

ECE 445: Senior Design Laboratory Spring 2026

**Project:**

**Electric Scooter Battery Management System with  
Integrated SOC Estimation**

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**Project No. 35**

## **1. Introduction:**

### **1.1 Problem:**

Electric scooter (E-scooters) batteries are a safety and lifecycle critical component that can directly affect the safety of the rider, the range, and long-term cost of ownership for electric scooters. E-scooters often experience frequent full and partial charge as well discharge cycles along with extended storage periods. E-scooters also feature regenerative braking, which is a high stress factor impacting the battery. Such harsh conditions accelerate battery degradation and increase the risk of over-discharge, overcharge, cell imbalance, or thermal runaway of the battery if not managed properly. This thus necessitates the need for having batteries to be well managed via some kind of advanced battery management system (BMS).

### **1.2 Solution:**

To address the aforementioned problems with E-scooter batteries and BMS's, we decided to work on a project focused on designing and constructing a compact and efficient BMS that seamlessly integrates reliable real-time protection. Our primary algorithm for estimating the battery's State of Charge (SOC) will be coulomb counting, which relies on continuous current measurement. We might also try to implement an Extended Kalman Filter for more accurate calculation, particularly under dynamic load conditions, if time permits.

Our BMS will continuously monitor individual cell voltages, pack current, and temperature to ensure safe operation and to detect abnormal conditions such as over-voltage, under-voltage, over-current, and thermal stress. In case of an abnormal event or a fault, the BMS will isolate the battery pack and the main current path. To support long-term reliability, the BMS will implement passive cell balancing to reduce voltage mismatch between series-connected cells during charging to maintain performance and extend pack range.

All measurements, including fault and operational diagnostics, will also be streamed to an external dashboard for real-time visualization, diagnostics, and performance analysis when the scooter is connected to the BMS Viewer, such as during charging or maintenance periods. If time permits, we may integrate onboard flash memory or a microSD card to support continuous data logging during in-field operation as well. Additionally, by analyzing SOC history, voltage behavior under load, current profiles, and temperature data, we will also optionally attempt to estimate the State of Health of the battery (if we implement onboard flash memory or a microSD card). Tracking SOH over time will allow us to accurately predict SOC over multiple discharge cycles, i.e., observe capacity fade, internal resistance growth, and overall degradation trends across repeated charge–discharge cycles.

