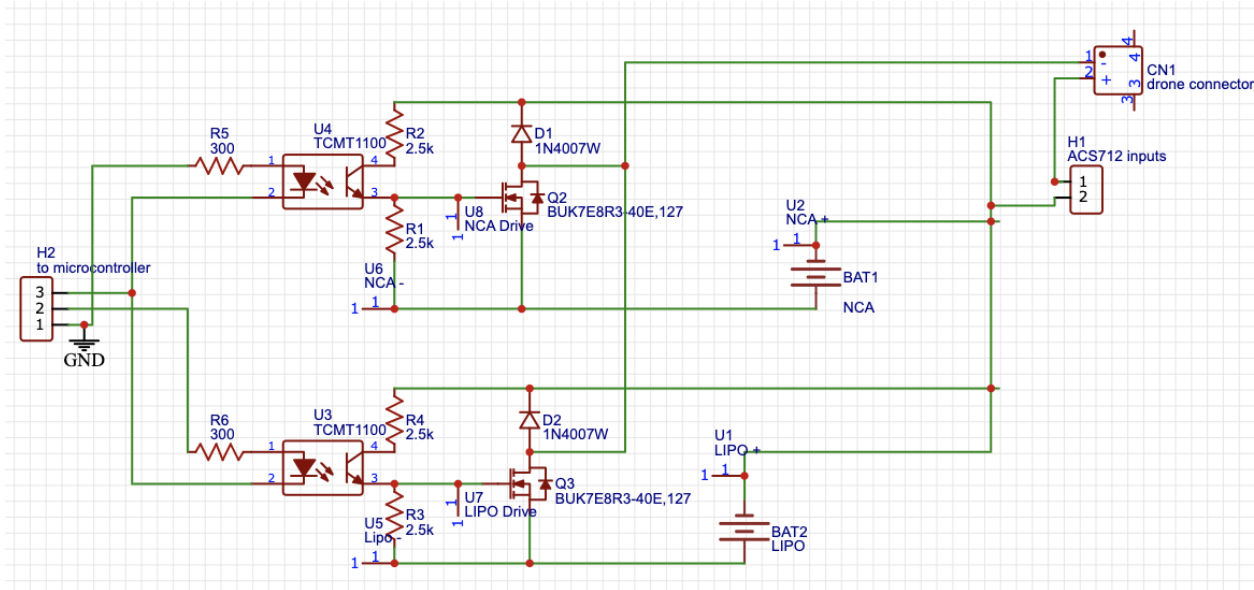


Figure 5: Final Switching Circuit Schematic

2.2 Data Collection

The data collection subsystem has the goal of capturing flight data for our switching algorithm. The end goal is to collect all data relevant to the flight and the batteries themselves in order to give the algorithm as much data as possible to predict current spikes.

2.2.1 STM32

The initial plan for this subsystem was to use an STM32 to collect data from the sensors and write the results to an SD Card or transmit them via Bluetooth. After testing the STM32 extensively, we struggled to make significant progress in writing the drivers to connect to the sensors that we were using to collect information. In order to prioritize finishing the project, we decided to switch to an Arduino for this section. In a production environment, we would use the STM32 for power efficiency.

2.2.2 Arduino & Sensors

For this version of our project, we decided to measure the current draw, X, Y, Z rotation and acceleration, and temperature. We used an ACS712 hall effect current sensor to measure current draw, and an MPU6050 3 Axis Accelerometer Gyroscope Module to measure all the positional and temperature data. All of this data is written to an SD card in the form of a CSV, for use in the switching algorithm.

2.2.3 Example Flight Data

A few rows of data obtained from a real flight is shown below in Table 1:

Table 1: Example Data Collected by Arduino

Curr	X Accel	Y Accel	Z Accel	X Rot	Y Rot	Z Rot	Temp
-0.22	0.3	0.9	8.76	-0.03	-0.03	-0.03	29.11
-0.15	0.33	0.9	8.76	-0.03	-0.04	-0.03	29.12
-0.15	0.31	0.92	8.73	-0.03	-0.04	-0.03	29.13

2.3 Switching Algorithm

The switching algorithm subsystem has the goal of predicting when a power spike is going to happen and dictating when to switch between the two energy elements. Continuous dramatic power spikes impact the long-term health of a battery, so the goal is to alleviate these stressors from the high-capacity element as much as possible. Removing these spikes will increase the cyclic stability of a battery, which is how we plan to make experimental battery chemistries with extremely high energy densities but low cycle lives, such as Li-S, commercially viable. The data used to formulate this algorithm is all sourced from the data collection subsystem detailed in 2.2.

