Design Document

Smart Scooter Battery

ECE 445

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Team 15

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1. Introduction

1.1 Problem

Rechargeable batteries are inherently limited due to properties specific to their chemistry and production methods. The most common are traditional lithium-ion batteries. Battery chemistries such as lithium-titanate can charge and discharge much quicker than the dominant lithium-ion batteries but have lower energy densities, whereas battery chemistries such as lithium-sulfur exhibit much better energy density than standard lithium-ion batteries yet struggle with the problem of cyclic stability. Existing solutions fail to bridge the gap between high-energy cells and high-power cells. The reason lies in the fact that high-energy cells traditionally struggle with cyclic stability, meaning that they do not retain their capacity after many charge/discharge cycles. This happens for a multitude of reasons. While some of those reasons are inherent to the battery, others such as the discharge curve that the battery experiences during each cycle and the depth of discharge are controllable, and even optimized by a smart battery management system that can selectively shift power draw to another cell.

Simply stacking a high energy cell and a high power cell in parallel (assuming ORing diodes are used and cell voltages are the same), would not ensure that the high energy cell follows any particular discharge curve. The first reason is that the high energy and high power cells do not have internal resistances that are at all proportional to their relative cyclic stability, and their maximum discharge rate. Put simply all of these batteries have similar internal resistances, unlike capacitors which have minimal internal resistance relative to batteries. This is why output capacitors are effective in such a simple arrangement, as buffers to deal with large current spikes. The problem with capacitors in general, as energy storage elements, is their incredibly poor energy density which makes them impractical for usage in consumer electronics as a significant energy storage system. Rechargeable batteries, which universally contain energy densities several orders of magnitude above most capacitors, are really the only viable options in practice. These current spikes are what cause a battery's discharge curve to have a chaotic shape.

Say in an electric scooter, during a period of acceleration where the cell current draws spikes, although the high power cell would absorb part of the spikes, the high energy cell would still experience a larger current draw during this period. Although the impact that this has is minimal in the scope of one cycle, the constant fluctuation in the current draw would tremendously impact the total lifespan of the batteries. So in order for two rechargeable batteries with different chemistries to work in conjunction a more sophisticated solution is needed. A solution where the high power cell (which can survive for several times as many charge cycles) can be intelligently used as a power buffer to control the discharge curve of the high energy cell.

1.2 Solution

The solution is a “smart” battery management system. Our goal is to construct a battery that consists of two separate energy buffers: one which consists of a high energy battery chemistry and the other which consists of a high power battery chemistry. A low-power microcontroller will manage the high side switching circuits which connect each buffer to the load and also control the duty cycle of a specially designed power converter that brings charge from the high energy buffer to the high power buffer. The microcontroller should be able to precisely control the timing and more importantly the speed at which the high energy cell charges the high power cell. This is important because we intend to develop a fairly sophisticated control algorithm to manage the discharge curve of the high-energy cell during a real-life use case in an actual electronic device. In order to do so, our smart BMS (Battery Management System) system will measure current draw, and the state of charge of each buffer at all times and evaluate the exact timings for each buffer to supply power to the load whilst simultaneously determining how quickly the high power buffer recharges. To develop this algorithm we intend to build the management system and report these three pieces of data constantly via Bluetooth serial or Wifi.

On the backend with the data recorded above, we will create the "true" discharge curve of each cell during each cycle. With that knowledge, we will train an algorithm to best emulate an ideal discharge curve. The ultimate goal is to get the high-energy cell to very closely follow a constant discharge over time as opposed to a constantly changing curve that normally exists. To demonstrate this we intend to build a smart battery pack for an RC plane. We chose this use case as the battery size is big enough for the power usage of our digital and analog electronics to not significantly matter, yet not too big as to exceed what would be practical for a senior design project. Also, an rc plane requires large current spikes quite often, and, during regular use, is not pushed to its capacity limit with each and every cycle. This creates the perfect system to demonstrate how our smart BMS would in practice extend the usable lifespan of high-energy rechargeable batteries, as it would detect these conditions and adjust the power buffers to best ensure long-term battery health. As such, the smart BMS would also contain a gyroscope and accelerometer to help create the switching algorithm.