### 1.3 Visual Aid:

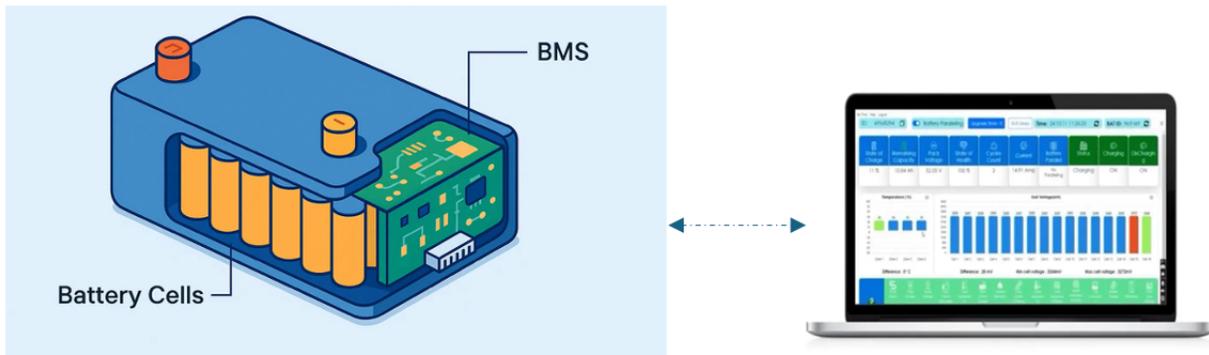


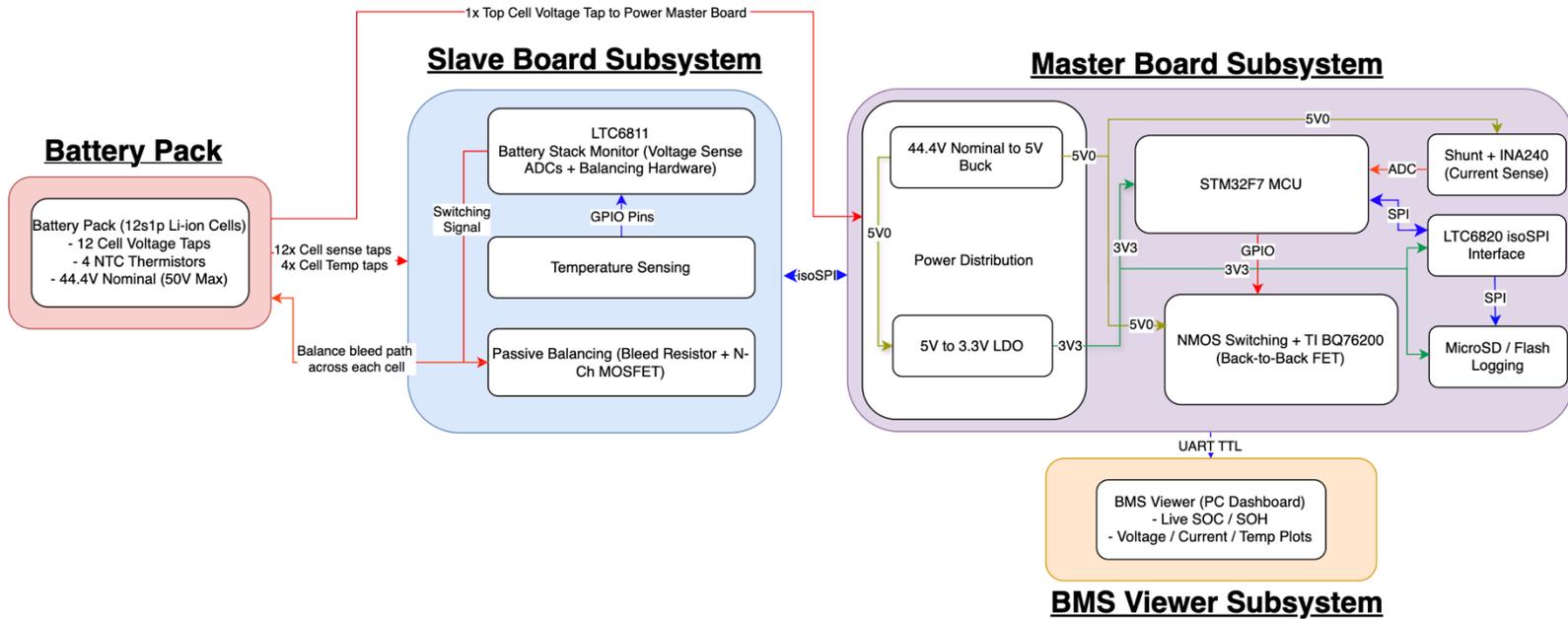
Figure 1: BMS to battery. Source [1] Figure 2: BMS Viewer. Source [2]

### 1.4 High Level Requirements:

- The BMS should be able to detect and respond to critical fault conditions within 300ms.
- The BMS should be able to estimate the battery SOC with an accuracy within  $\pm 6\%$  of its true SOC.
- The BMS viewer should be able to update as well display the battery pack voltage, pack current, temperature, SOC at a refresh rate of around 1 Hz.

## 2. Design:

### 2.1 Block Diagram



### 2.2 Subsystem Overview:

#### 2.2.1 Master Board System

The Master Board is the central controller of the BMS. It will be responsible for pack-level decision making including fault detection, battery pack isolation, SOC/SOH estimation, and external communications. It will consist of a STM32F7 MCU to perform all the functions and to run the cell balancing algorithm. The board will be powered using the pack voltage wherein a buck converter will convert the pack voltage to 5V. The 5V will be further converted to a 3.3V rail using an LDO [3].

To monitor current and calculate SOC of the pack, a shunt resistor with a TI INA240 current-sense amplifier for precise power tracking will be present. A back-to-back N-channel MOSFETs configuration will be implemented to electrically isolate the battery and the main current path in case of a safety fault.

Downstream, the master board will communicate with the slave board using isoSPI communication and the LTC6820 IC, aggregating cell temperature and voltage data. Upstream, to visualize live cell temperature and voltage data when E-scooter is at rest to protect from undervoltage and overtemperature, the master board will stream live telemetry data to the BMS Viewer via UART communication.

