Design Report of Low Voltage Battery Pack for Formula SAE electric

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***Figure 1.1**: UoP8e on 3D CAD*

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***Figure 1.2**: UoP8e on Formula ATA competition*

Overview

The Low Voltage (LV) System is responsible for designing, implementing, and managing all components of the vehicle that operate at 33.6V or less. It plays a critical role in the overall architecture of the car, especially in terms of safety and control. The LV system governs essential safety mechanisms such as the Shutdown System and interfaces with the High Voltage (HV) system through dedicated safety circuitry. Beyond safety, the LV subsystem manages the vehicle's sensor infrastructure, including various analog and digital sensors strategically placed throughout the car. The LV system is composed of multiple custom-designed printed circuit boards (PCBs), each fulfilling a specific role within the vehicle's electronic architecture. Communication between these boards is primarily achieved through a Controller Area Network (CAN), enabling real-time data exchange across the system. In addition to critical electronics, the system includes user interface components like LEDs and buttons in the cockpit, as well as actuators such as fans and pumps that support the car's cooling systems.

All design work is carried out in accordance with the rules and regulations defined by the FSAE competition. These regulations establish the necessary safety and performance requirements without restricting innovation or engineering creativity. They provide a structured framework that guides the development of the system while allowing for custom and optimized solutions tailored to the team's design goals. A general scheme of the LV architecture is explained in figure 1.2.

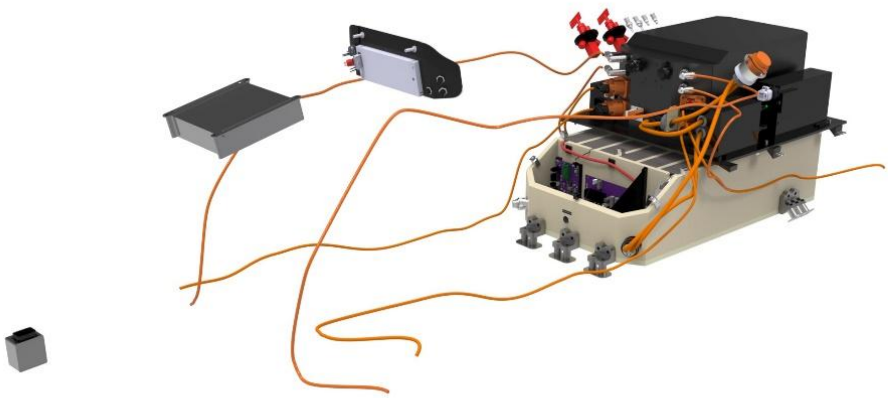

***Figure 1.3**: Global architecture on 3D CAD*

1. Low Voltage Battery Pack

1.1 Description

According to T 11.1, the Low Voltage System (LVS) is defined as every electrical part that is not a part of the TS system with a maximum permitted voltage that may occur between any two electrical connections in the LVS up to 60 VDC. That said, a dedicated battery pack had to be designed for the non-TS parts of the system.

***Figure 1.4**: Low Voltage Battery Pack*

1.2 Calculating the energy consumption on the car

To specify the energy needed for the vehicle's operational needs, the first step is to define the time that the vehicle is supposed to operate continuously. The easiest way for such a definition is to monitor endurance's longest dynamic event in an FSAE competition. The endurance has 22 kilometers and most often comprises 20 track laps, timed usually at 60 to 120 seconds, with an intermediate driver's change mid-event, which is up to 3 minutes—taking that into as a fact, we got 43 minutes as the worst case.

The second step is to calculate the wattage that the vehicle needs for its operation:

Part name	Power consumption (W)
AMK Inverter control unit	48
Bender Isometer IR155-3204	2
Cooling fans	134
Couling Pumps	180
Tractive system active light	2.5
IVT current sensor	1
Rest Printed Circuit Boards	20
Sensors	10
Total Consumption = 397.5 W.	

Table 1: Energy *consumptions of the vehicle*

1.3 Choosing the battery chemistry

As already pointed out, an FSAE competition is aiming at training the new engineers. Still, it simultaneously aims to make the team compete for the top place and, of course, design the best formula-type vehicle. Choosing the correct battery type balances minimizing the LV accumulator's weight due to the vehicle's weight target and making a quick-service fail-safe design. In Table 1.2, the reduction in weight and volume achieved by the team is presented, resulting from the transition from $LiCoO_2$ pouch cells used in the previous racing single-seater to cylindrical cells with Li-$NiMnCoO_2$ battery chemistry. Lithium-ion batteries have dominated the electric-automotive industry due to their high energy-to-weight ratio. Getting this as a fact, the most notable lithium-ion cells will be analyzed and compared before selecting the cell for our application.

