ECSE Capstone Project Proposal

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Contents

Glossary of Terms

- **ADC**: Analog-to-Digital Converter
- **CRUD**: Create, Read, Update, Delete
- **ECU**: EVolocity Control Unit
- **LED**: Light Emitting Diode
- **MCU**: Micro Controller Unit
- **MVP**: Minimum Viable Product
- **PCB**: Printed Circuit Board
- **PoC**: Proof of Concept
- **RPi**: Raspberry Pi
- **SMD**: Surface Mount Device
- **SMT**: Surface Mount Technology
- **SMPS**: Switch Mode Power Supply

Introduction

This project addresses an operational challenge faced by EVolocity, an organization that hosts competitions for primary, intermediate, and high school students to design and race electric vehicles. Currently, EVolocity officials spend a lot of time manually collecting performance data from each vehicle's control unit, creating delays in race-day operations.

Our solution implements a comprehensive wireless data collection system that integrates hardware, firmware, and software components. The hardware team is developing a custom PCB with voltage and current sensing capabilities along with wireless transmission functionality. The firmware team is creating resilient data acquisition, storage, and transmission protocols to ensure reliable measurements even in the challenging race environment. Lastly, the software team is building a relational database with an intuitive web interface that allows officials to efficiently manage competitions, teams, and real-time performance metrics.

By eliminating manual data collection, this system will reduce operational overhead, improve data accuracy, and enhance the overall competition experience.

Problem Statement

At EVolocity competitions, race officials retrieve data from the ECU of each vehicle manually by connecting to each one via USB-C. The current implementation is time consuming and inefficient, particularly in fast-paced environments where quick data access is critical. End users, including race officials and event organisers, rely on this data to validate results and ensure fair competition. A wireless system to collect ECU data is needed to streamline this process and improve overall event efficiency.

Proposed Solution

Our solution will provide a wireless data collection system to retrieve, store, and display ECU data. The overall system architecture is shown in Figure 1.

The hardware consists of a custom-designed PCB that works together with an embedded RPi Pico W microcontroller to transmit and validate data to enable scoring, event tracking, and race management. The firmware, running on the RPi Pico W, handles wireless transmission of data between the ECU and the backend server ensuring the data is reliably validated and timestamped. The software includes a backend server and a web-based interface that enables race officials to view scoring, monitor energy efficiency and manage competition data.

Compared to the current manual method, our system reduces data retrieval time and improves operational efficiency. Key advantages include access to race metrics, and a streamlined user-friendly dashboard tailored to race-day workflows.

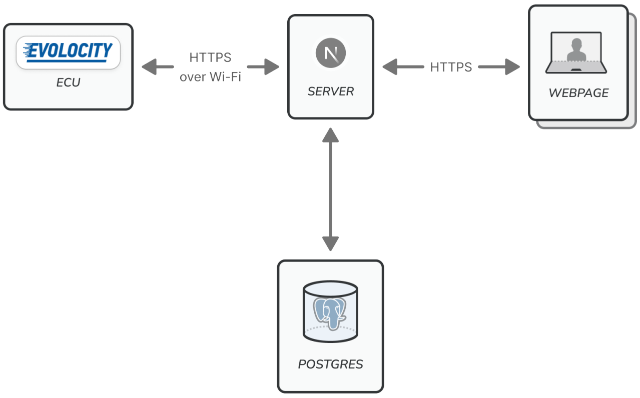


Figure 1: Basic high-level system architecture diagram.

MVP Scope & Features

Hardware

Objectives

- Develop an energy monitor with voltage and current sensing capabilities for the race vehicle.
- Demonstrate the core functionality of the system through a simplified PoC.

Must Have

- Voltage & current sensors.
  - Accuracy: ±1% without calibration per unit.
  - Precision: ±5% when taken as an average per batch.
- Power regulation (12V to 5V and 3V conversion).
- Wireless transceiver (for ECU data transmission).
- Basic power indicator LEDs.

Could Have

- Debug/Status LEDs to show system status.
- Custom buck converter instead of using linear regulator to improve power efficiency.
- Buffer (voltage follower) for the voltage sensing circuit.
- Reverse polarity protection and TVS diodes or zener diodes on input and outputs for ESD and over-voltage protection.
- Better schematic layout to:
  - Avoid current loops (causes magnetic fields to be induced, resulting in more noise).
  - Avoid long ground traces and make 5V regulator to sink paths more straight/direct.

Would Have

- Higher quality operational amplifier (e.g. LT6221 – $14.70/unit) - better signal conditioning.