The long-term goal is using high-energy battery chemistry such as lithium-sulfur, which currently struggles with cyclic stability. However, for this project, we simply want to demonstrate that a hybrid battery system that could solve this problem, is possible. So for our particular plane battery pack, we intend to use readily available Lithium Nickel Cobalt Aluminum Oxide cells (Li-NCA) as our high energy buffer and Lithium Iron Phosphate (LFP) cells for our high power buffer. Both are commercially available on Digikey and other common electronic vendors and exhibit complementary strengths and weaknesses. Even though we are utilizing off-the-shelf batteries to simply demonstrate this idea, we still intend to create a plane battery pack that matches the maximum discharge rate of any regular LFP battery system, while having a higher total energy density by virtue of the high energy Li-NCA battery.

1.3 Visual Aid

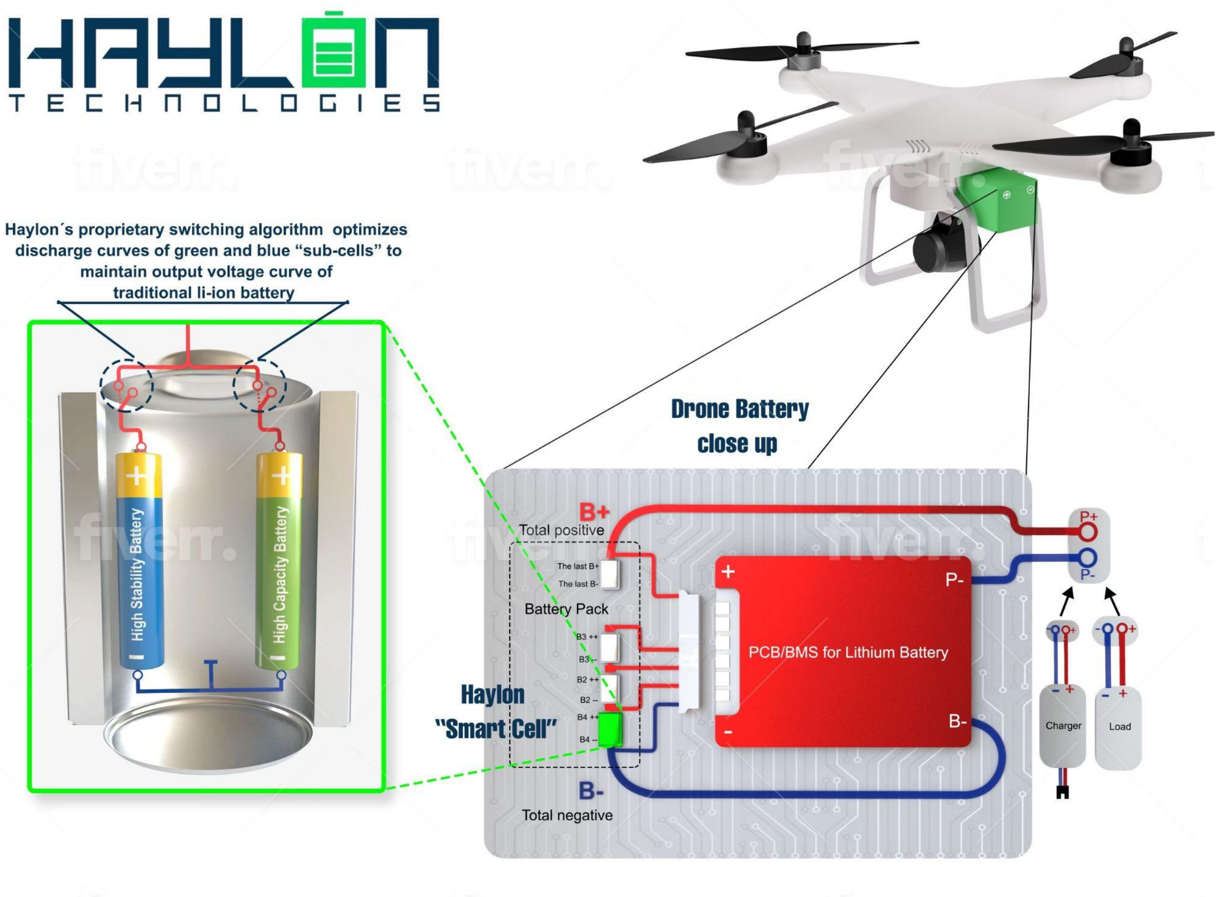

Figure 1: Device Visualization

1.4 High-level requirements

We realize that improving the usable lifespan of high-energy batteries is somewhat arbitrary and difficult to quantify at the end of the semester, so below are some measurable criteria of success that we will aim for.

