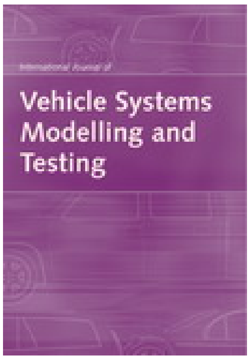

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Design and development of a Formula Student electric racecar's control system

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Abstract: The Formula Student electric racecar 'Thunderblade 4.0' control system developed by Team Kratos Racing Electric at Pimpri Chinchwad Education Trust's Pimpri Chinchwad College of Engineering has undergone significant improvements. Implementing a centralised power distribution unit has resulted in notable wiring harness optimisation. The proposed work has also focused on enhancing the functionality of the circuits. The team incorporated wire fault detection circuits, advanced logic circuits, and test points to improve the vehicle's safety and reliability. In addition to these improvements, it has also incorporated software tools like the Saturn Printed Circuit Board Toolkit and Altium Designer Rule Wizard. These tools have enabled the team to develop better printed circuit board designs. Overall, the control system has successfully analysed the failures of the previous season and proposed solutions to ensure the development of a reliable and competitive vehicle. The control system components are described, and the initiative has achieved its objectives of weight optimisation, power delivery efficiency, and improved functionalities of the circuits.

Keywords: electronics control unit; Formula Student electric racecar; Printed Circuit Board; design; safety circuits; STM32.

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1 Introduction

A new age has begun to unfold for us. More than ever, there is an excellent awareness of the importance of environmental protection. The electrification of the automotive industry is a natural consequence of environmental movements and increased regulatory pollution standards for conventional internal combustion engine (CV) vehicles. Since this transformation is occurring much more quickly than anticipated, the industry is resolved to give up on CVs and enter the market for electric vehicles (EVs) (Miller, 2017; Zhang and Chris, 2018). Major automobile producers, significant electricity production, distribution, commercialisation firms, and governments worldwide have made sizeable financial investments and begun participating in fresh international initiatives like the EV100 to hasten this transition. The sector of racing and competition is equally devoted to this change. In the past several years, new contests, such as Formula-E, have emerged to push the + D on electric vehicles. In electric vehicles, I + D, or R&D (Research and Development), refers to the activities conducted to improve technology, efficiency, and performance. Formula Student competitions have increasingly emphasised the electrification of vehicles and the advancement of driverless vehicle (DV) technologies.

The paper in the thesis (Chen, 2008) highlights the significance of having a thorough electronic architecture in contemporary automobiles, prioritising safety and fault tolerance. It proposes a design approach that is based on models for creating secure and reliable electronic systems, along with the inclusion of safety measures like redundancy and fault detection. A detailed and comprehensive manual on designing and constructing an electric vehicle, providing guidance on essential topics like battery technology, motor selection, and power electronics, is reported in Leitman and Brant (2009). This resource is precious for building a safe and dependable electric vehicle. Moreover, rulebooks from various Formula Student competitions, such as those found in sources (Formula Student Germany, 2022; Formula Student UK, 2022; Formula Bharat, 2022), give comprehensive regulations and specifications on the technical and safety requirements for electric racecars participating in their respective competitions. These resources offer valuable information to those seeking to participate in electric racing competitions and ensure they comply with the necessary regulations to ensure their safety and success. The master's thesis (Porra, 2018) discusses the electronic architecture of a Formula Student Electric Car, covering power electronics, battery management systems (BMSs), and safety features. The thesis proposes a modular design approach to facilitate maintenance and upgrades. The paper provides insights into designing and implementing an electronic architecture for an electric racecar.

A research paper (Singh, 2021) presents a simulation of the STM32 BluePill microcontroller library in Proteus software, which can help design the control system of an electric racecar (Olson, 2019) This comprehensive textbook covers various types of electronic circuits, such as amplifiers, filters, and digital circuits, among others, and their analysis and design. Additionally, the book provides an introduction to operational amplifiers and their applications. It is a well-regarded resource for students and professionals in the field of electronics and can be beneficial in designing the safety system of a formula student electric racecar. The technology known as AVR SCM is utilised for creating high-performance electric control systems for racing purposes, as mentioned in the source (Wan et al., 2014). This technology involves the selection of microcontrollers, integration of sensors, and software development.

Further resources such as sources (Bibi, 2016; Jain, 1997) offer comprehensive guides for designing and programming STM32 microcontrollers, while sources (Neamen, 2002; Gayakwad, 2019) cover the analysis of various types of circuits, including amplifiers, digital circuits, filters, and others. These resources are precious for gaining insight into the technical complexities of developing a racing electric control system and providing practical guidance in designing and executing such a system. By utilising these resources, one can better understand the technical aspects of developing electric control systems for high-performance racing applications. The sources listed (Badal, and Regas, 2019; Formula Student Team Delft, 2021; Mohan et al., 2003; Texas Instruments, 2022; LEM, 2020) provide valuable information on the design and analysis of different aspects of a Formula Student electric racecar.

Vu et al. (2012) implemented online electric vehicle (OLEV) technology for the first time for Formula SAE vehicles for wireless power transfer in the powertrain, thereby increasing vehicle performance. An electric power train was successfully modelled in Simulink and implemented (Blaszykowski, 2013). In CarMaker simulation software, they prepared the complete model of an electric power train and its control module. Ebaid et al. (2016) designed and built a Formula Students racing car as per SAE regulations with an essential feature of engine capacity limited to 610cc and a fibreglass body. The requirements of various parts were analysed using COMSOL Multiphysics software.

In 2016, the University of Canterbury Motorsports (UCM), NewZealand developed a formula SAE race car with AMKASYN KW26-S5-FSE-4Q quad-package, three-phase full-bridge inverter controlled the four AMK DD5-14-10-POW permanent-magnet synchronous servo motors, each of which could be controlled separately (Barham, 2017). Galbraith (2019) designed and developed optimised powertrain elements for UCM SAE electric race car. He powered a 120 kW quadruple motor and inverter with an entirely student-designed lithium-ion battery pack. Loof et al. (2014) used a combination of 3-DOF and 7-DOF vehicle models and tyre models based on ten parameters. They also demonstrated that the vehicle with traction control performs substantially better regarding longitudinal and lateral acceleration driveability. Ji (2020) proposed a traction control system for a vehicle with rear-wheel drive an open-wheel formula racer with a peak power output of 80 kW (600 V). The direct torque control (DTC) system is modelled using vector space theory to ensure that the proposed DTC permanent-magnet synchronous motors (PMSM) drive will have a high level of performance. Bohác (2020) under his bachelor's project, designed and implemented the first autonomous racecar for his team, eForce, in a driverless formula competition. He described the architecture of an autonomous system with motion planning and trajectory tracking algorithms.

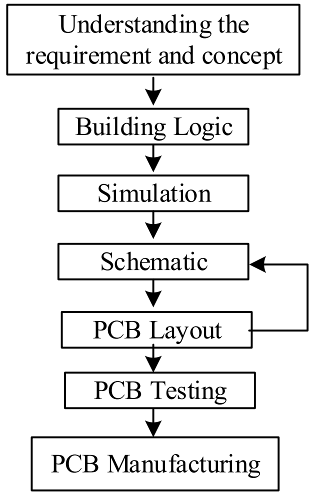
A group of researchers (Badal, and Regas, 2019) analysed various powertrain configurations for a formula-style electric racecar, providing insight into the selection and optimisation of the powertrain system. The Design Presentation by Formula Student Team Delft (Formula Student Team Delft, 2021) showcases the design of their DUT21 racecar, including the power electronics and BMS (Mohan et al., 2003) and offers a comprehensive guide to converters, applications, and design, which is a helpful resource for developing the electronic systems of an electric racecar. (Texas Instruments, 2022; LEM, 2020) are also essential sources of information for the power electronics system of a racecar, providing technical specifications and application examples for these components.

2 Methodology

The methodology is set according to the objectives and is product-oriented. The process is divided into five phases: Literature, Simulation and Design, Manufacturing, Assembly and Integration, and Testing. As it is a highly critical system in the vehicle, the focus of the proposed work would be reliable functionality, failsafe logic, and validation through testing (Zhang and Chris, 2018).

Developing a safety circuit is shown in Figure 1, which involves understanding the requirements and concept, building logic, simulation, schematic design, PCB layout, PCB manufacturing, and PCB testing. Each step is critical to ensure the safety circuit works as intended and protects against hazards. The process starts with identifying safety-critical aspects and defining safety goals. The logic is devised utilising suitable technology, subjected to simulation for issue identification, and then proceeds to create a schematic diagram, followed by the design and production of the PCB. Finally, testing is conducted to verify that the safety circuit meets the requirements and specifications.

Figure 1 Process of developing a safety circuit



2.1 Block diagram

In the shutdown circuit of an electric vehicle, the PDU is responsible for distributing power to various components such as the motor controller, BMS, and other electronics. The PDU receives power from the battery pack and routes it to the different systems through fuses and relays. In case of an emergency shutdown, the PDU also has a shutdown signal input, which is connected to the shutdown switch. When the switch is activated, the PDU will cut power to all connected systems to ensure the safety of the passengers and the vehicle. The PDU is a critical component in the shutdown circuit as it helps quickly isolate the power source in an emergency.

In an initial literature review (Chen, 2008; Leitman and Brant, 2009) for the design and development of a Control System for a Formula Student electric racecar, the fundamental architecture is established in conjunction with the overall electrical system of the vehicle. The following can be seen in Figure 2.

2.2 Elements of block diagram

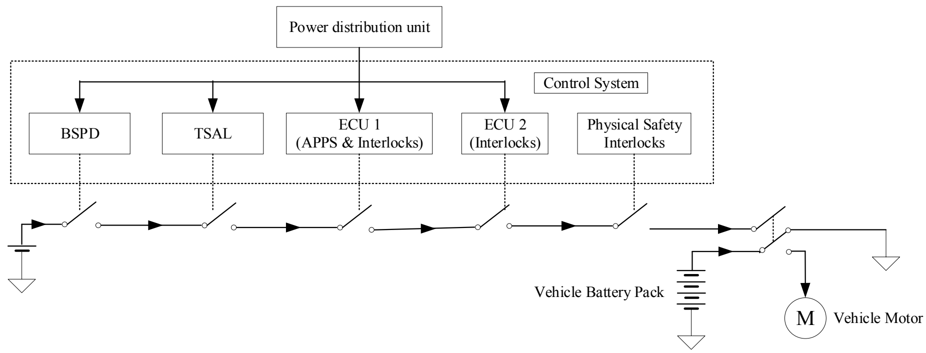
2.2.1 The brake system plausibility device (BSPD)

The BSPD is a standalone non-programmable circuit that checks two conditions (Formula Student Germany, 2022; Formula Student UK):

i Power delivered to the motor is measured in terms of current using LEM’s DHAB S/161 current sensor.

ii Hard braking is measured via a brake system encoder (Wika S-10 Pressure Transmitter).