	UoP 7e	UoP8e	
Volume	3,063 cm3	1.974 cm3	35.55 %
Weight	3.148 kg	1.802 kg	42.75 %

Table 2: *Energy consumptions of the vehicle*

1.4 Lithium-ion cells comparison

Chemistry	Lithium Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Manganese Oxide	Lithium Iron Phosphate	Lithium Nickel Cobalt Aluminum Oxide	Lithium Titanate Oxide
Short-form	Li-cobalt	Li-manganese	NMC	Li-phosphate	Li-aluminum	Li-titanate
Abbreviation	$LiCoO_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNiMnCoO_2$ (NMC)	$LiFePO_4$ (LFP)	$LiNiCoAlO_2$ (NCA)	Li_2TiO_3 (LTO)
Nominal voltage	3.60V	3.70V (3.80V)	3.60V (3.70V)	3.20, 3.30V	3.60V	2.40V
Full charge	4.20V	4.20V	4.20V (or higher)	3.65V	4.20V	2.85V
Full discharge	3.00V	3.00V	3.00V	2.50V	3.00V	1.80V
Minimal voltage	2.50V	2.50V	2.50V	2.00V	2.50V	1.50V (est.)
Specific Energy	150–200Wh/kg	100–150Wh/kg	150–220Wh/kg	90–120Wh/kg	200-260Wh/kg	70–80Wh/kg
Charge rate	0.7–1C (3h)	0.7–1C (3h)	0.7–1C (3h)	1C (3h)	1C	1C (5C max)
Discharge rate	1C (1h)	1C, 10C possible	1–2C	1C (25C pule)	1C	10C possible
Cycle life (ideal)	500–1000	300–700	1000–2000	1000–2000	500	3,000–7,000
Thermal runaway	150°C (higher when empty)	250°C (higher when empty)	210°C(higher when empty)	270°C (safe at full charge)	150°C (higher when empty)	One of safest Li-ion batteries
Packaging (typical)	18650, prismatic, pouch cell	prismatic	18650, prismatic and pouch cell	26650, prismatic	18650	prismatic
History	1991 (Sony)	1996	2008	1996	1999	2008
Applications	Mobile phones, tablets, laptops, cameras	Power tools, medical devices, powertrains	E-bikes, medical devices, EVs, industrial	Stationary with high currents and endurance	Medical, industrial, EV (Tesla)	UPS, EV, solar street lighting
Comments	High energy, limited power. Market share has stabilized.	High power, less capacity; safer than Li-cobalt; often mixed with NMC to improve performance.	High capacity and high power. Market share is increasing. Also NCM, CMN, MNC, MCN	Flat discharge voltage, high power low capacity, very safe; elevated self-discharge.	Highest capacity with moderate power. Similar to Li-cobalt.	Long life, fast charge, wide temperature range and safe. Low capacity, expensive.

***Table 3**: Comparison of different types of Li-ion batteries. Source batteryuniversity.com*

To choose the correct configuration for the battery pack, a series of requirements were defined. First of all, the battery pack would have to deliver 500 Watts for up to an hour. Moreover, the battery nominal voltage would have to be as high to reduce ohmic losses while powering up the car simultaneously being less than 35 volts, which is the maximum input voltage of the typical linear voltage regulators used in the vehicle's PCBs. The hardware used for monitoring the battery pack should be as minimal as possible to reduce complexity and limit the fail-points. Special notice would also be given in the battery pack's serviceability, for example, how easily a damaged cell can be replaced. Lastly, as mentioned above, keep the weight of the battery pack minimum while satisfying all of the above. The design constraints are summed as follows:

- Energy ≥ 500 $W\ h$
- Higher as possible total voltage of the pack while under 35 Volts
- Minimum needed hardware for monitoring the battery pack to minimize a sensor fail.
- Serviceability
- Minimum weight

$$\frac{35\ V}{4.2\ V} = 8.33 \sim 8\ cells\ in\ series$$

The following table describes some of the most notable market-available configurations of cells that fulfill the voltage and energy targets and are constructed from the shortlist of chemistries derived in the above analysis.