- 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

2.1 Block Diagram

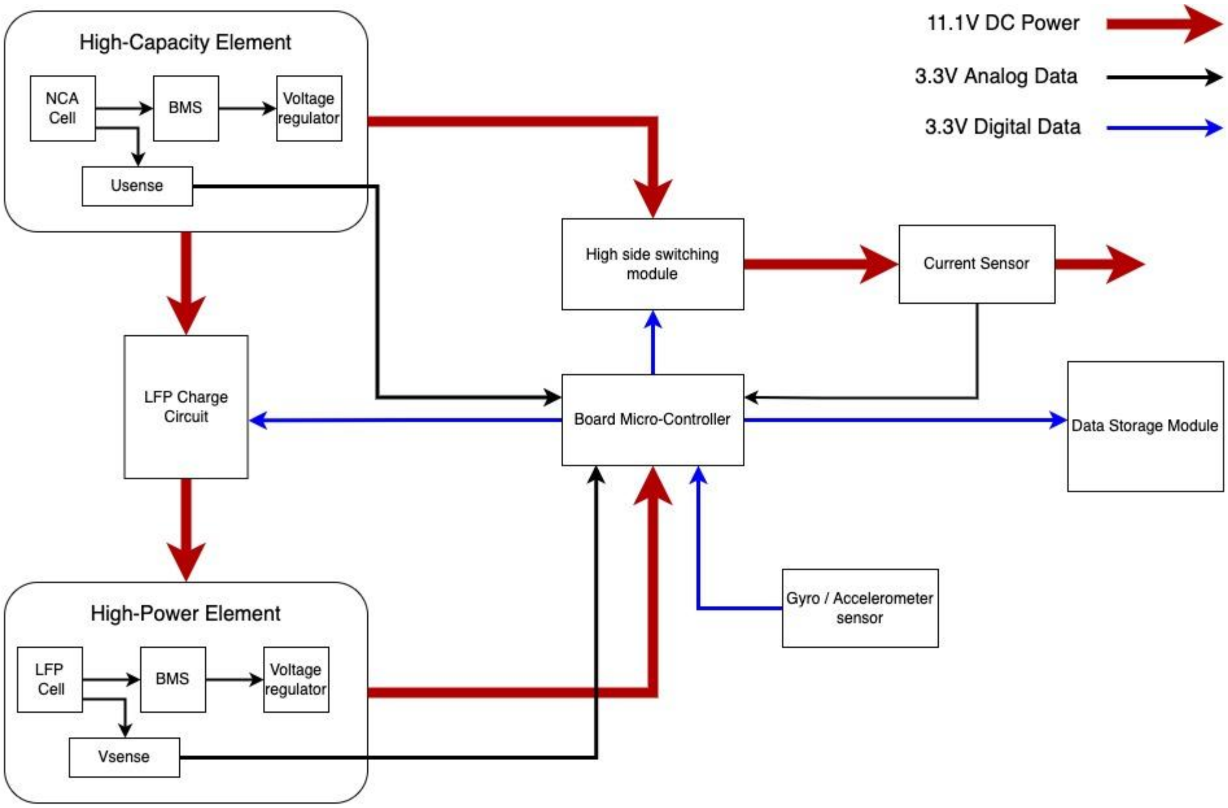

Figure 2: Block diagram of the entire system

2.2 Switching And Inter-Battery Charging Circuit Subsystem

2.2.1 Subsystem Requirements

1. The microcontroller should be able to precisely control the timing and more importantly the speed at which the high energy cell charges the high power cell. This should be a feature of the aforementioned charge controller.
2. The charge controller should be able to charge the high-power cell at rates between 0.1c and 2c depending on a signal from the microcontroller. We will test this at 0.1c, 0.2c, 0.5c, 1c and 2c.