Figure 2 Block diagram of shutdown circuit



2.2.2 The tractive system status light (TSAL)

Tractive system status light (TSAL) is a visual indicator in a shutdown circuit. It flashes red at 2.98 Hz when the tractive system and GLVS are active, signifying operational readiness. The green state indicates that only the GLVS is active, suggesting a potentially safer state useful for maintenance or non-operational periods. It provides quick visual feedback on system status for safety and operational assessment.

The TSAL flashes in RED with a frequency of 2.98 Hz when both the Tractive system and GLVS are active and in GREEN if only the GLVS is active (Formula Bharat, 2022; Porra, 2018). The electronic control unit (ECU) 1 contains an accelerator pedal position sensor (APPS) (Torque Encoder) and ready to drive sound (RTDS).

2.2.3 ECU1

ECU 1 refers to the first ECU in an electric vehicle. Accelerator Pedal Position Sensor (APPS) is a sensor that detects the position of the accelerator pedal and sends a signal to the ECU to control the torque of the motor. The Torque Encoder is a type of APPS that measures the torque applied to the accelerator pedal. RTDS is an auditory signal the electric vehicle plays to indicate that it is ready to be driven. The ECU 1 in an electric vehicle is responsible for receiving and processing signals from the Torque Encoder and the RTDS to ensure the safety and readiness of the vehicle before it can be driven.

i *APPS*

- a Two linear GEFRAN PZ-12 potentiometers of nominal resistance 2K are used as pedal positioning sensors.
- b Obtain different transfer functions from the sensors. One of the potentiometers is supplied with 10 V and the other with 3.3 V.

ii *RTDS*

The vehicle enters the ready-to-drive state by pressing the start button and brake pedal. Once the vehicle enters the ready-to-drive mode, the motor controller will respond to APPS.

2.2.4 ECU 2 – interlocks

The digital signal generated by a fault in the Insulation Monitoring Device (IMD) or BMS is given to the Latching circuit. This results in opening the respective shutdown relay in the shutdown circuit and the circuit is latched. Even if the fault is gone, the shutdown circuit will remain open until the reset button is pressed. It is located on BMS Master.

2.2.5 Physical safety interlocks

These components are all physical safety interlocks in an electric vehicle. The tractive system master switch (TSMS) is a high-voltage switch that disconnects the tractive system from the rest of the vehicle when opened. The low voltage master switch (LVMS) disconnects the 12V system from the rest of the vehicle, including the tractive system, when opened. The brake over travel switch (BOTS) detects when the brake pedal is fully depressed and is an important safety feature in case of unintended acceleration. The shutdown buttons (SDB) are emergency stop switches that can immediately shut down the tractive system or the entire vehicle. The Inertia Switch is a crash sensor that can trigger the deployment of airbags or shut down the fuel pump in case of an accident. The high voltage disconnect (HVD) interlock ensures the HVD is opened before service personnel or technicians can work on the high-voltage system. Finally, the High Voltage Connection Interlock ensures that the vehicle cannot be driven or charged unless the high-voltage connector is connected correctly.

3 Software implementation

The Software Implementation in the System is mainly for ECU-1 with two major algorithms for APPS and RTDS functionality. STM32F103c8t6 Controller is programmed using STMCubeIDE to meet the required functionality.

It is a software development environment used for programming STM32 microcontrollers and developed and tested the code using the IDE's features like debugging profiling and integrated software libraries. STMCubeIDE allowed for quickly identifying and fixing any issues, resulting in a reliable and efficient system for monitoring various sensors on the Racecar (Olson, 2019; Gayakwad, 2019).

The steps followed are as given below:

i **Setting up the STMCubeIDE development environment and creating a new project**:

Upon installation of STMCubeIDE on the computer, the first step is to select the appropriate microcontroller type and clock frequency to initiate a new project for the safety system. The software generated preliminary code automatically, which is utilised for further work.

ii **Configuring the project settings**:

After selecting the Microcontroller and clock frequency, the project is configured to meet the safety system's requirements. This process included the setup of pins and configuration of peripherals such as the pulse width modulation (PWM) and analog-to-digital converter (ADC) modules.

iii **Writing and testing the code for the safety system:**

Created and tested the safety system's code using the STMCubeIDE editor and debugging tools. This process includes writing code to read sensor values, track system health, and respond appropriately to emergencies. The debugging tools in STMCubeIDE allowed us to detect and fix any issues by stepping through the code line by line, setting breakpoints, seeing variables, compiling the code, and uploading it to the Microcontroller. The code is written and tested before compiling it using the built-in compiler in STMCubeIDE. The programming capabilities of the STMCubeIDE are then utilised to generate a binary file, which is uploaded to the Microcontroller. A programming connector is employed to connect the Microcontroller to the computer, and the code is then uploaded to the device's flash memory through STMCubeIDE. This process is carried out to ensure that the code can be executed successfully on the Microcontroller.

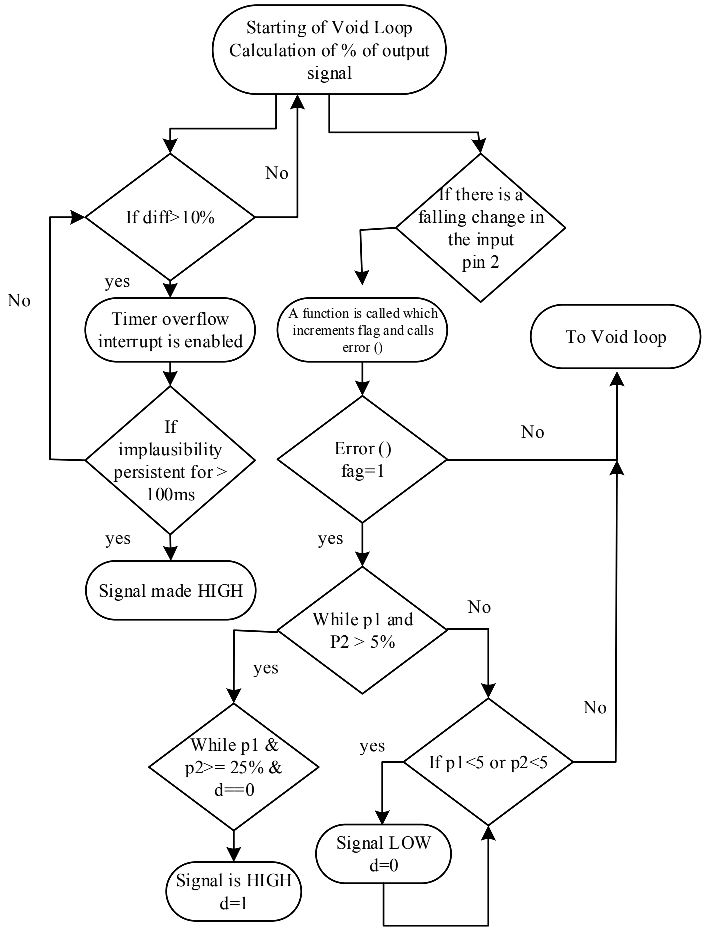
iv **Testing the safety system on the Racecar:**

The racecar's safety system is tested last to ensure it is functioning correctly. In order to confirm that the safety system responded appropriately, this required operating the racecar and simulating emergency circumstances. Using the debugging tools in STMCubeIDE operations, step 3 is tested again for changed code as necessary if any problems are discovered. In starting, the calculation loop is running continuously. In that, the per cent is calculated of the output signal. Then, that signal is sent to two different conditions. In the first condition, the two apps' signal difference is compared. If it is greater than 10%, the timer interrupt is enabled and forwarded for an implausibility check. If it remains for more than 1000 ms, the signal is high. Otherwise, it returns to the condition. In the second condition, if one signal is missing, an error flag is generated, and the signal is high. If everything is okay, then it returns to the main loop.

3.1 Electronic control unit 1 – APPS algorithm

The calculation loop is initially executed continuously to compute the output signal percentage, as shown in Figure 3. This output signal is then directed to two distinct conditions. Under the first condition, the difference between the signals from the two applications is compared, and if the difference exceeds 10%, the timer interrupt is enabled, and the signal is forwarded for an implausibility check. If the signal persists for more than 1000 ms, it is set high. Otherwise, the loop returned to the same condition. In the second condition, an error flag is triggered, and the signal is set high if either of the signals is missing. If no errors were detected, the program returned to the main loop for further execution.

Figure 3 APPS algorithm



3.2 RTDS algorithm

The RTDS algorithm is a safety feature incorporated into electric and hybrid vehicles to alert pedestrians and other road users of the vehicle's presence, mainly when operating at low speeds. This algorithm produces a sound that mimics the noise of a conventional combustion engine to signal the vehicle's proximity to pedestrians or other road users. The RTDS algorithm utilises various inputs, such as the vehicle's speed, direction, and accelerator pedal position, to determine the appropriate volume and pitch of the sound produced. Figure 4 shows the algorithm for the ready-to-drive sound that involves the following steps:

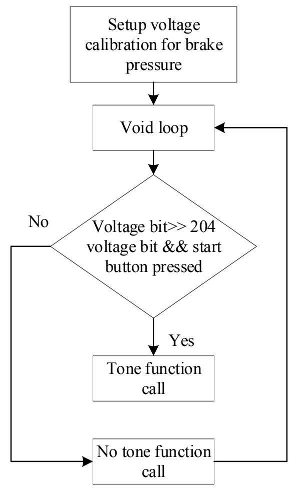
i Set up voltage calibration for brake pressure.

ii If the voltage is greater than 204 voltage bit:

  a Call the tone function.

iii If the voltage is less than 204, repeat the steps to recheck the voltage continuously.