Cell Model	Type of cell	Configuration	Capacity of one cell (mAh)	Total energy (W/h)	Number of cells	Total Weight (kg)
SLPB6975110	LiPo	8S2P	5000	296	16	1.696
SLPB7249135	LiPo	8S2P	5000	296	16	1.632
SLPB6945135HV	LiPo	8S2P	5200	316.16	16	1.408
INR18650-25R	Li-NiMnCoO2	8S4P	2500	288	32	1440
US21700VTC6A	Li-NiMnCoO2	8S3P	4100	354.24	24	1744.8
INR21700-50S	**Li-NiMnCoO2**	**8S2P**	**5000**	**288**	**16**	**1.152**

***Table 5**: Battery Pack Configurations with various cell models*

1.5 The chosen cell's electrical specifications

Cell Manufacturer and Type	Samsung INR21700-50S
Cell nominal capacity:	5000 mAh
Maximum Voltage:	4.2 V
Nominal Voltage:	3.6 V
Minimum Voltage:	2.5 V
Maximum nominal output current:	25 A
Maximum charging current:	6 A
Maximum Cell Temperature (discharging)	60°C
Maximum Cell Temperature (charging)	45°C
Cell chemistry	Li-NiMnCoO2

Table 1.6: Cell Description

Figure 1. 5: *Samsung Cell*

1.6 Design of the Cell mounting

The 8 cylindrical lithium ion pairs of 16 battery cells are connected in series, as shown in the figure below:

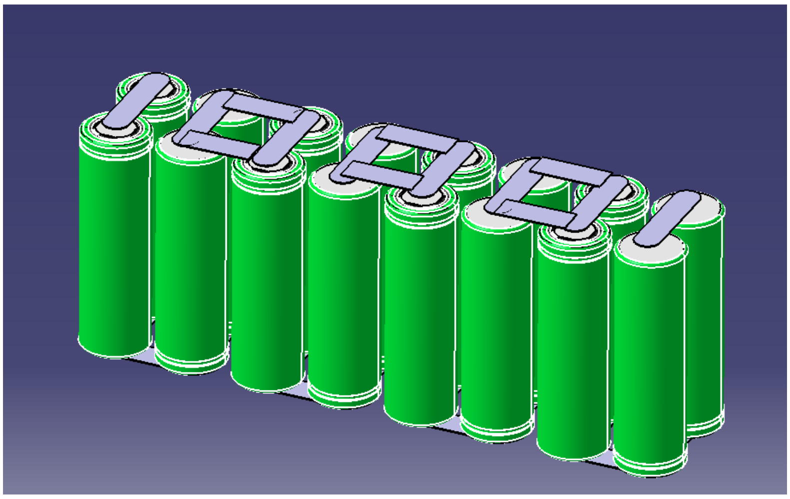

Figure 1.6: *8S2P electrical configuration*

As for their mounting, according to the T 11.7.7, the LV batteries must have a fire-retardant, rigid and sturdy casing (T11.7.4). To comply with these rules, a 3D printed casing was designed and made from a UL-94V0 material. The casing, along with 3mm UL-94V0 foams, in between and around the cells.