Firmware

Objectives

- Collect ECU data from sensors and transmit it wirelessly using the RPi Pico W.
- Ensure accurate data collection, robust transmission, and secure temporary storage.

Must Have

- State machine, all tasks done sequentially with no concurrency.
  - Avoid Wi-Fi uploading whilst sampling from ADC to improve accuracy.
- ADC sampling for voltage & current readings.
  - ±1% system accuracy (from the hardware to the GUI).
- Wireless data transmission.
  - Minimum range: 10 meters. Automatic retries until the connection succeeds.

    - Less than 5 minutes to transfer 1 hour of data
- Sampling interval: minimum of once every 5 seconds.
- Ensure data is properly received and transmitted.

Should Have

- Wear-leveling for flash memory, or a better alternative would be support for SD card storage to extend logging capacity.
    - Spread out writes across all parts of the NAND chip to prolong overall lifespan of the ROM.
    - Better data handling in the event of power loss (e.g. better resilience against corruption compared to onboard flash).
- Use efficient formats like Protocol Buffers instead of JSON.

Could Have

- Integrate alternative modules to account for the shortcomings of RPi Pico W.
    - e.g. ESP32 to improve wireless range and speed.
    - Dedicated ADC peripheral or another microcontroller with a more accurate ADC, e.g. ATmega328P/ATmega328PB.

Software

Objectives

- Provide a user-friendly interface for managing and visualising ECU data, teams, events, and race results.
- Enable wireless data retrieval from ECUs.
- Allow offline data storage on competition day, with later syncing to an online database when the user has internet access.

Must Have

- **User Interface**
    - Simple and functional design (internal tooling, not a public-facing site).
    - Mobile-friendly views for all pages.
    - Competitions Page. (CRUD operations for competitions).
        * Each competition has three events by default.
        * Teams can be assigned to any number of events.
    - Events and Event Types Page. (CRUD operations for events & event types).
    - Scoreboard.
    - Teams Page. (CRUD operationsfor teams).
    - Energy Monitors Page.
        * Display ECU properties (timestamp, temperature, average voltage, average current, energy).
        * Energy graphs.
    - ECU configuration & multi-race support.
- **Backend**

  - Local area network (LAN) connection to ECUs.
  - API endpoints for ECU data uploads.
  - Automatic team scoring.
- **Integration**
  - Frontend-backend integration using Next.js (Server Actions as middleware).
  - Warnings for corrupt or conflicting data.
  - Time and data synchronisation with ECUs.

Should Have

- CRUD operations for wheel configurations.
- TLS encryption for API endpoints.

Could Have

- Real-time viewing using a real-time database (e.g. Supabase).
- Battery status monitoring from the interface.
- User authorisation for using the tool (auth system).

Project Plan

This section outlines our project strategy, including deliverables, milestones indicated by Figure 2. Our approach ensures efficient resource allocation and clear responsibility assignments to meet the project requirements within the given timeframe.

Implementation Timeline

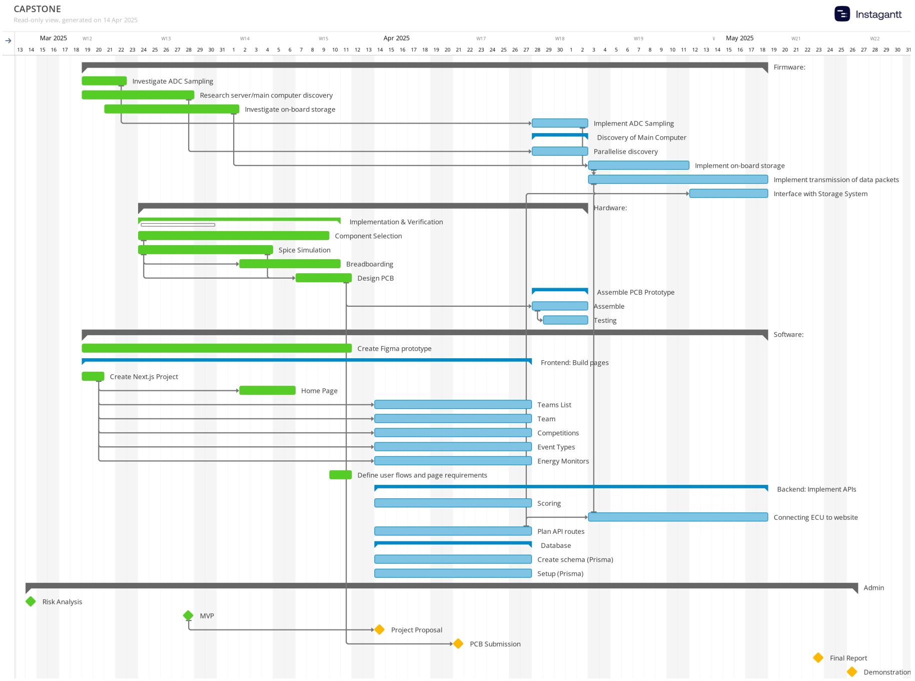


Figure 2: Project timeline Gantt chart showing key milestones, task dependencies, and estimated completion dates. For a more detailed breakdown of the tasks and deliverables, please refer to Appendix A and Appendix B.