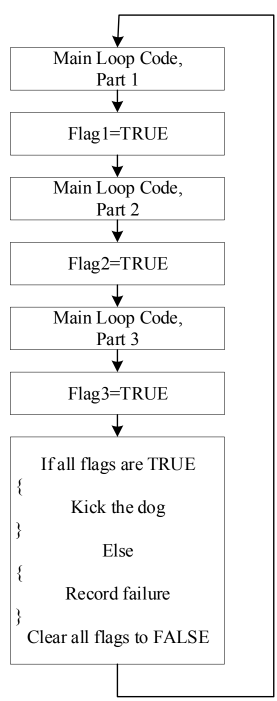
Figure 4 RTDS algorithm



3.3 Watchdog timer algorithm

Figure 5 shows the watchdog timer algorithm. The watchdog timer communicates with the Microcontroller at a set interval. If the MCU does not output a Flag or outputs too many Flags or Flags that differ from a predetermined pattern, the timer determines that the MCU is malfunctioning and sends a reset signal to the MCU.

Figure 5 Watchdog timer algorithm



A watchdog timer is a hardware element integrated into many microcontrollers and intended to stop the Microcontroller from malfunctioning or getting stuck in an infinite loop. In order to accomplish this, the watchdog timer periodically sends a signal to the Microcontroller. If the Microcontroller does not answer within a predetermined time, the watchdog timer assumes that the Microcontroller is broken and resets it. The watchdog timer sends a signal to the Microcontroller at predetermined, programmable intervals. The Microcontroller periodically resets the watchdog timer, which outputs a flag or pulse before the timer expires.

4 Schematics

4.1 Power distribution unit (PDU)

With an 18Ah low-voltage battery acting as the input source for the PDU, our system can operate between 12 V and 15 V. The Race Capture Pro MK3, TSAL, Motherboard, brake light, Speaker, pump, fans, and BMS master receive power from the PDU, which also has separate fuses for increased safety. Additionally, the BMS, which obtains temperature information from the Motor Controller via the CAN 2.0 Communication Protocol, is used in our system to enable intelligent cooling control. The BMS can efficiently control cooling operations thanks to this data. Additionally, steering buttons on the steering wheel allow for manual cooling control.

The Proteus 8 Professional software creates schematic diagrams and simulates the schematics (Singh, 2021). Developed by Labcenter Electronic Ltd, Proteus 8 Professional is a software package commonly used for circuit simulation and PCB design. The software can assist in designing, testing, and debugging electronic circuits before producing a physical prototype. Additionally, the Saturn PCB Toolkit is utilised for PCB-related calculations to estimate the current capacity of a PCB trace via its properties and other parameters. In contrast, the Altium Designer created the schematics and PCB design (Olson, 2019).

Altium Designer is an integrated software package for electronic product development, including schematic capture, PCB layout, and design verification. It is commonly used for designing complex PCBs, and the tool provides advanced routing and layout capabilities, including support for high-speed signals, differential pairs, and embedded components. Individual blocks of the system are designed using these software tools, selected for their capabilities in designing and testing complex electronic systems. Individual blocks of the system are designed as follows:

4.2 TSAL

The TSAL Logic Section is designed to blink in red when there is >60 V outside the accumulator. The TSAL glows green when all the AIRs and the precharge relay are open, indicating deactivated TS. TSAL will be in a safe state if there is an open wire in the system, independently if the HV system is on, and it will glow green only when LVMS is opened and closed again. Figure 6 shows the schematic of TSAL logic.

Figure 6 TSAL logic (see online version for colours)

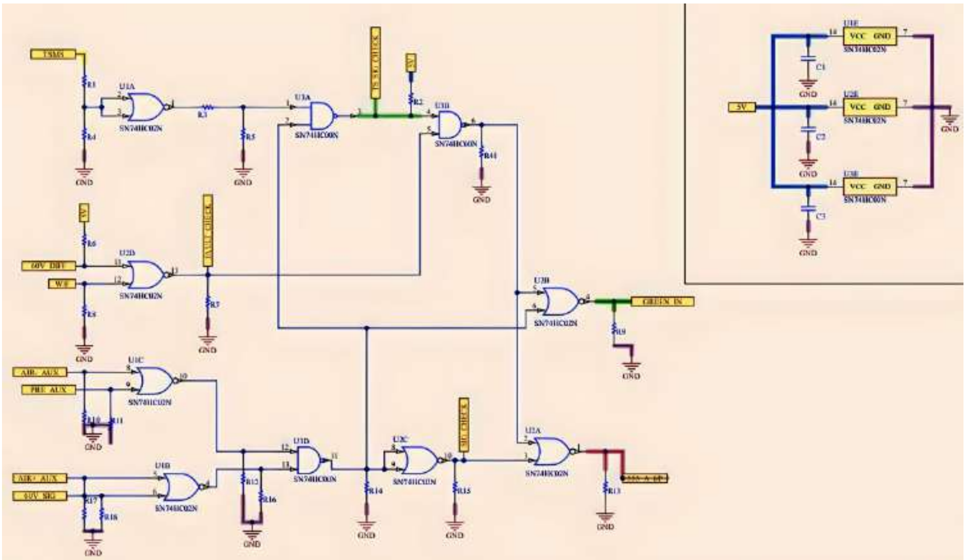
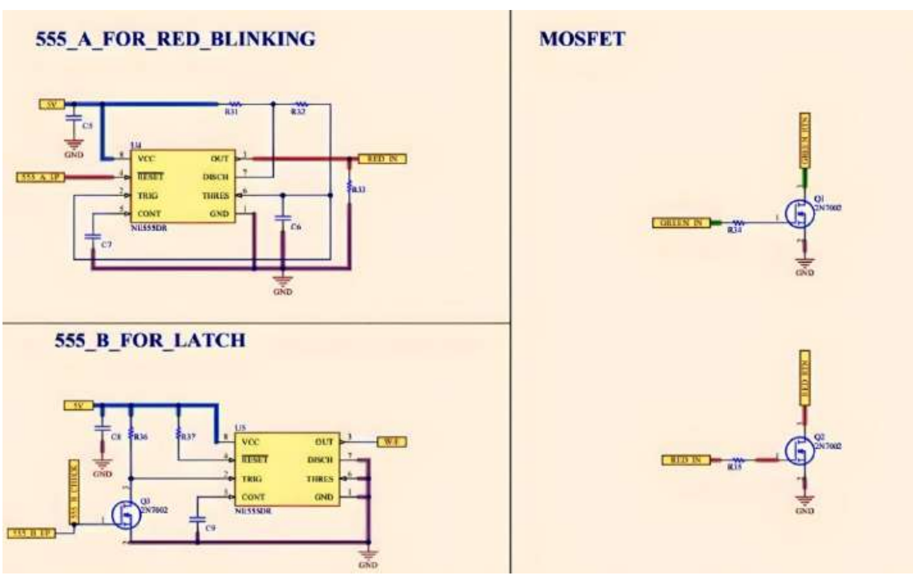


Figure 7 shows the logic of NE555 and MOSFET, which are used to control the LED in the vehicle.

Figure 7 555 logic (see online version for colours)



The wire fault detection circuits depicted in Figure 8 are engineered to detect and address wire faults in the accumulator isolation relay and precharge state signal wires.

Figure 8 Wire fault (see online version for colours)

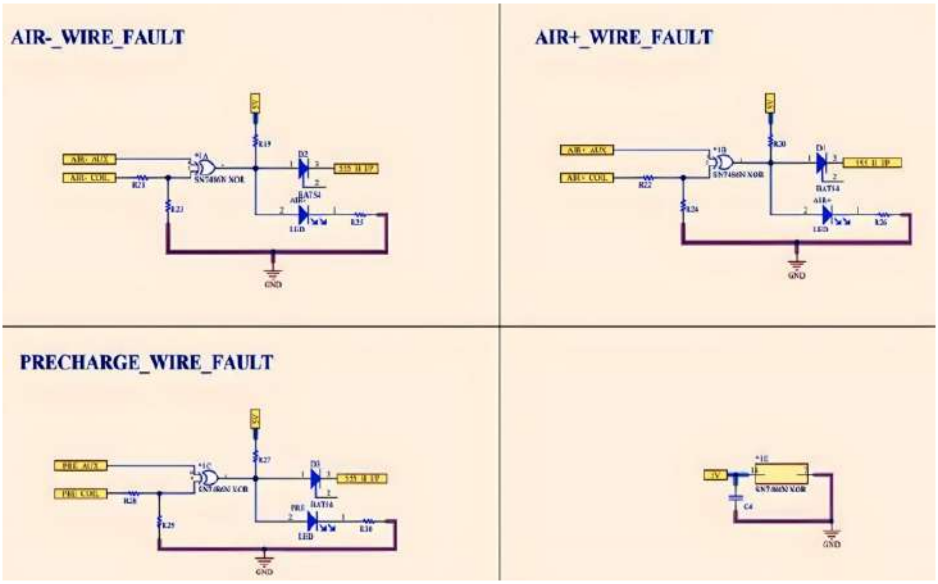
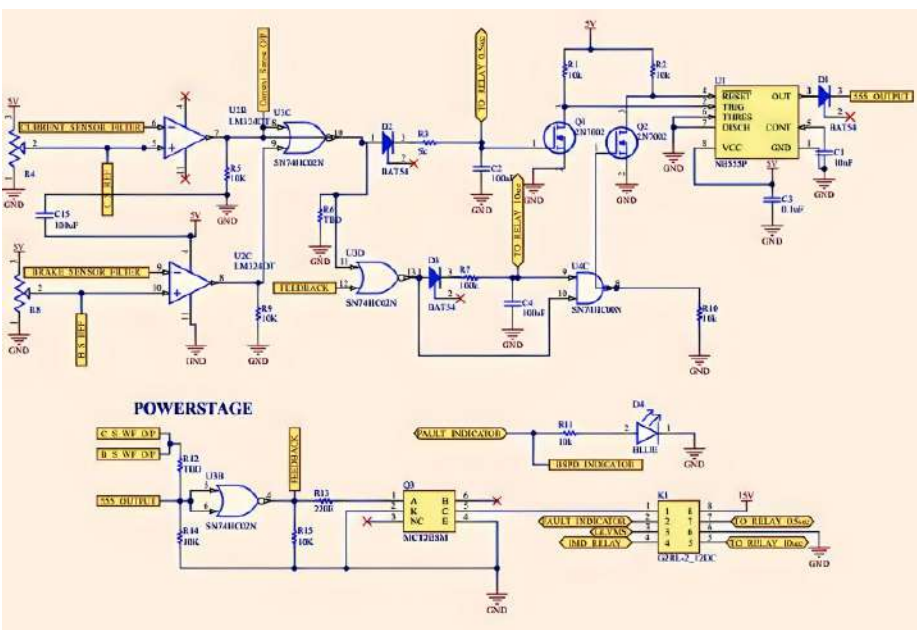