2.3.1 Initial Plan & Issues

Entering the project, our team's goal for the switching algorithm was to employ some sort of machine learning to create an algorithm to predict these switches. Additionally, the algorithm would dictate when and how fast to recharge the high-power element from the high-capacity element. As we moved away from implementing the LFP charge circuit shown in the block diagram, in Figure 1, a major part of the algorithm was removed. We hoped to still collect data from flying the plane to optimize the ratio between the LFP and NCA batteries, but after we failed to fly the plane without crashing and experiencing the plane falling out of the sky after the PCB burnt while in use, we realized that we won't be able to obtain real flight data. Without this real data, we were unable to apply any legitimate machine learning to the data.

2.3.2 Final Frontend and Regression

As a true machine learning model was not feasible without real data, we decided to create a frontend to display flight data and perform basic regression analysis. We can take the data collected from a flight and save it to an SD card and upload it to the UI. From there, the website will display all the data collected and present the user with a linear regression summary which can be used to formulate an algorithm. A screenshot of the UI is shown below, in Figure 5:

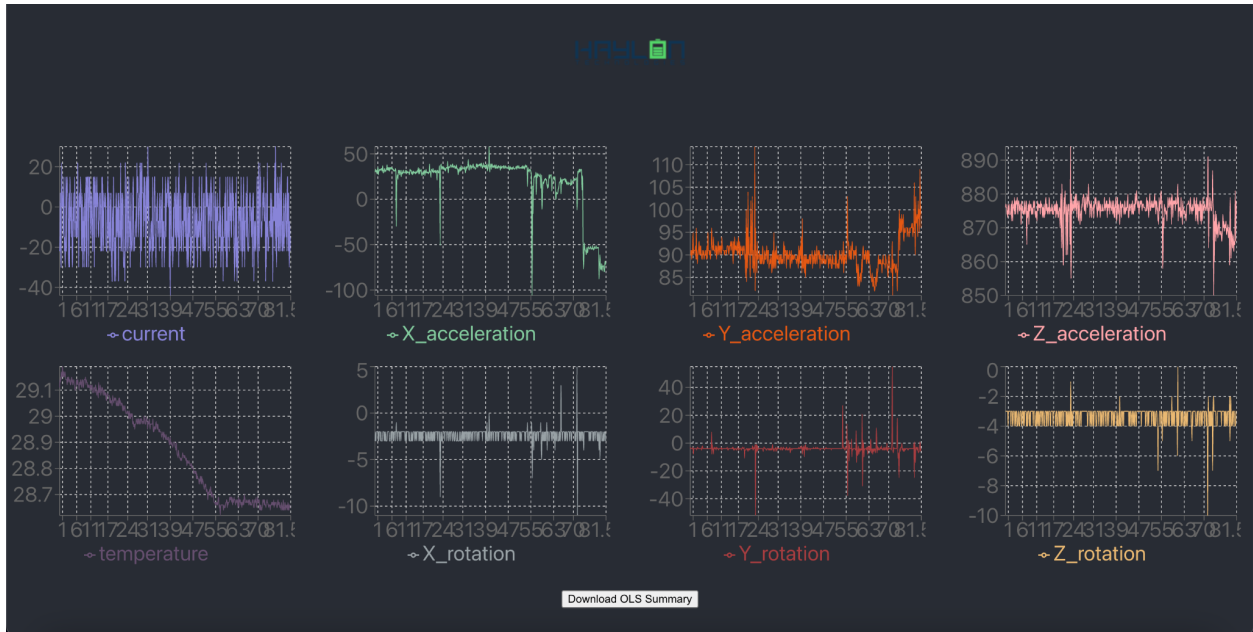


Figure 5: Screenshot of Analysis Frontend

The frontend is a React application hosted locally, and the backend is a Python script hosted on Google Cloud, utilizing Numpy and statsmodels linear regression. In the long run, the goal would be to leverage the wider range of Google Cloud machine learning services to apply true machine learning to the uploaded data. In a final project, this data would be uploaded every time the battery is connected to a charger, allowing for us to continually tweak and improve the algorithm to further improve battery life and cyclic stability.