Technical Design

System Overview

The system integrates custom hardware (PCB with RPi Pico W), firmware for data handling, and web-based software to enable wireless collection and display of ECU data. The components work together to provide reliable data transmission, storage, and visualization for race officials as indicated in Figure 3.

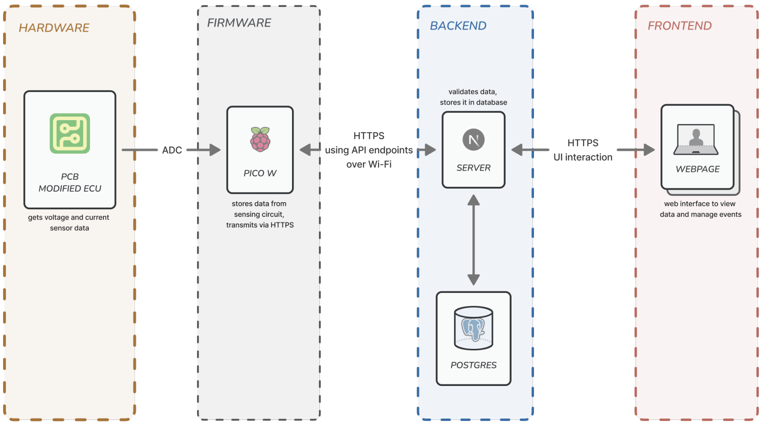

HARDWARE
PCB
MODIFIED ECU
gets voltage and current sensor data
ADC
FIRMWARE
PICO W
stores data from sensing circuit, transmits via HTTPS
HTTPS
using API endpoints
over Wi-Fi
BACKEND
validates data, stores it in database
SERVER
POSTGRES
HTTPS
UI interaction
FRONTEND
WEBPAGE
web interface to view data and manage events

Figure 3: Detailed system architecture diagram showing the interaction between hardware, firmware, and software components.

Hardware

Tools & Technologies

- Simulation: LTspice
- PCB Design: Altium Designer

Component Selection

Linear Regulator (L78L05): Converts 12V to 5V for the RPi Pico W, which requires 1.8-5.5V input. The 5V feeds into the Pico's built-in SMPS, which generates 3.3V for the RP2040 microcontroller. Originally planned to use LD1117 due to local availability, but switched to L78L05 due to Altium library constraints.

ADC Reference: Implemented with a voltage divider by using resistors in parallel providing a stable 3V reference. This reduces electrical noise from the RPi's built-in SMPS, which can generate interference due to magnetic and switching characteristics. This approach was more cost-effective than using high-capacitance electrolytic capacitors.

Power LED: Provides essential visual feedback that confirms the PCB is receiving power and operating correctly. This visual feedback is particularly important during races when no testing equipment is available on the track.

Microcontroller: RPi Pico W selected for its wireless communication capabilities. Power is supplied through either V_{bus} (USB port) or V_{sys} (external power) pins. When using both power sources simultaneously, Schottky diodes are arranged in an 'OR'ing configuration to allow seamless power switching when programming.

Bill of Materials

Table 1 below shows the prices from PCBWay [8], DigiKey [2] [3] [5] [6] [7] [9] [10] [11] [12] and Element14 [4] for the components used when ordered in bulk to manufacture 50 ECUs.

Table 1: Bill of Materials (BOM) for the ECU hardware components.

Item No.	Component	Part Number	Qty	Unit Cost
1	Op-Amp	LM324DR2G	1	$0.64
2	Shunt Resistor	ER74R10KT	2	$1.80
3	Linear Regulator	L78L05	1	$1.37
4	Schottky Diode	SP304	1	$0.95
5	LED	LTST-C191KRKT	1	$0.20
6	RPi Pico W	SC0918	1	$11.59
7	Test points	5003	5	$0.26
8	Electrolytic Capacitors	TH	1	$0.26
9	Ceramic Capacitors	0805 SMT	5	$0.02
10	Resistors	0805 SMT	11	$0.06
11	PCB	-	1	$5.00
			Total	$25.65

Circuit Schematic

Current sensing uses a 3W-rated 0.1Ω shunt resistor to handle the peak motor current of 3A, as standard 100mW SMT resistors would be insufficient. Voltage sensing uses two resistors (10kΩ and 1.5kΩ) in series, with values chosen in the kΩ range to minimize power dissipation while staying below 100kΩ to reduce thermal noise and environmental sensitivity. Figure 4 displays both the current and voltage sensor schematic. An overall schematic of the whole monitor can also be viewed in Appendix C and D.