Figure 9 BSPD logic (see online version for colours)



4.3 BSPD

The logic section of BSPD as shown in Figure 9 is designed such that it will trigger at the current value of 10.63 Amp, which corresponds to 5 kW, considering the maximum voltage of the accumulator, which is 470 V and also, if the pressure exceeds 30 bars, hard braking is considered, above which the BSPD will trigger (Formula Bharat, 2022; Bibi, 2016). When both these conditions cooccur for more than 500 ms, the BSPD will send a signal to the latching circuit, which an RC circuit checks on the BSPD PCB. The signal is given to the base of an N-channel MOSFET, which drives the IC 555. The IC 555 is used as the Latching Circuit in its bistable multivibrator configuration (Neamen, 2002). The output of IC 555 is given to a logic inverter, which is given to the optocoupler, which drives the shutdown relay.

The Wire Fault Detection Circuits, as depicted in Figure 10, are specifically engineered to identify and address potential wire faults within the signal wires of both the current sensor and the brake pressure sensor (Gayakwad, 2019; Badal and Regas, 2019; Formula Student Team Delft, 2021).

Figure 10 Wire fault detection circuit (see online version for colours)

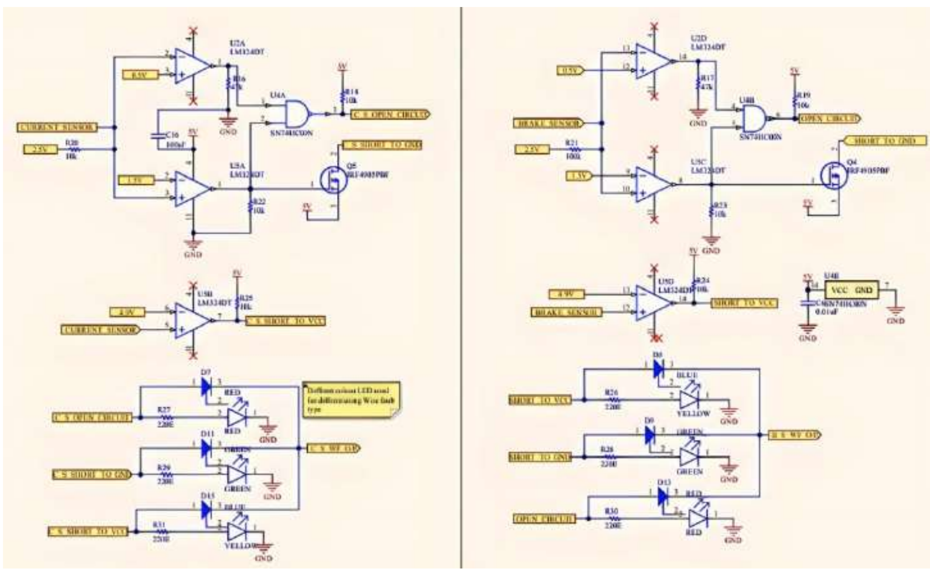


Figure 11 depicts the use of a TPS5430 Voltage Regulator to convert the battery supply to 5V for circuit power (Mohan N. et al., 2003). Connector pin allocation improves PCB routing, and signal line filters enhance data quality (Texas Instruments., 2022).

4.4 ECU – 1

The ECU – 1 APPS section logic as shown in Figure 12 is designed in such a way that the output signals of the potentiometers are fed to the STM32F103c8t6 controller to check for implausibility (LEM, 2020)

- The analogue values are converted to percentage values, and implausibility occurs if their absolute difference is greater than 10%.
- If the implausibility occurs and is persistent for more than 100 ms, then the MOSFET is turned on through the controller, which cuts off the signal to the motor controller.

- If hard braking occurs whilst the pedal travels >25%, the signal to the motor controller is made LOW until the pedal travel is <5%.

Figure 11 Connector and voltage regulation section (see online version for colours)

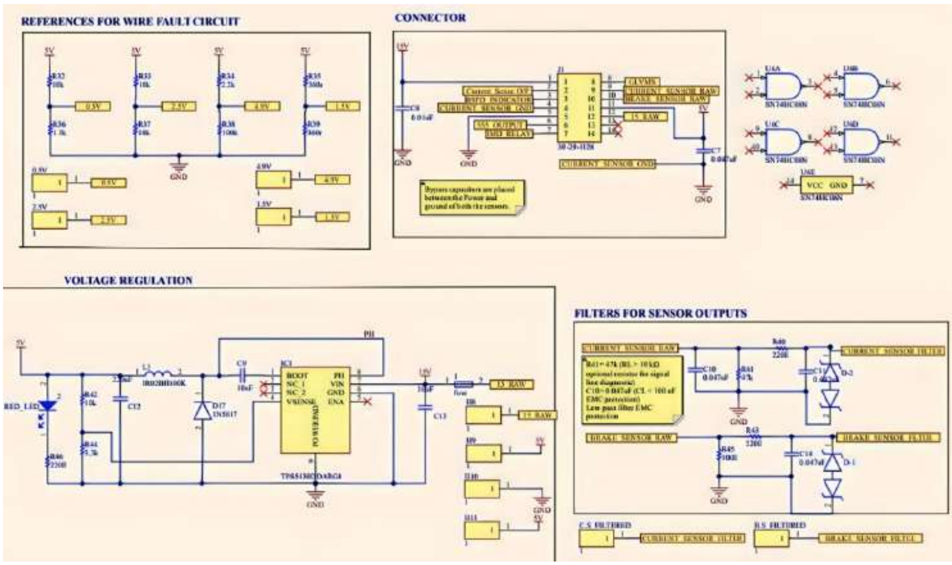
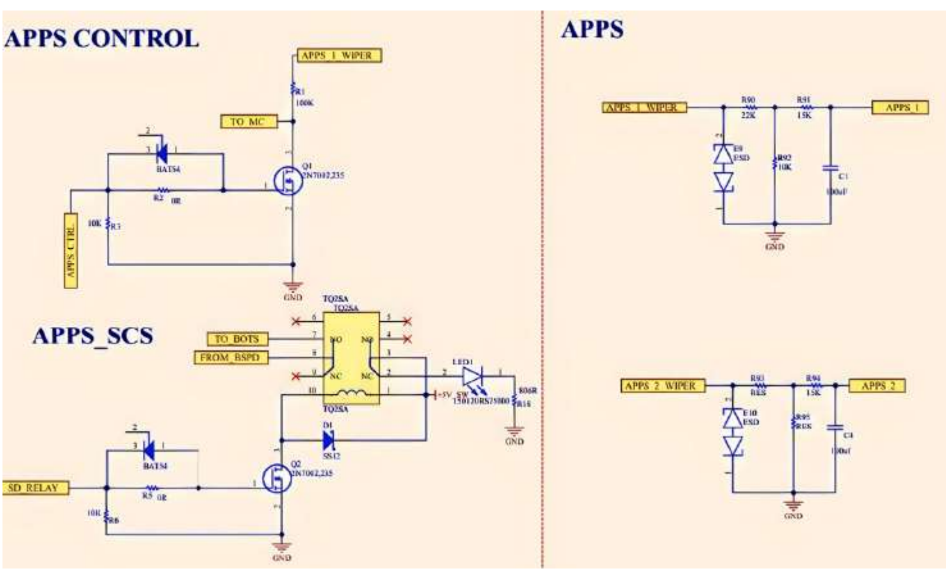


Figure 12 APPS logic (see online version for colours)



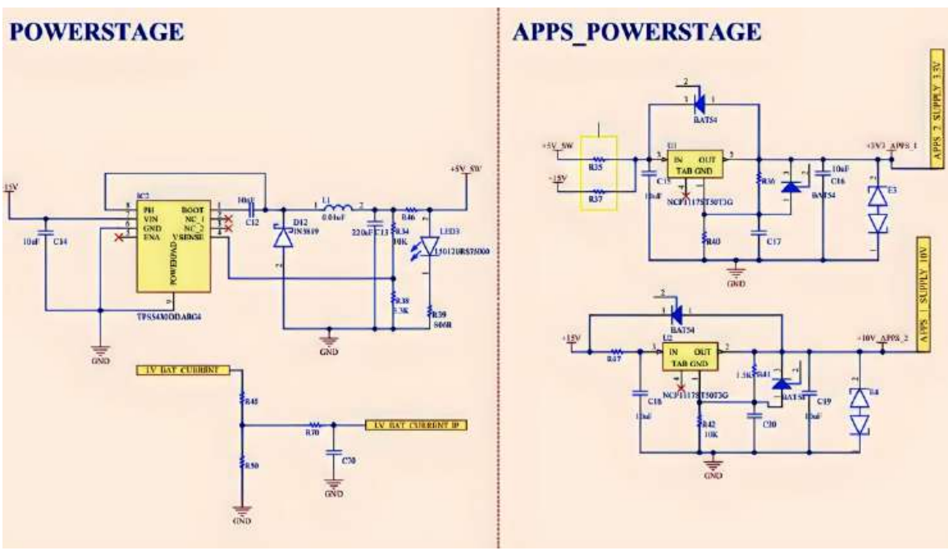
A relay that is included in the shutdown circuit will be actuated through the controller on the ECU if any of these conditions occur (Singh, 2021; Olson, 2019):

- short circuit to supply
- short circuit to ground

- out-of-range values
- open circuit.