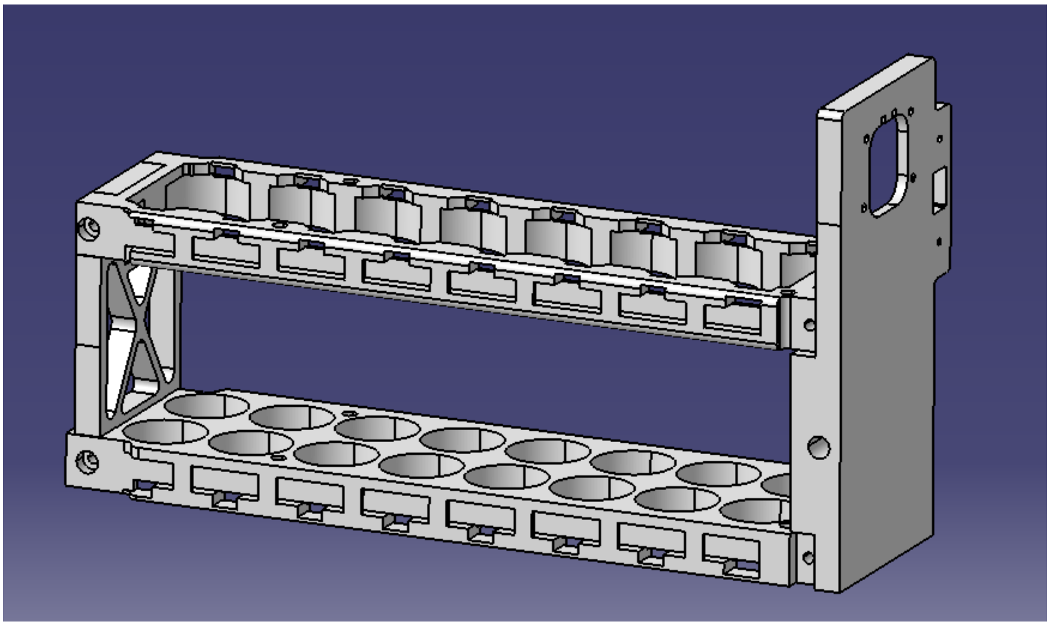

***Figure 1.7**: Mounting of 8s2p inside the casing*

***Figure 1.8**: Fully Assembled Battery Pack*

1.7 Designing the Battery Monitoring System (BMS)

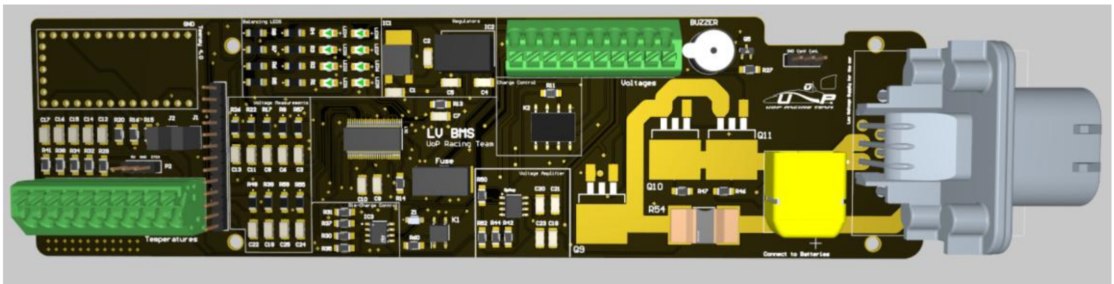

***Figure 1.9**: Low Voltage BMS Printed Circuit Board 3D render*

Since the Li-NiMnCoO2 type of battery is not Lifepo4 chemistry and is considered unsafe by the competition rules without monitor to be operated , BMS is to be designed. The BMS is expected to monitor the temperature of at least 30% of the cells utilized and all cell voltages. The circuit was built around LTC6811-2 multicell battery stack monitor, which features the following characteristics:

- Measures Up to 12 Battery Cells in Series
- 1.2mV Maximum Total Measurement Error
- 16-Bit ADC with Programmable Noise Filter
- Built-in isoSPI Interface
- 1Mb Isolated Serial Communications
- Uses a Single Twisted Pair, up to 100 Meters
- Low EMI Susceptibility and Emissions
- 290µs to Measure All Cells in a System
- Passive Cell Balancing with Programmable Timer
- 5 General Purpose Digital I/O or Analog Inputs
- 4µA Sleep Mode Supply Current

In other words, the LTC6811-2 is responsible for all the measurements related to the temperature and voltage. It can feed the related data upon an SPI request to an SPI-compatible programmable device. Its filtered ADC contributes to reliable monitoring of the cells. This operation is critical in an electric vehicle, as noise disturbance is expected due to the high current path to the motors and the high frequency switching noises of their inverters. Its high polling frequency also contributes to the system's reliability. The multiple measurements translate into a higher probability of getting a valid measurement and resetting the time interval before the system declares a faulty situation and unexpectedly shut down the supply to the vehicle. The microcontroller chosen to supplement the LTC6811-2 is a teensy 4.0. Teensy 4.0 is a 5V based on ARM Cortex-M7 microcontroller operating at 600 MHz. Its excellent processing speed, a high number of digital and analog I/O inputs, SPI and CAN but compatibility and programmability with a classic Arduino IDE make this microcontroller an excellent choice for the BMS by offering simplicity without at the same time sacrificing performance.