*Note:* Additionally, storing in-flight SOC and cell data via a microSD or onboard flash might be a good optional functionality, in case it is required for later off-field e-scooter battery analysis. The microSD or onboard flash will communicate via SPI with the MCU.

### **Requirements:**

- The master board should be able to measure pack current within  $\pm 10\%$  accuracy.
- The master board should be able to command the back-to-back MOSFET switching stage to disconnect the battery within 200ms.
- The master board should be able to communicate via isoSPI to the LTC6811 IC to start balancing by commanding the discharge FETs on.

### **2.2.2 Slave Board System**

The slave board PCB is responsible for monitoring cell voltages, cell temperatures using thermistors, and conducting passive balancing of the E-scooter battery pack. The slave board is powered through the battery stack and interfaces with the master board via isoSPI communication link, reporting cell data for processing for SOC/SOH estimation.

The slave board will use the Analog Devices LTC6811 multi-cell battery pack monitor, which integrates 12 cell voltage ADC channels, passive balancing control hardware, and built-in diagnostics. Passive balancing will be implemented using bleed resistors and N-Channel Mosfets which will be driven by the battery pack monitor [4].

Temperature Sensing will be implemented via 10k $\Omega$  NTC thermistors placed physically near the cells (1 thermistor per 3 cells to mitigate cost and hardware complexity) as LTC6811 has only 5 GPIO pins [4].

### **Requirements:**

- The slave board should be able to conduct passive balancing with a minimum balancing current of 20mA.
- The slave board should be able to measure cell temperatures with an accuracy of  $\pm 4^\circ\text{C}$ .
- The slave board should be able to communicate to the master board subsystem over isoSPI to provide constant updates for pack monitoring.

### 2.2.3 BMS Viewer

The BMS Viewer Dashboard will act as the main real-time interface for monitoring the battery when the E-scooter is in maintenance. It will display individual cell voltages, total pack voltage, pack current, pack power, temperature readings, SOC, and the estimated SOH (if implemented). Cell voltages and temperatures will be shown using simple bar graphs with color-coded indicators so that normal, warning, and fault conditions can be easily identified. Fault conditions like over-voltage, under-voltage, over-current, and over-temperature will also be clearly highlighted to allow quick detection of abnormal behavior.

In addition to showing live data, the viewer will also be able to store time-stamped measurements and fault events so that performance can be reviewed later and SOC and SOH calculations can be evaluated. This feature is an addition add-on feature that will only be possible to implement on the BMS viewer if an onboard flash or microSD is added on the master board.

Overall, this subsystem serves as the connection between the BMS and the user, supporting both immediate monitoring and long-term battery analysis.

#### **Requirements:**

- The BMS viewer should be able to update as well display the battery pack voltage, pack current, temperature, SOC at a refresh rate of around 1 Hz.
- The BMS viewer should be able to indicate faults for over-voltage, under-voltage, over-current, and over-temperature conditions based on BMS thresholds.

### 2.2.4 Battery Pack Subsystem

We plan to use CosMX 95B0D0HD 13Ah cells for development, with an in-house-designed resistor ladder circuit as a backup cell simulator. The resistor ladder will include series resistors with parallel capacitors to emulate cell voltage behavior and the inrush transients seen when a battery pack is first connected to the BMS. The batteries are 12s1p lithium-ion batteries with nominal voltage of 3.7V per cell. The overall battery pack will thus be nominal 44.4V and 13 Ah. The battery will also be supplying the low voltage power to the voltage sensors, temperature sensors, and the master board using buck and LDO converters.

#### **Requirements:**

- The battery pack shall supply 44.4V nominal voltage to the system in absence of fault.
- The cells shall be rigidly connected to each other and mounted to the enclosure with protection against vibrations and requisite electrical isolation and safety.

### 2.3 Tolerance Analysis

One of the main risks in our design is the accuracy of the current sensing circuit, since our SOC estimation relies primarily on coulomb counting. Coulomb counting works by integrating the measured current over time, and thus small measurement errors can accumulate and cause lead to a drift. This means that tolerances in the shunt resistor, current sense amplifier, and ADC directly impact the overall SOC accuracy of the system.

In our design, current is measured using a low-value shunt resistor and the TI INA240 high-side current sense amplifier. The dominant sources of error include shunt resistor tolerance (around 1%), amplifier gain error (around 0.5%). There are also small, yet non-negligible input offset voltages in the amplifier and ADC that lead to inaccuracies in current measurement. When these errors are aggregated under typical operating currents, the total current measurement error is estimated to remain under approximately 2%.