The shutdown circuit includes a relay that the controller on the ECU can trigger if certain conditions occur. These conditions include a short circuit in the supply, which can cause an excessive current flow that may damage the circuit. A short circuit to the ground can also trigger the relay, which can occur if an unintended electrical connection between a wire or component and the chassis or earth. Additionally, out-of-range values, such as voltage or temperature levels, can also cause the relay to be actuated by the ECU. This could happen if a sensor provides inaccurate readings or if there is a fault in the system. Finally, an open circuit, where a wire or component fails to provide a complete circuit, can also trigger the relay. In all these scenarios, the relay in the shutdown circuit is used to prevent the vehicle from further operation and mitigate any potential safety risks. Figure 13 illustrate the powerstage circuit.

Figure 13 Powerstage (see online version for colours)



Redundancy circuits are also used. connector pin allocation is done for better trace routing on PCB as shown in Figure 14.

4.5 ECU – 2

In Figure 15, the ECU receives input signals from several sensors, such as the IMD and BMS. In the event of a sensor fault, a digital signal is produced and transmitted to the latching circuit. This signal triggers the opening of the shutdown relay, disrupting power to the tractive system and effectively turning off the vehicle.

Once the shutdown relay is triggered, the circuit becomes latched, which means it will remain open even if the fault condition is no longer present. This ensures the vehicle remains shut down until the reset button is pressed and the fault is addressed. The latching circuit is designed so that it requires a manual reset to re-energise the system.

This safety feature prevents the vehicle from being accidentally restarted and ensures that the fault is identified and resolved before the vehicle is back in operation.

Figure 14 Connector (see online version for colours)

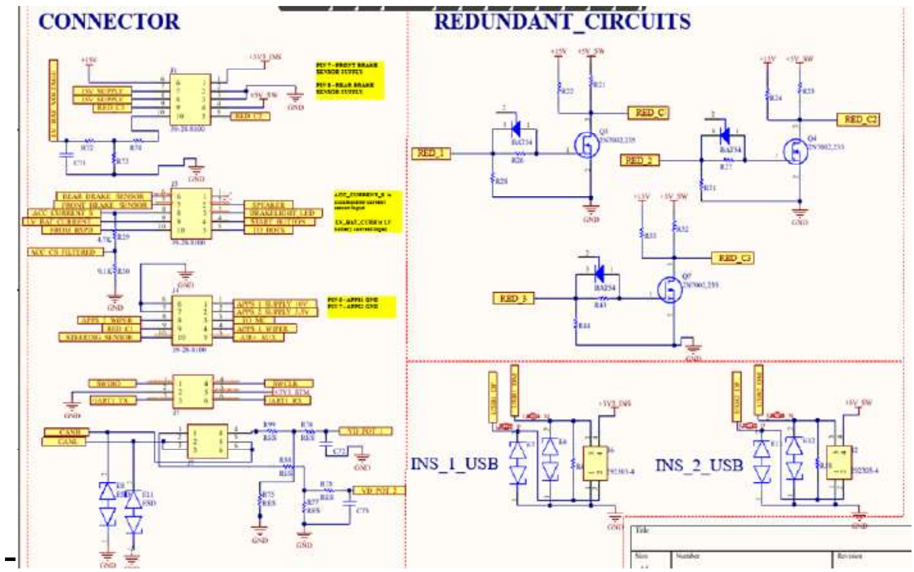


Figure 15 Latching circuit (see online version for colours)

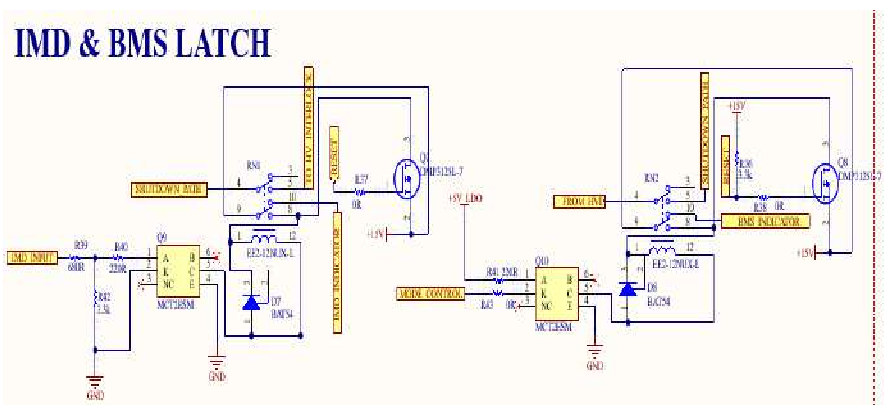


Figure 16 shows that the TPS5430 Voltage Regulator converts Battery Supply to 5V to power up the circuit.

4.6 PDU

- In Figure 17, TPS5430 Voltage Regulator converts Battery Supply to 5V for powering up the circuit (Mohan et al., 2003; Texas Instruments., 2022).
- NCP117 Voltage regulator is used to convert 8–3.3 V.

Figure 16 Power stage (see online version for colours)

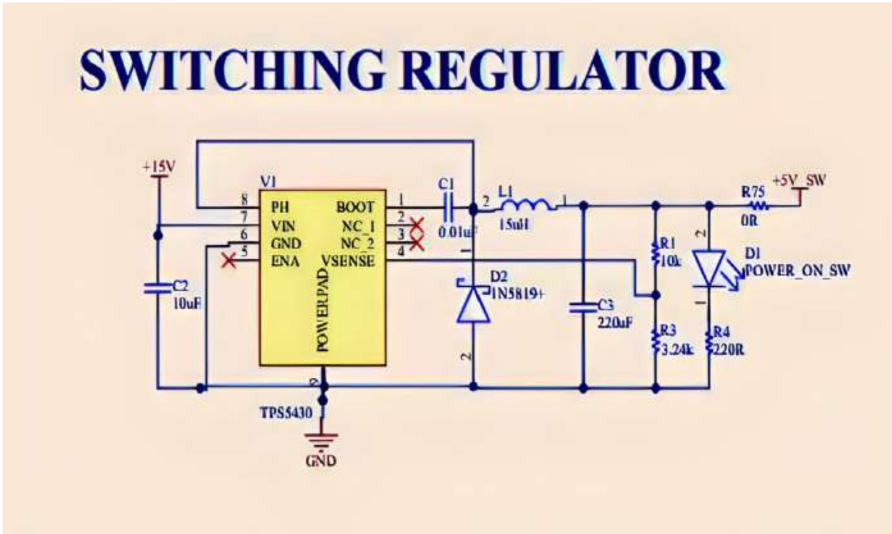


Figure 17 Voltage regulator (see online version for colours)

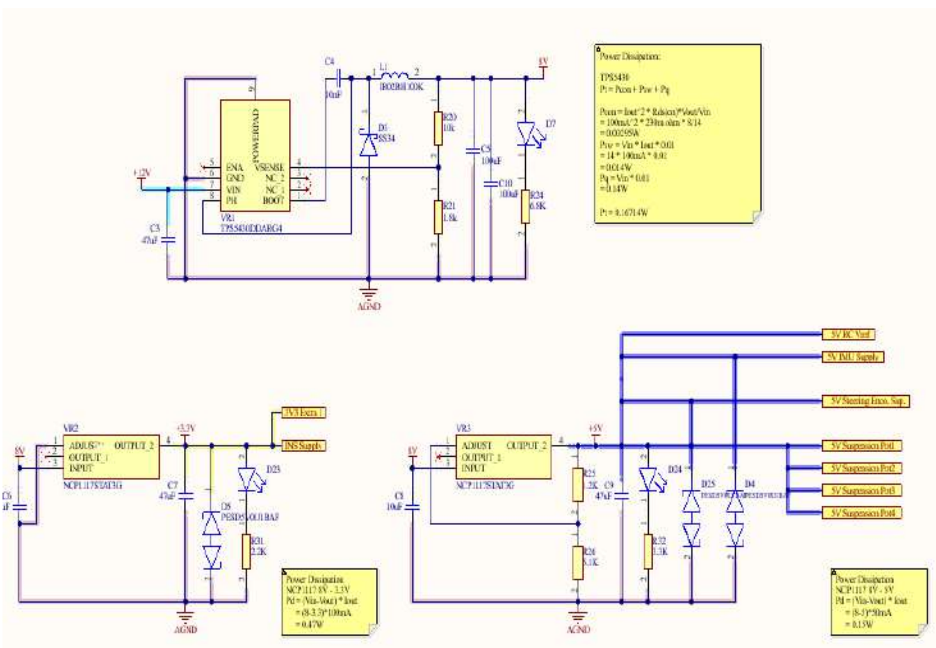


Figure 18 shows the unfused supply to different circuits via PDU.

Figure 18 12V unfused (see online version for colours)

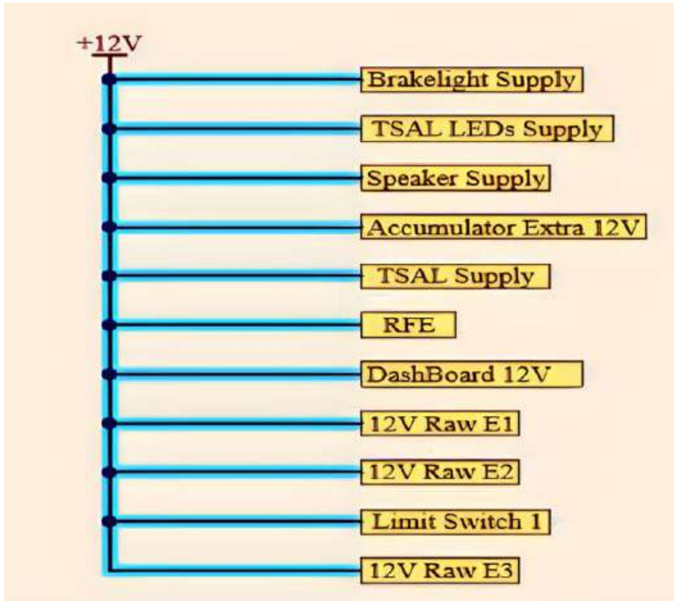
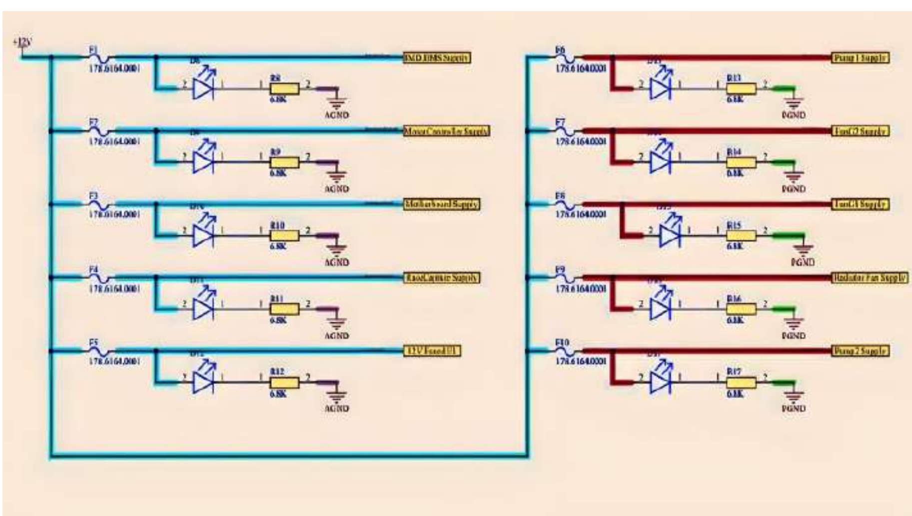


Figure 19 shows the fused supply to different circuits via PDU.