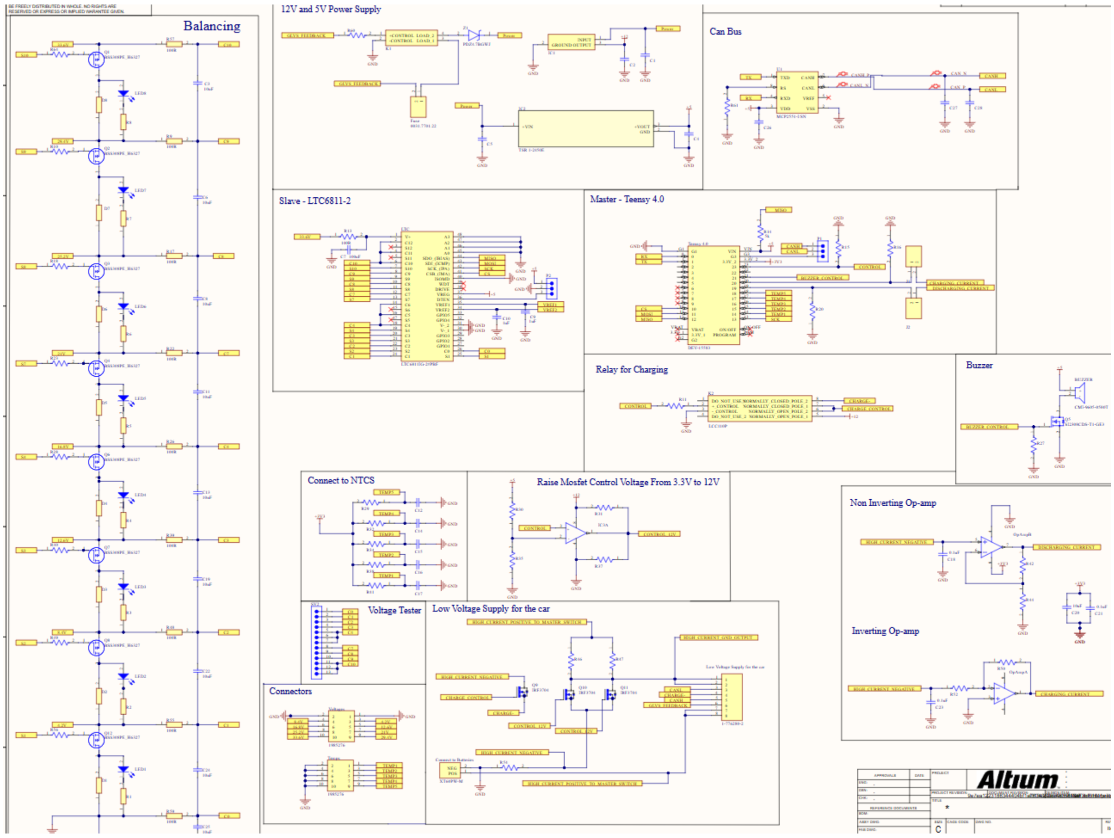

***Figure 1.10**: Low Voltage BMS Printed Circuit Board Schematic*

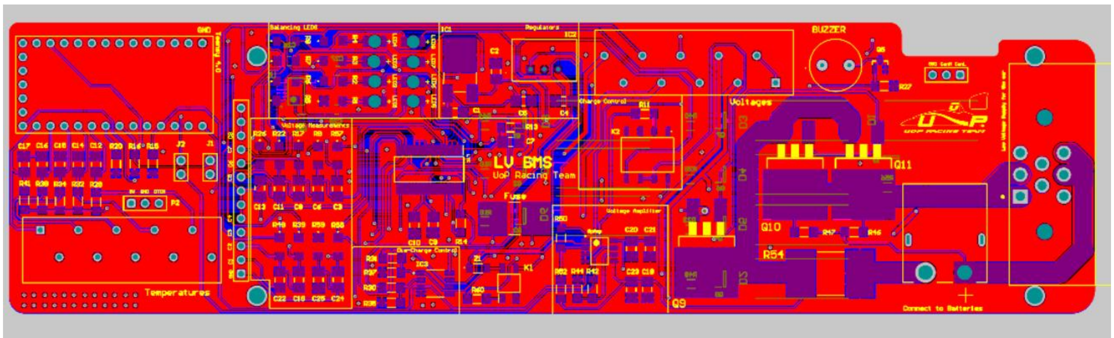

***Figure 1.11**: Low Voltage BMS Printed Circuit Board layout*

1.8 Cell Balancing

Lithium-ion cells have high columbic efficiency, therefore, they cannot be effectively self-balanced like other cell chemistries. Additionally, cells intrinsically differ from one another from the manufacturing process even if the cell chemistry is exactly the same which means that their electrical characteristics are different as well. The absence of a mechanism that mitigates the battery imbalance will result in effective cell capacity loss during operation. To maintain battery performance over a long service life in a large-format battery system, it is usually necessary to implement a charge balancing strategy to extract the maximum possible energy for the battery pack. An effective cell balancing system maintains the desired level of battery performance throughout the life of the battery with an appropriate safety margin, without adding excessive cost, weight, or complexity. The cell balancing system should ultimate meet at least one of the following design requirements:

• Minimize difference in charge between cells: The effective capacity of the pack is reduced by the difference in charge between the most and least charged cells.