3. Design Verification

The Switching Circuit subsystem detailed in 2.1 had the following requirements and verifications:

3.1 Requirement #1

Requirement: The switching module should be able to deliver up to $15 \pm 1A$ through the high power cell.

Verification Method: A multimeter will be placed between the battery output and the drone's ESC input. The drone will then be throttled till the meter reads 15A and the indication LED for the high power cell illuminates. The measured current draw from high power should be at least $15A \pm 1A$.

Tested results: Throttle was moved until current on multimeter exceeded 15 Amps:

Table 2: Requirement #1 Verification

Battery Voltage	Output Current
12.2V	16.68A

3.2 Requirement #2

Requirement: The switching module should be able to deliver up to 6A through the high energy cell.

Verification Method: A multimeter will be placed between the battery output and the drone's ESC input. The drone will then be throttled till the meter reads 6A and the indication LED for the high-energy cell illuminates. The measured current draw from high energy should be at least $6A \pm 2A$.

Tested results: Throttle was moved until current on multimeter exceeded 6 Amps:

Table 3: Requirement #2 Verification

Battery Voltage	Output Current
10.8V	6.03A

3.3 Requirement #3

Requirement: The on-state resistance should be less than 20 mOhms for both switches.

Verification Method: The switching module will be powered by a lab bench power supply. A multimeter will be used to measure the output voltage and current at the output of the system. In a steady on-state, the power at the output will be compared to the power output of the power supply. The difference should be less than 5mW.

Tested results: The following results were obtained using a power supply and multimeter:

Table 4: Requirement #3 Verification

Power Supply Output	Multimeter Readings (10Ω)
11V Output 1.1001 Amps P = 12.1011W	V = 10.998V I = 1.10 Amps P = 12.0978W
$12.1011W - 12.0978W = \mathbf{3.3mW < 5 mW}$	

4. Costs

4.1 Parts

Table 5: Cost of Goods

Part	Manufacturer	Cost (\$)	Quantity	Total Cost (\$)
TCMT1100CT-ND	Vishay Semiconductor Opto Division	0.43700	16	6.99
541-CRCW0603300RJ NEBCT-ND	Vishay Dale	0.03300	20	0.66
13-RT0603FRE135K6 2LCT-ND	YAGEO	0.02390	100	2.39
1528-3886-ND	Adafruit Industries LLC	6.95000	2	13.90
SFH618A-4-ND	Vishay Semiconductor Opto Division	0.97000	6	5.82
3647-26430-ND	UNIVERSAL-SOLDER Electronics Ltd	16.90000	1	16.90
GNB3803S90AHV	Gaoneng	25.25000	1	25.25
ACS712	WayinTop	11.99000	1	11.99
3-01-0038	HiLetgo	6.99000	1	6.99
B01G9KSAF6	DSD TECH	9.99000	1	9.99
60F5W-YT-6SE-6SE	Chanzon	0.11650	60	6.99
LTO-14500-500	AA Portable Power	9.95000	5	49.75
LTO-1020-20	AA Portable Power	7.50000	5	37.50
3145-LIFE04-18650- ND	Dantona Industries	8.99000	10	89.90
NCR18650GA	Panasonic	7.08000	25	177.00
1727-7248-ND	Nexperia USA Inc.	0.90000	100	90.00
Total				552.02

4.2 Labor

Over the course of the semester, the amount of work we put in per week varied depending on pitches, other classwork, and part orders. We estimate that as a group, each teammate averaged 15 hours per week on the project. Starting the week of February 28th, following our design being reviewed, and removing the week of spring break, we worked on the project for 8 weeks. At a labor cost of \$50 per hour, we estimate the total labor cost to be $\$50 \times 15 \text{ hr/week} \times 8 \text{ weeks} = \6000 .