Figure 19 12V fused (see online version for colours)



STD35NF3LLT4 power MOSFET is used to supply fans and pumps.

Figure 20 Cooling supply and control (see online version for colours)

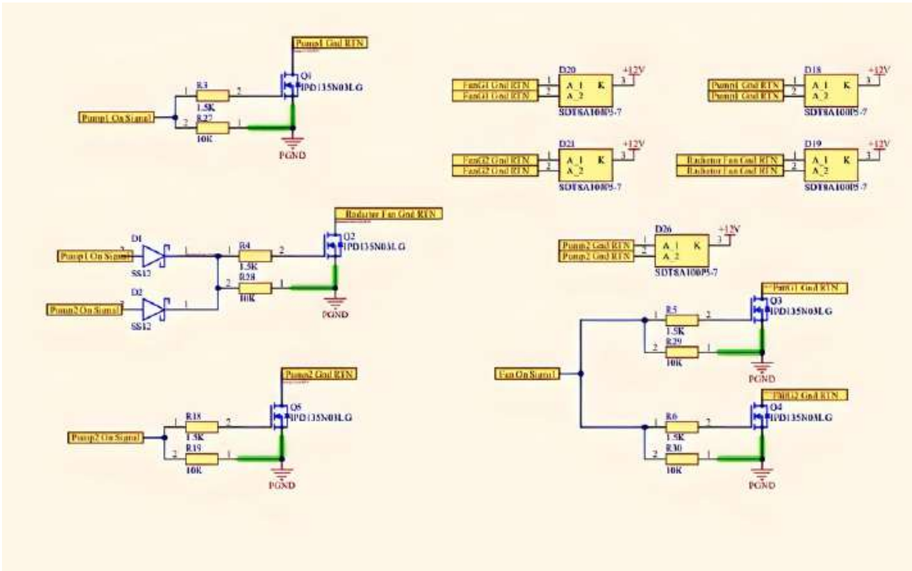
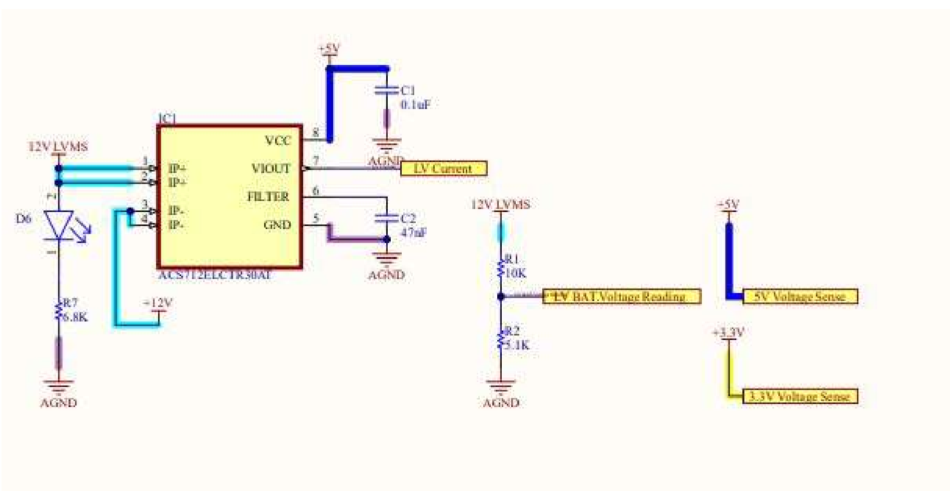


Figure 20 illustrates the cooling supply and control system, while Figure 21 displays the current and voltage sensing components. The ASC712 current sensing IC is employed to detect battery current, and a voltage divider is utilized to measure battery voltages.

Figure 21 Current and voltage sensing (see online version for colours)

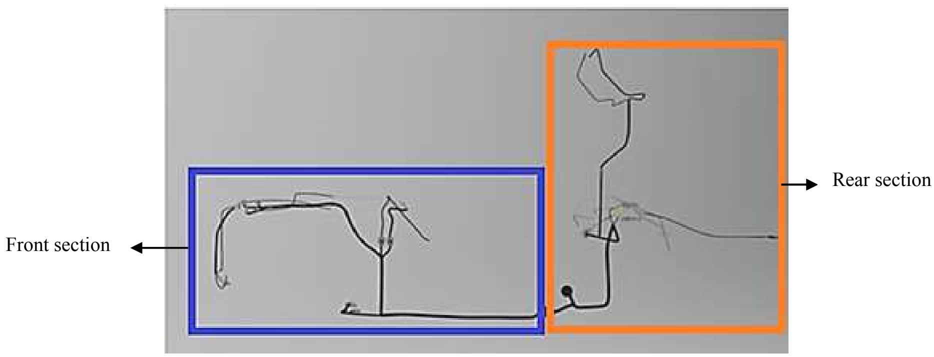


4.7 Harness

Figures 22 and 23 shows the harness CAD and 3D CAD model of the harness, respectively, in the vehicle.

- The routing of the harness is done using CatiaV5 and 3D Experience.
- Effective space management has been achieved by using computer-aided harnessing.
- All electrical equipment is placed considering higher serviceability and signal criticality.
- 0.35 mm^2 (22AWG) and 0.5 mm^2 (20AWG) wires are used in the Low Voltage system, rated for 1100 V and capable of carrying current up to 4 A and 8 A, respectively.
- Shielded and twisted pair cables carry signals from the sensors.
- The harness has been sorted using a colour-coding technique sorted according to sub-systems.

Figure 22 Harness CAD (see online version for colours)



5 Manufacturing and assembly of the system

The PCBs are designed to generate Gerber files and are used to manufacture the PCBs. A Bill of Material (BoM) is created, and the necessary components are procured accordingly. The assembly process is subsequently divided into two stages:

1 SMD components assembly process.

2 through hole components assembly process.

5.1 SMD components assembly process

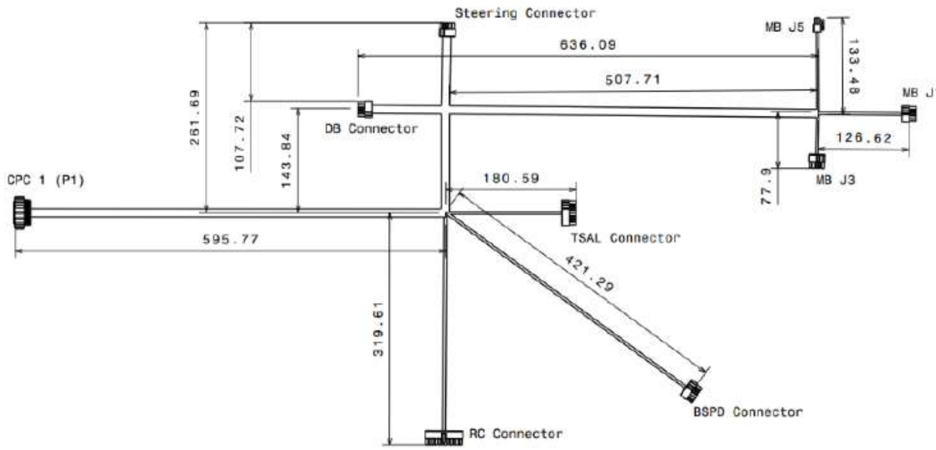
1 Solder paste application

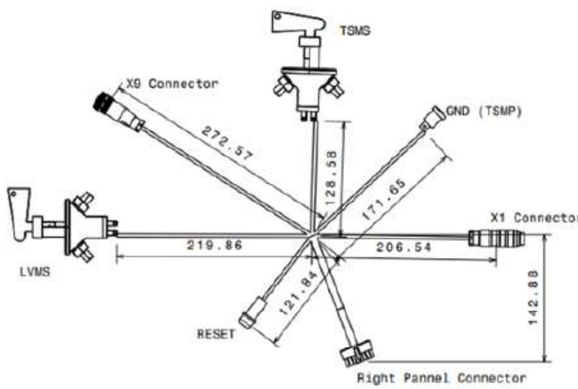
2 pick and place components

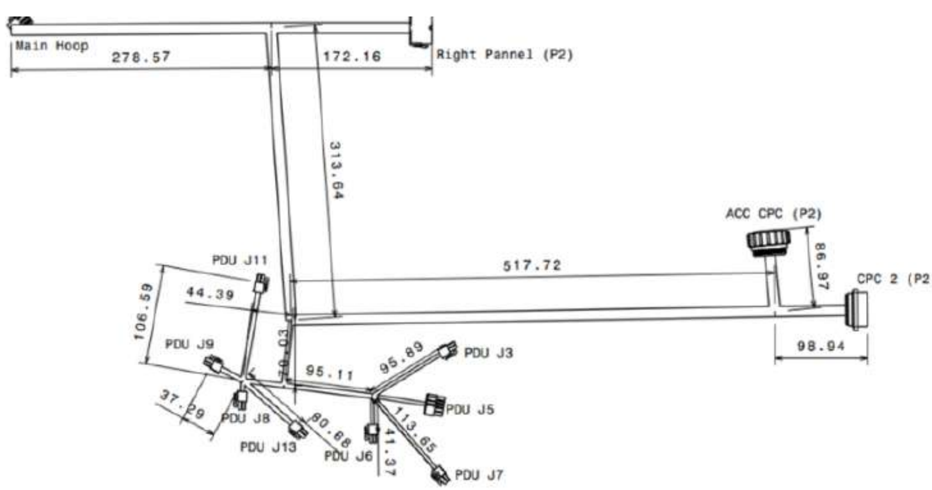
3 reflow soldering

4 inspection – manual checks.