• Maximize available battery energy: If cells are not of equal capacity, cells with higher capacity will still contain useful energy when the lowest capacity cells reach full discharge, but because this energy cannot be extracted without over-discharging the "smaller" cells, the energy will be stranded. If charge can be moved from the larger cells to the smaller ones, this stranded energy can be recovered.

• Maximize available battery energy: Cells at different SOCs have different power capabilities due to the influence of SOC on cell impedance. If cells drift to high or low SOC, they will limit the battery power capability as well as the energy capacity.

Charge Transfer Balancing vs Dissipative Balancing

The most popular types of balancing system are the **Charge Transfer Balancing** and the **Dissipative Balancing**, both of them have strong advantages and disadvantages and thus the balancing system type selection should be decided after careful consideration. Obviously, the charge transfer balancing systems are capable of transferring charge between cells which means that the energy losses are reduced. The principal advantage of this technique is that when a cell with less available energy of lower SoC is detected, this balancing system transfers charge from the ones that have the higher SoC. This can increase the overall energy capacity of the battery pack by an amount up to the energy imbalance between cells due to both capacity and SOC inequality. The topologies that utilize such balancing methods are presented below:

1. Flying Capacitor
2. Inductive Charge Transfer Balancing
3. Transformer Charge Balancing

The dissipative balancing topology is a lower-cost strategy which dissipates energy from cells that are determined to be too high in SoC using resistive devises. Besides that, it seems intrinsically wasteful because the energy is not converter into useful work, this solution is used by many battery management systems as it offers a higher level of simplicity related to the charge transfer topologies.

The switches in dissipative balancing systems must only switch across a single cell voltage, minimizing the cost and size of the switch needed to turn on the balancing circuit. Despite their large number, the switches are small in size and having a single switch and resistor per cell is very inexpensive.

On the downside, the heat generated by the balancing resistors must be appropriately dealt with. If PCB mount resistors are used, they may likely become the warmest components on the circuit board when the balancing circuits are in operation. The power rating of the components must be adequate, but more careful attention is required to the circuit board design to ensure that the overall hardware is robust. The reliability trade-offs with a dissipative balancing system should be carefully weighed. Increased temperature reduces the expected reliability of the neighboring electronics and can lead to higher failure rates from a system that is at a first glance expected to be simpler and more robust. Although a single switch is adequate to control the balancing function, there are failure modes associated with failure of the switch or of its control logic. Because a closed switch leads to discharging of a cell, if the switch fails in the closed position, the cell will continue to discharge uncontrollably. Depending on the situation, this could result in the cell entering an over discharge condition and becoming irreparably damaged. If the switch fails in the open position, balancing of that cell will be impossible. Adding switches in parallel or series will reduce the likelihood of one of these failure modes while increasing the likelihood of the other.

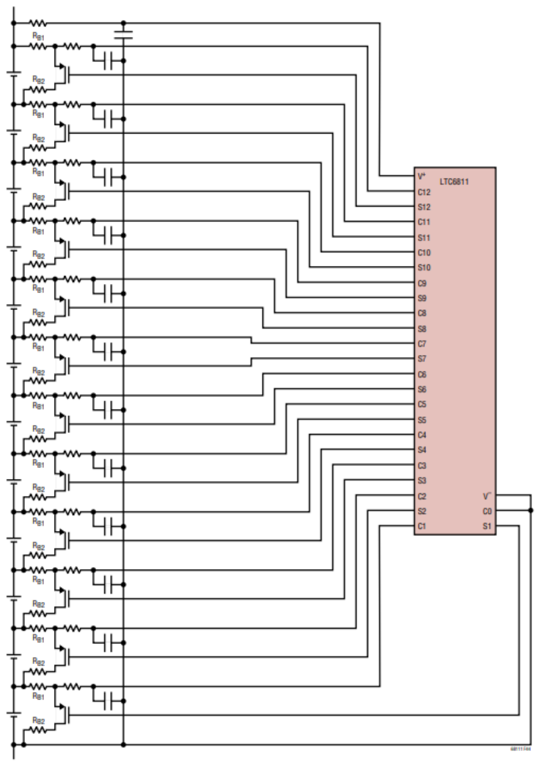

***Figure 1.12**: : Schematic Diagram of a passive balancing circuit with external mosfets.*

1.9 Manufacturing Process

Figure 1.13: *Casing with Batteries*

The manufacturing and assembly of the battery pack were carried out entirely in-house, allowing for complete quality control and precision throughout the process.