5. Conclusion

5.1 Project Accomplishments

Considering the issues and setbacks we faced through the course of this project, we are proud of what we have accomplished and are excited to continue development of our work. Our final product demonstrates the ability to switch between two different energy sources depending on the load required of the battery at a given time. The results of our project compared to the high level requirements we laid out at the beginning of the semester are shown below, in Table 6:

Table 6: High Level Requirements Stats

High Level Requirement	Fulfilled Status
Successful high side switching circuits that allow the microcontroller to alternate between energy buffers that supply to the load at will. This switching should occur seamlessly, within a few clock cycles.	Upon a current spike, the Arduino is able to successfully drive the MOSFET to switch from the high-capacity element to the high-power element in roughly 40 clock cycles. Given that 16 MHz on board clock has 16 million cycles a second this is definitely acceptable as a few, therefore, this requirement is fulfilled .
A successful version of the switching algorithm that visually improves the shape of the discharge curve of our Li-NCA cell, when compared to the discharge curve from typical use.	Naturally, by successfully alleviating the stress of high current spikes from the Li-NCA cell, the discharge curve of that cell is improved. This was verified by viewing a 1 minute discharge curve on an oscilloscope with and without our system. Our system removed spikes successfully therefore, this requirement is fulfilled .
Our battery provides 11.1 volts, maintains a 20A max output, similar to a standard drone battery, and holds 50% more energy than a standard drone battery at the same weight.	Our battery provides 11.1 Volts and can maintain a 20A output through the high-power element. The 3 Li-NCA batteries weigh 48 grams each and hold 3450 mAh. The LFP battery weighs 32 grams and holds 380 mAh. When hybridized, these batteries hold 3830 mAh total and weigh 176 grams. A standard drone battery holds 2200 mAh and weighs 175 grams. Therefore, this requirement is fulfilled .

Obviously, the combined weight of the perfboard and other materials required for our battery significantly increased the weight, and therefore energy density, of our battery, we are confident that with proper manufacturing, the weight of all these additional components can be brought down to less than 5 grams. With that, we would have a battery that is significantly more energy dense than any drone battery on the market, without sacrificing discharge rate or cyclic stability.

5.2 Uncertainties

Our biggest uncertainty going forward is the ability to safely and effectively build the LFP charging circuit. Once this aspect is built, we can truly experiment with different sizes of the LFP battery and find the ratio of LFP-NCA that maximizes the capacity without sacrificing performance. Additionally, this circuit will allow the algorithm to start truly taking shape and allow us to apply true machine learning principles to the analysis.

5.3 Ethical considerations

We faced a slightly dangerous situation when an early version of our charge circuit was being tested. As a simple boost circuit we hoped that simply increasing its output voltage would correspond to an increase in charging speed. Our thinking erred in that the high power cell quickly imbalanced its charge and overcharge a cell. This resulted in the battery expanding and causing a short circuit discharge which actually started a fire melting both our breadboard circuit as well as the battery pack. This event caused us to re-evaluate the safety of including this charge circuit, so we instead opted to size our high power cell accordingly so that it lasts an entire flight. This placed a greater emphasis on the data collection and analysis aspect of our project.

As we were working with batteries the whole semester, in order to uphold IEEE standards of safety [4] when building and testing our project, we followed all OSHA guidelines related to handling and use of lithium-ion batteries [5].

5.4 Business Accomplishments

During the span of this semester, we had the opportunity to participate in two startup competitions, one being the College New Venture Challenge (CNVC), a joint competition between the University of Chicago Booth School of Business and Grainger Engineering, and the other being the COZAD New Venture Challenge, run by the University of Illinois. We presented the same technology we worked on during this project in those competitions, as part of the Haylon team. We ended up finishing 2nd place in CNVC, accompanied by a \$30,000 SAFE note to continue building our business. We finished 1st place in COZAD, a \$40,000 SAFE note and an additional \$25,000 of in-kind services. We have also worked to apply to multiple different accelerator programs, already being accepted into the NewChip, mHub, and Polsky BUILD accelerators as well as being on the final round for several others.

5.5 Future work

We plan to continue working on Haylon after graduation, and work on taking this project to a real, purchasable product. Our next step is to raise a true pre-seed round, which we are aiming for \$600,000, and use this funding to take the circuit we have now and shrink it down to an ASIC. We have connected with multiple contract manufacturers, and estimate that we will be able to produce between 100-200 pilot batteries, which we will use to run paid pilots with companies. If these batteries do what we say they do, these pilots will translate into purchase orders. Once we validate our technology in the drone market, we hope to enter the scooter and power tool markets. Then, we will be able to leverage advances in battery chemistry technology and low power computing to take on the global 100 billion dollar rechargeable battery market.

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