Figure 23 2D harness schematic







5.2 *Through hole components assembly process*

1 Tining of legs of components
2 pick and place components
3 manual soldering
4 inspection – manual checks.

6 Results

Figure 24 shows the assembled board of Tractive System Active Light PCB, with 3 logic gates, 1 relay, and a TPS5430 voltage regulator.

Figure 24 Tractive system active light (see online version for colours)

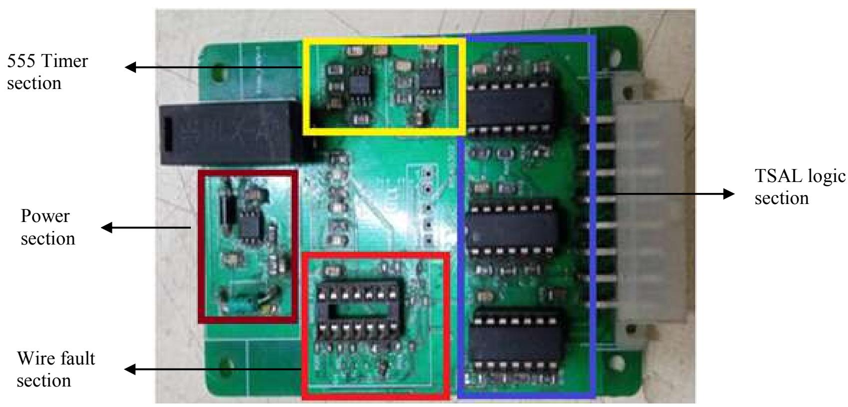


Figure 25 shows the assembled board of BSPD PCB on which there are 2 logic gates, 1 relay, TPS5430 voltage regulator, Op-amp, etc.

Figure 25 Brake pressure plausibility device (see online version for colours)

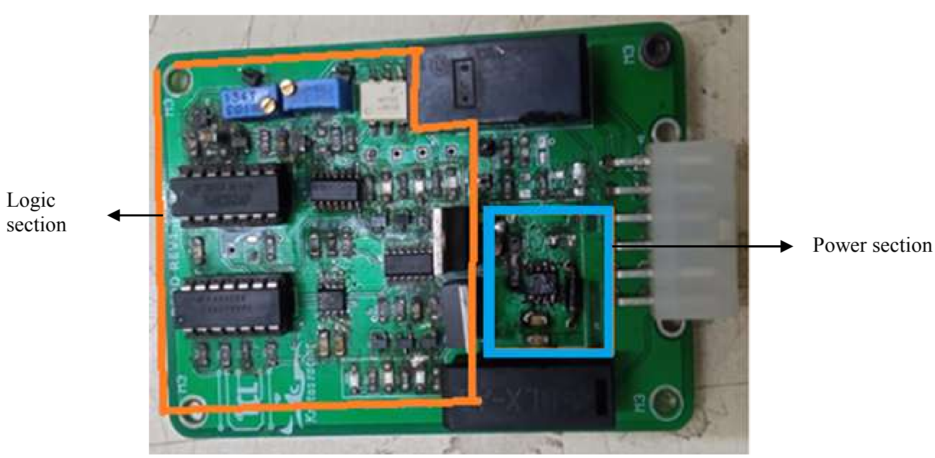


Figure 26 shows the assembled board of ECU 1 PCB on which there is an STM32 microcontroller, APPS control circuit, and RTDS.

Figure 26 ECU – 1 (see online version for colours)

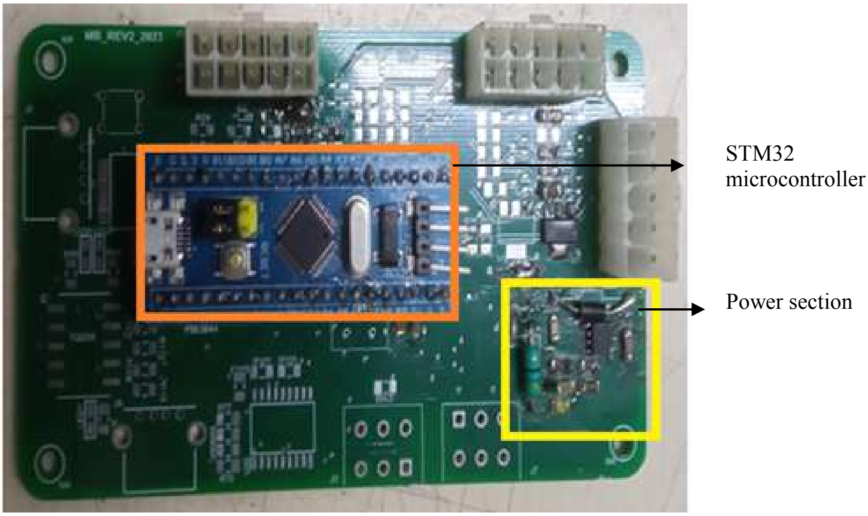


Figure 27 shows the assembled board of ECU 2 PCB on which the latching circuit is relays.

Figure 27 ECU – 2 (see online version for colours)

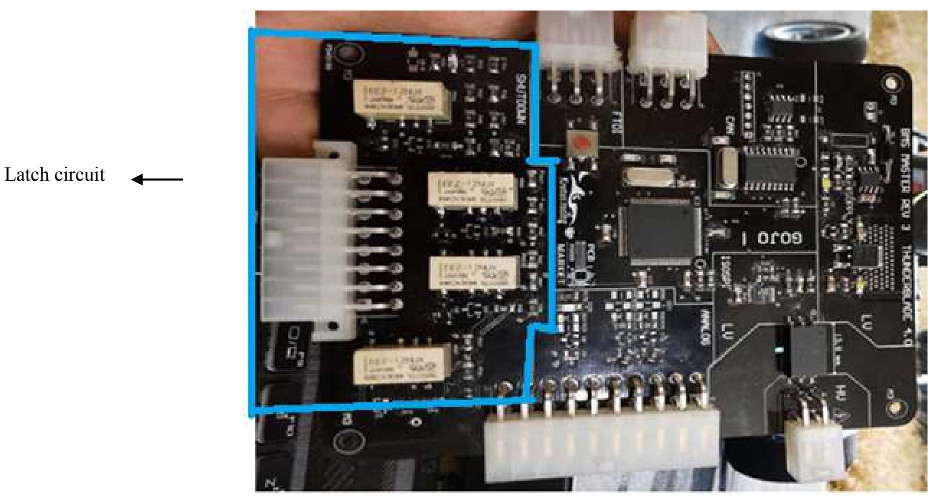
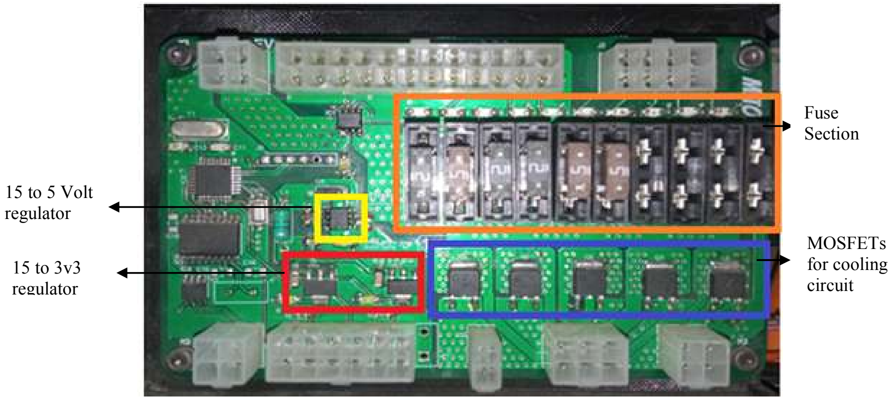


Figure 28 shows the assembled board of PDU PCB on which there are MOSFETs and blade fuse holders.

Figure 28 PDU (see online version for colours)



7 Testing

The testing phase in the statement is carried out to ensure a product's basic functionality and safety parameters. This phase can be crucial in ensuring the final product meets the required specifications, functions as intended, and is safe for use. The testing phase began with functional tests carried out on development boards. Development boards are used to test the functionality of electronic circuits before the PCBs are designed and manufactured. Before procuring the components, the development board tests helped ensure the electronic circuits' basic functionality.

After procuring the necessary components, the PCBs are designed and manufactured. PCBs, or Printed Circuit Boards, are the backbone of electronic devices and provide mechanical support, electrical connectivity, and signal routing. After the PCB manufacturing, the next step is to solder the components onto them.

The next step in the testing phase involved testing the functionality of the PCBs with the components soldered onto them. This step helps ensure the components are soldered correctly and the circuitry is functional. Additionally, safety parameters are checked to ensure the product meets safety standards and is safe for use.

In summary, the testing phase involved performing functional tests on development boards, manufacturing PCBs, soldering components onto them, and testing the PCBs for functionality and safety parameters. This process helps ensure that the final product meets the required specifications, is functional, and is safe for use. Tables 1–5 show the TSAL, BSPD, ECU-1, ECU-2 and PDU test cases.