For the interconnection of the cells, pure nickel busbars were used. The choice of pure nickel over alternatives such as nickel-plated steel was made for several key reasons:

- High electrical conductivity (~14.3 MS/m), which minimizes power losses across connections.
- Excellent corrosion resistance, especially in humid or electrochemically active environments—critical for the safety and long-term reliability of the battery pack.
- Superior weldability, enabling strong and consistent spot welds during the assembly process.

The spot-welding process was performed using the VEVOR 801D Battery Spot Welder, which provides precise current control and consistent weld quality. Using this method, we successfully constructed an 8s2p configuration (8 series-connected groups with 2 cells in parallel per group), delivering the required nominal voltage and current capacity for the low-voltage system**.**

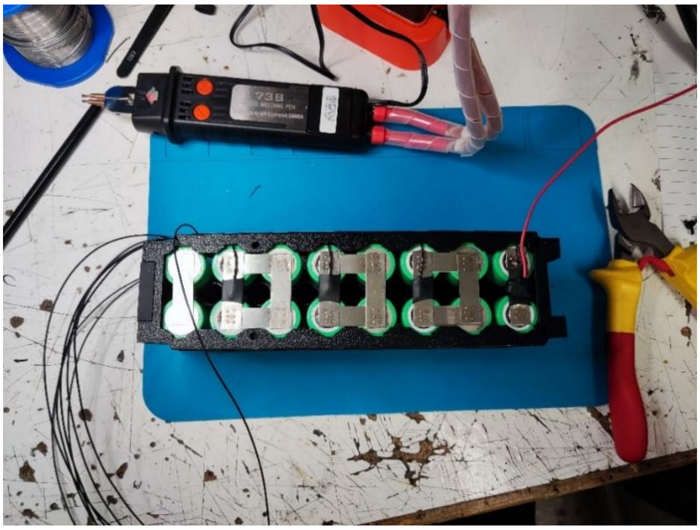

Figure 1.14: *Spot Weld process*

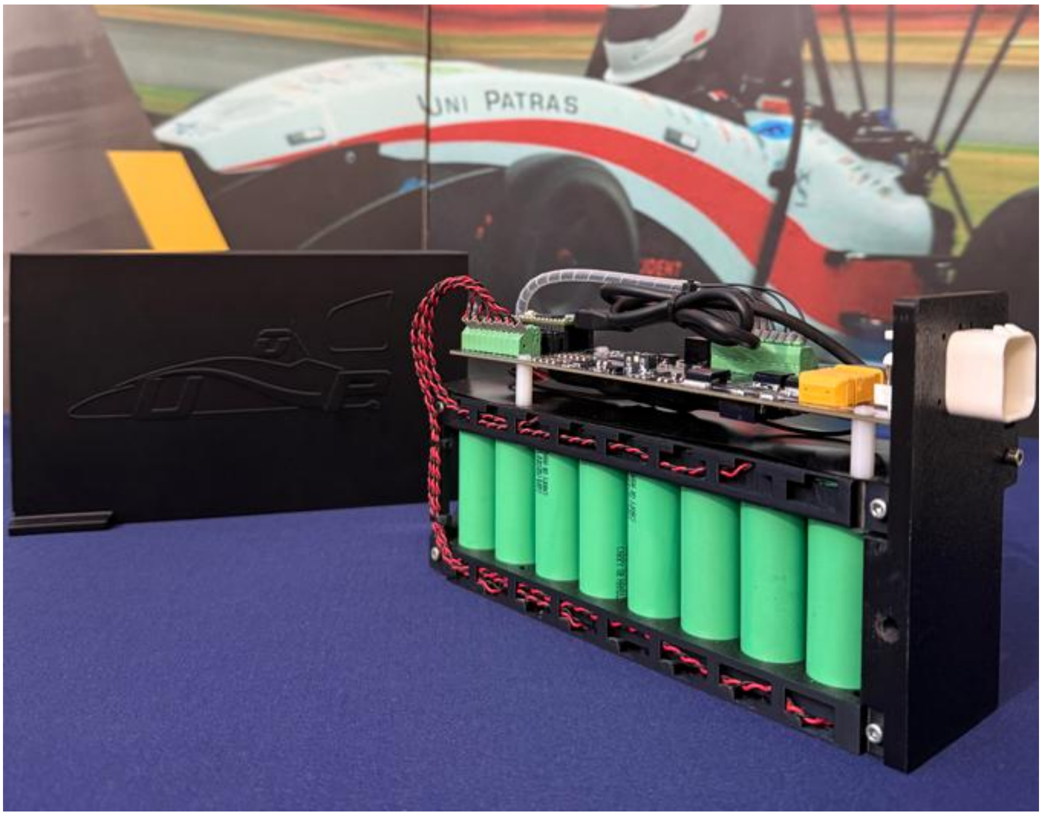

***Figure 1.15**: Fully Assembled Module Management Unit.*

The initial test setup, shown in **Figure 1.12,** includes the Module Management Unit, a regulated bench power supply, and a laptop running the serial monitoring software. The setup was used to verify communication protocols and monitor real-time system behavior during development.

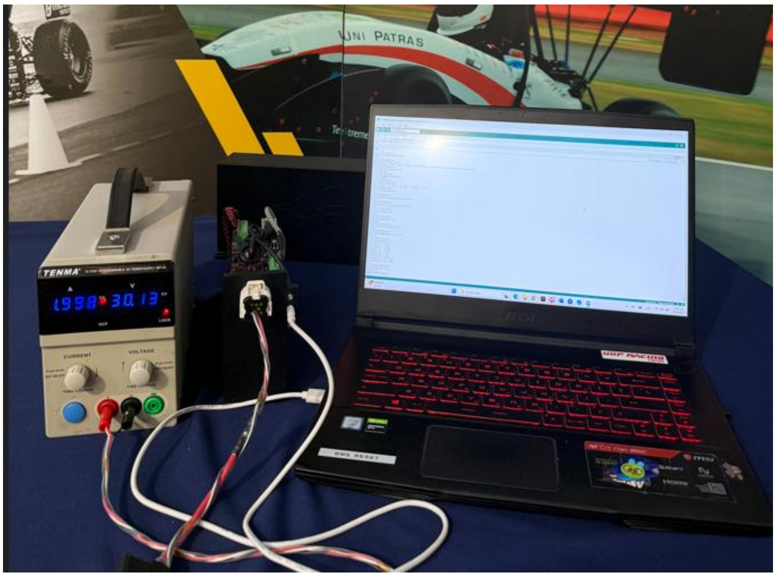

***Figure 1.16:** Setup for Software Testing*

After a full discharge of the battery pack under competition conditions, the constant power (W) discharge curve of the battery is shown in F**igure 1.13**:

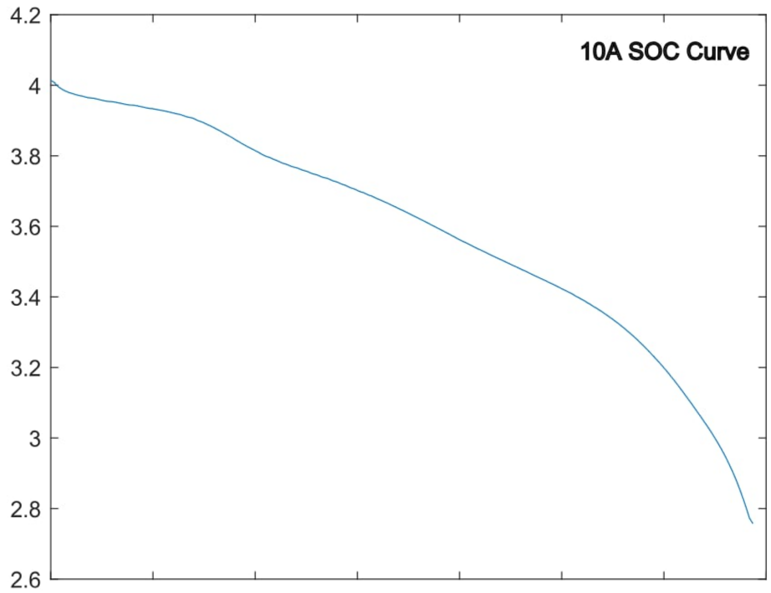

Figure 1.17*: Constant Watt Battery curve*

Figure 4.4: *UoP8e during Endurance Event*