2.2.2 Circuit Schematic

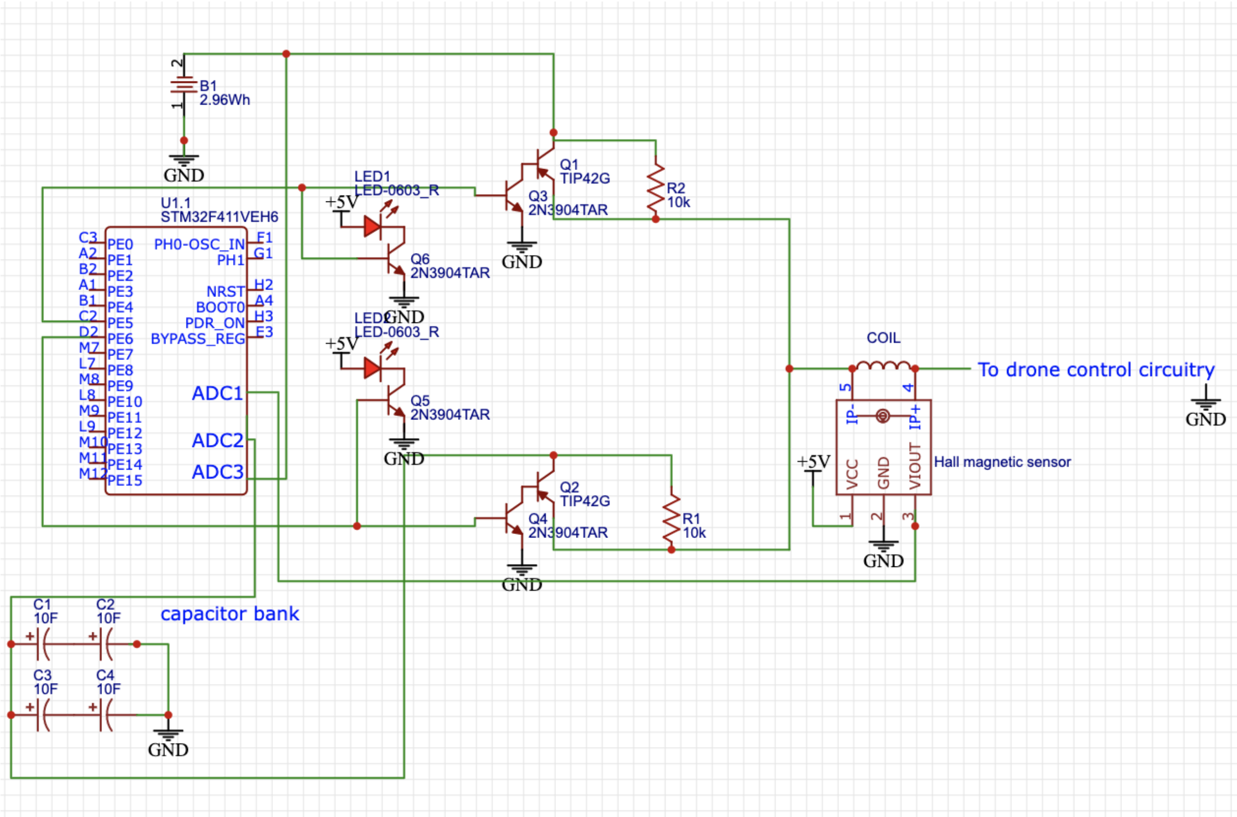

Figure 3: Circuit Schematic

2.2.3 Requirements & Verification Tables

Table 1: Requirements and Verification Table

Requirement	Verification
The switching module should be able to deliver up to 15 +- A through the high power cell.	A multimeter will be placed between the battery output and the drones 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 atleast 15A +- 1A.
The switching module should be able to deliver up to 6A through the high energy cell	A multimeter will be placed between the battery output and the drones 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 atleast 6A + -2A
The on state resistance should be less than 20 mOhms for both switches	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.

2.3 Hybridization Algorithm Subsystem

This consists of:

1. Data Collection: we need to collect as much data as possible on battery usage in our use case, in this case, an RC.
2. Data analysis: we need to analyze the patterns in this data to collect information such as how often power spikes occur, how long power spikes last, how long constant power draw lasts for and charging tendencies.
3. Algorithm: using the analyzed data, we need to develop the algorithm that controls our hybrid battery. We need the algorithm to intelligently manage the charge between the two batteries so it is prepared for a power surge whenever one occurs while maintaining optimal charging and discharging curves for the high energy element.