As our battery pack is 13Ah, SOC error due to proportional current measurement error is governed by the following equations:

1) *Coulomb Counting based SOC Estimation:*

$$SOC(t) = SOC(t_0) - (1 / (3600 \cdot Q_{nom})) \int I(t) dt$$

**Where:**

SOC(t) = SOC at time t

SOC(t<sub>0</sub>) = Initial SOC at start time t<sub>0</sub>

Q<sub>nom</sub> = Nominal battery capacity (Ah), here 13 Ah

I(t) = Pack current as a function of time (A)

t = Time variable of integration (s)

2) *SOC error due to current measurement error:*

$$\Delta SOC(t) = - (1 / (3600 \cdot Q_{nom})) \int \Delta I(t) dt$$

**Where:**

ΔSOC(t) = Accumulated SOC error at time t

ΔI(t) = Current measurement error as a function of time (A)

3) For constant current error over time  $\Delta t$ :

$$|\Delta SOC| = (|\Delta I| \cdot \Delta t) / (3600 \cdot Q_{nom})$$

**Where:**

$|\Delta SOC|$  = Magnitude of SOC error

$|\Delta I|$  = Magnitude of constant current error (A)

$Q_{nom}$  = Nominal capacity (Ah)

4) Now if dominant error is proportional (gain error  $\epsilon_I$ ):

$$|\Delta SOC| = \epsilon_I \cdot (Q_{moved} / Q_{nom})$$
$$Q_{moved} = (1 / 3600) \int I(t) dt$$

**Where:**

$\epsilon_I$  = Fractional current gain error (e.g., 0.04 for 4%)

$Q_{moved}$  = Total charge transferred during operation (Ah)

$Q_{nom}$  = Nominal battery capacity (Ah)

5) For our 13 Ah battery pack:

$$|\Delta SOC| = \epsilon_I \cdot (Q_{moved} / 13)$$

Therefore, assuming a one-hour ride which transfers a 10 Ah and a 4% current gain error:

$$\Delta SOC \approx 0.04 \times (10 / 13) \approx 3.08\%$$

This means the expected SOC drift for the aforementioned very common drive profile is 3.08%. This is well within our  $\pm 6\%$  SOC accuracy requirement.

Furthermore, at very low currents, offset errors in the shunt resistor, amplifier, and ADC become more significant relative to the measured signal, which can increase current measurement error to roughly 4-5%. While this presents a potential risk, its overall impact on SOC estimation is limited because low-current periods contribute less total charge accumulation over time. Overall, although current sensing tolerances introduce accumulation error risk, our estimated worst-case SOC drift remains within acceptable limits, and with proper component selection and basic calibration, this subsystem is feasible for meeting our BMS accuracy requirements.

### 3. Ethics, safety and societal impact

Our E-Scooter Battery Management System utilizes lithium-ion batteries, which can discharge large amounts of amperes if shorted. We will be avoiding shorting the battery with the correct usage of insulating tapes, connectors, and plugs with the respective dielectric strength. The degradation of the lithium-ion batteries is also a safety concern within our project. We will mitigate this concern with storing the batteries in the correct temperature range and in a fire-retardant bag, when possible, while handling the batteries with prevention of any mechanical or electrical damages that may occur to the batteries [5]. The batteries will also only be changed and discharged in the presence of the ABC Dry Chemical or Carbon Dioxide fire extinguisher and within the assigned laboratory space.

The mismanagement or improper storage of battery cells can easily lead to thermal events, equipment damage, or safety incidents that may harm workers and the public. Therefore, the system is designed to uphold the responsibility to prioritize, “the safety, health, and welfare, while also adhering to ethical design and sustainable development practices” [6]. To reduce potential risks, access to sensitive system data and controls will remain private, and clear safety recommendations provided by battery manufacturers will be incorporated and communicated to users to help ensure proper handling, storage, and operation.

Our battery management system improves societal safety and reliability by extending scooter lifespan, and providing users with accurate information about battery condition, which can prevent accidents and unexpected shutdowns. Economically and environmentally, the design helps reduce long-term ownership costs and electronic waste by slowing battery degradation, while on a global scale it improves the feasibility of using E-scooter as a viable transportation method.

### References

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