Table 1 TSAL test cases

Test name	*Test description*	*Output*
Voltage regulator	12–5 V regulation	Output voltage ranges between 4.9–5.1 V
Circuit logic	Test input signals to every logic stage	Desired output from every logic stage
Wire fault check	Test input signals to every logic stage	Desired output from every logic stage

Table 2 BSPD test cases

Test name	*Test description*	*Output*
Voltage regulator	12–5 V regulation	Output voltage ranges between 4.9–5.1 V
Implausibility present	Relay open	Fault LED ON

Table 3 ECU – 1 test cases

Test name	*Test description*	*Output*
Voltage regulation	12–5 V regulation	Output voltage is 4.9–5.1 V
Voltage regulation	5–3.3 V	Constant voltage output of 3.3 V
ADC (Neamen, 2002)	Response of sensor output in ADC	ADC values visible for calibration
CAN communication	CAN communication with other devices	CAN messages transmitted and received

Table 4 ECU – 2 test cases

Test name	*Test description*	*Output*
Voltage regulation test (TPS5430)	12–5 V regulation	Regulated 5V at output of TPS5430
BMS Latching circuit test IMD Latching circuit test TS-ON Latching circuit test	Latching and reset functionalities of all latching circuits from a voltage range of 10.2–13.5 V	1. Conditional Shift between modes, and each mode is functional 2. Hardware latching circuits, shutdown logic functional

Table 5 PDU test cases

Test name	*Test description*	*Output*
Voltage regulation	Testing regulation of 12–8 V from TPS5430 Regulator	Regulated 8 V at the output of the Regulator
Voltage regulation	Testing regulation of 12–5 V of NCP1117 Linear Regulator	Regulated 5 V at the output of the Regulator
Voltage regulation	Testing regulation of 12–3.3 V of NCP1117 Linear Regulator	Regulated 3.3 V at the output of the Regulator
LV Current sensing	Getting the voltage value at the output of current sensor ACS712 and getting the current value from it	Getting the current value output of the sensor equal to the current value on DMM
Temperature rise	Checking the temperature rise of the MOSFETs, which control cooling fans and pumps	No high temperature in the case of MOSFETs
Supply lines	Checking voltage at each supply output after soldering the fuse holders	Getting the battery/Power Supply voltage at the connector

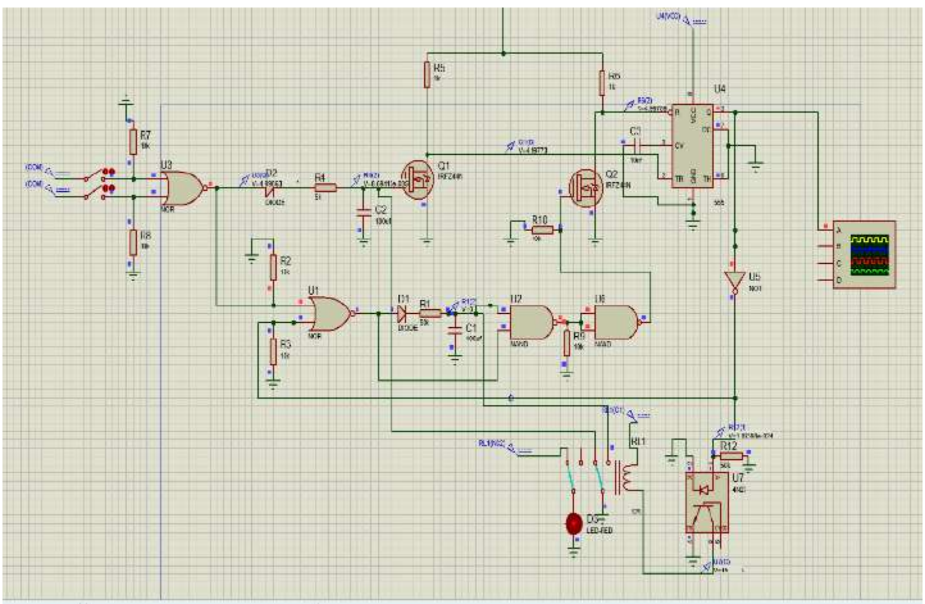
8 Experimental results

8.1 BSPD

The functionality of the BSPD circuit is achieved when the driver presses the throttle and brake simultaneously while driving. This triggered the fault state, and the vehicle shuts down if this condition persists for more than 500 ms.

Fault triggering is observed while the condition is present for the second time, as the RC circuit capacitor could not discharge. This issue is solved by adding a discharge path. Figure 29 shows the simulation of BSPD fault detection.

Figure 29 BSPD fault detected (see online version for colours)



Tables 6 and 7 provide an overview of the BSPD and TSAL fault results.

Table 6 BSPD fault results

Condition	*Expected result*	*Obtained result*
Implausibility present	Relay Open Fault LED ON	Relay Open Fault LED ON

8.2 TSAL

When there is an open wire on the high-voltage side, the LED will not glow. The functionality for the same is achieved. TSAL fault detection simulation is shown in Figure 30.

Figure 30 TSAL fault detected (see online version for colours)

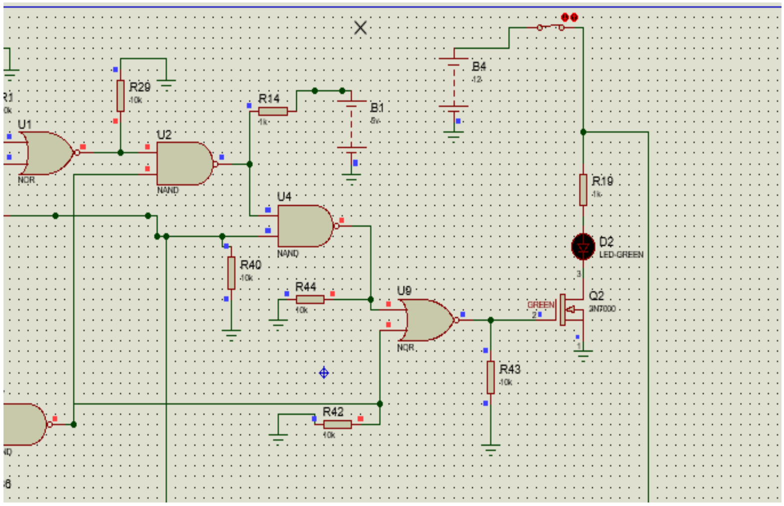


Table 7 TSAL fault results

Condition	*Expected result*	*Obtained result*
Open wire	LED is OFF	LED is OFF

8.3 PDU

The single-point ground method avoided any shift in ground voltage levels, resulting in no disturbance to reference voltage levels. Generation of voltage spikes higher than rated is observed across the supply. These spikes are usually generated by high inductive loads such as cooling pump motors and relay coils. This damaged the MOSFET as the voltage across the Drain and Source exceeded the rated voltage. Using metal oxide varistors on PDU helps eliminate any voltage spikes in the supply and clamp to a rated voltage.

Weight optimisation:

As per the weight analysis based on CAD designs, a total weight of 1.51 kg is calculated for the vehicle's harness. After actual implementation, the weight is observed to be 1.43 kg. This is achieved by selecting wire gauges rated for application current and lightweight connectors made from ABS material with high voltage isolation.

Table 8 Weight comparison

	Thunderblade 2.1's Season 2021–2022	*Thunderblade 4.0's Season 2022–2023*
Control system	7.27 kg	6.10 kg
Vehicles harness	2.879 kg	1.682 kg

Table 8 demonstrate a comparison between Thunderblade 2.1 and Thunderblade 4.0, showcasing a system's weight reduction from 7.2 kg to 6.1 kg by implementation of various measures. Firstly, wires of 0.35 mm^2 were selected instead of 5 mm^2 for signal lines. This helped to reduce the system's weight without compromising its functionality. Secondly, lightweight connectors were chosen based on factors such as the connector position in the vehicle, current and voltage rating. This enabled the system to maintain its connectivity while reducing its overall weight.

Additionally, 3D printing is utilised to create the circuit casing, which results in a lighter weight than traditional manufacturing methods. The wire count is also reduced, further reducing the system's weight. Lastly, a proper selection of components is implemented, which helps reduce the system's weight without compromising functionality or reliability.

Combining these measures made the system significantly lighter without sacrificing its performance, making it more efficient and easier to handle. The weight of the system is reduced from 7.27 kg to 6.10 kg.

Power optimisation:

Power optimisation is achieved considering the system's number of components and efficient power distribution. Table 9 shows the power distribution and optimisation of the system. The current system works additionally on INS (Inertial Navigation System), PDU and suspension travel potentiometer but still utilises 15% less power than the previous system, as shown in Table 9.

Table 9 Power distribution

	2022	*This work* (*2023*)	*2022*	*This work* (*2023*)
Components:	*Current* (A)		*Power* (W)	
Acc, Fans x10	5	7.2	75	100.8
Pump	6	4	90	60
Motor Controller	3.4	2.5	51	35
Race capture	0.9	0.9	13.5	13.5
BMS	0.6	0.3	9	4.2
IMD	0.15	0.15	2.1	2.1
TSAL (5v)	0.1	0.062	1.5	0.868
BSPD (5v)	0.15	0.07	2.25	0.98
Motherboard (5v)	0.25	0.06	3.75	0.84
TSAL LED	0.14	0.14	1.96	1.96
Brakelight	0.07	0.07	1.05	0.98
Buzzer (RTDS)	0.08	0.08	1.2	1.12
Dashboard Indicators(x4)	0.056	0.056	0.784	0.784
APPS(X2)	0.002	0.002	0.03	0.028
Brake Sensor(x2)	0.04	0.04	0.56	0.56
Current Sensor(x2)	0.04	0.04	0.2	0.2
AIRs (x2)	0.92	0.26	13.8	3.64
Discharge Relay	0.25	0.46	3.75	6.44
Precharge Relay	0.25	0.46	3.75	6.44
INS	–	0.08	–	0.4
Total	18.398	16.85	275.184	240.44

9 Conclusion

The designed control system utilises 15% less power than the previous system and achieves a 19% reduction in the overall weight. The central focus of this work is to create a reliable, efficient control system that complies with the rules. The ineffective harnessing method is one of the issues contributing to the lack of reliability. Additionally, the new design will consider the manufacturer's suggestions. Thus, no issues should be anticipated, though testing will still be done. The TSAL Safety Circuit will be evaluated using an earlier version that includes all new components. Additionally, the Control System's components and electric powertrain systems will be sized to produce 80 kW of power. Last but not least, recording all the work done this season regarding the control system, defending the judgements made at each point and outlining prior failures will help prevent future team members from making the same mistakes.

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