2.4 Tolerance Analysis

Due to the importance of capacity, our smart battery has to limit its power losses to an absolute minimum. As a result the on-state resistance of our switches in our switching module is critically important as high currents will be flowing through them. Each side of the switching module will consist of the same switch so the resistive loss will be constant throughout a charge cycle. A reasonable limit for total power loss can be set at 1 mWh. Given the data sheet of our switch we can calculate what the power loss would be for the typical on-state resistance of 5.8 mOhms. Given that the intended capacity of our system is 3.800 mAh, we can calculate the total power loss through the one single charge cycle, by assuming the system is simply outputting 3.8 amps for 1 hour. $P = IR^2$, so for our system the typical power loss through one cycle is $3.8A * (0.0058Ohm)^2 = 0.000127Wh$ or $0.127mWh$. To perform the tolerance analysis, we can assume that the on-state resistance is in its worst case scenario and the temperature is at 175 degrees Celsius. In this case on-state resistance is 14.1 mOhms, as given by the data sheet. Power loss would then be $3.8A * (0.0141Ohm)^2 = 0.000755Wh$ or $0.755mWh$. This is still less than 1 mWh, so the tolerance analysis passes.

Table 2: Data Sheet of Switch

R_{DSon}	drain-source on-state resistance	V_{GS} = 10 V; I_D = 20 A; T_j = 25 °C; Fig. 11		-	5.8	7.4	mΩ
		V_{GS} = 10 V; I_D = 20 A; T_j = 175 °C; Fig. 12; Fig. 11		-	-	14.1	mΩ

3. Cost and Schedule

3.1 Cost estimate

3.1.1 Labor estimate

50 $/hr ✕ 15 hr/wk ✕ 3 teammates ✕ 10 weeks = $22,500

3.1.2 Parts estimate

Table 3: Parts Cost Estimate

Name	Description	Part Number	Quantity	Cost
RC Plane	RC Plane to be used for demonstration	N/A	1	$100
LFP Battery	Standard drone battery as a baseline for our product	N/A	1	$35
Small LFP Battery	Small drone battery to be used as high-energy element in our final product	2971	1	$14
Power Mosfets	N-Channel 40 V 75A (Tc) 96W (Tc) Through Hole I2PAK	BUK7E8R3-40E,127	2	$2.50
Microcontroller	ARM® Cortex®-M4 series Microcontroller IC 32-Bit 100MHz 512KB (512K x 8) FLASH 100-UFBGA (7x7)	STM32F411VEH6	1	$12
Semiconductor	Bipolar (BJT) Transistor NPN 40 V 200 mA 300MHz 625 mW Through Hole TO-92-3	2N3904TAR	2	$1

3.2 Schedule

- Week 1
    - Finalized schematic
    - Simulations to confirm the ability to handle extreme cases
    - Tolerance analysis
- Week 2
    - Assembly of circuit
    - Testing at limited power with stationary rotor
- Week 3
    - Build first version of charging circuit
- Week 4
    - Test charging circuit using power supply
    - Failure and extreme tolerance analysis of charging circuit
- Week 5

- Test charging circuit with LFP and Li-NCA batteries
- Integrate charging circuit with microcontroller

- Week 6
    - Begin collecting data by performing regular flights
    - Start basic analysis of flight data
- Week 7
    - Begin training process of machine learning switching algorithm
    - Install switching algorithm onto microcontroller
- Week 8
    - Collect data comparing hybridized battery vs standard drone battery
    - Finalize algorithm

4. Ethics and Safety

Because we are dealing with batteries, we have to make sure that our system is not endangering the user. One of the risks of danger faced with this project is dealing with lithium-ion batteries. Lithium-ion batteries are dangerous due to their high energy density and their instability. However, this danger is annihilated as long as the battery is not damaged in some ways or the battery is not used outside its capacity [1]. We will ensure safe battery operation (protection against overvoltage, undervoltage, overly high temperature); The system will shut off when any of the safe conditions are not respected.

Moreover, we will use a plane battery for our tests, we need to make sure that the plane will not suddenly fall down during a flight. This could result in anything from property damage to injuring someone so we intend on failure testing the flight reliability of our battery extensively. The team will also abide by the Lab safety guidelines while working on the project in the lab.

5. Citations

1. Safety and Health Information Bulletin
   https://www.osha.gov/sites/default/files/publications/shib011819.pdf