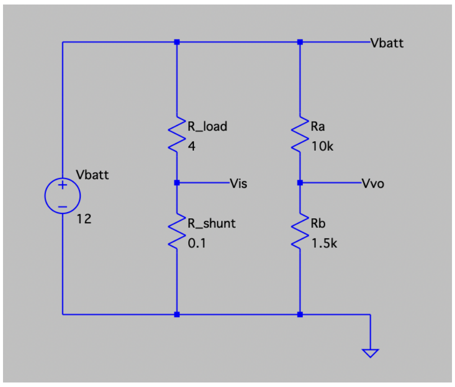


Figure 4: LTSpice circuit schematic showing the voltage and current sensing circuitry.

Decoupling capacitors are placed near to power sinks to resist against poor wire connections and extend the duration before brownout occurs, allowing more time for the RPi to react.

PCB Layout

Our initial PCB layout shown in Figure 5 was designed to seperate high-power, high-frequency (right side), and low-power signal processing components (left side) to reduce noise and interference. As the first prototype, it was also designed to be easy to solder and have good heat disappation characteristics. Optimization of the PCB for cost in a future revision, as the current design is not cost-effective for mass production. The high power connections, such as the input, output, shunt resistors and regulator are placed close to each other and connected via power planes to reduce resistance and noise generation. By using a 5V and Ground plane, we could take advantage of a little inter-plane capacitance.

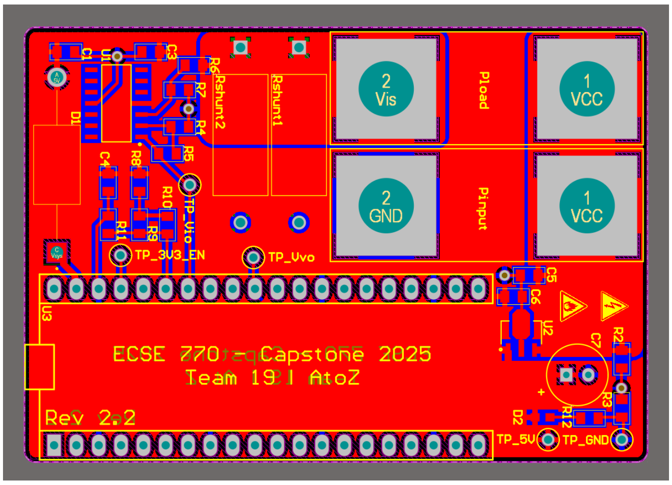


Figure 5: Altium Designer screenshot shoting Top Layer of PCB layout.

Firmware

Tools & Technologies

- Programming Language: C/C++
- Wi-Fi for connecting to the database since long uninterrupted range.
- Hardware dependencies: RPi Pico Integration with PCB and electrical components for sampling.

We selected C/C++ for optimized performance and direct hardware control, enabling faster server discovery and maximizing flash storage for offline data collection. This allows complete event operation even without main server connectivity.

Our firmware architecture (Figure 6) separates ADC sampling from wireless transmission to prevent power fluctuations that would affect measurement accuracy, especially important due to the RP2040's documented non-linear ADC behavior (errata RP2040-E11 [1]). We implement a microcontroller-specific calibration curve to compensate for this non-linearity.

Data management uses a chunked storage approach that optimizes both memory usage and network efficiency. Key features include:

- Round-robin transmission scheduling to prevent server overload
- JSON for ease of implementation with CRC32 checksums for data integrity verification
- Brownout detection to prevent data corruption during power failure

Data Storage Plan

Our firmware implements an efficient, resilient data management strategy:

- Configuration Persistence: Stores last connected server IP address for immediate reconnection on startup.
- Device Identification: Generates and maintains a unique identifier for each Pico device.
- Session Management: Creates a new "run" ID on each power cycle for organized data collection.

- Measurement Store: Records key measurements with timestamps in reasonable chunks.
- Optimized Transfer: Implements batch uploading to preserve limited RAM while ensuring data integrity.

Firmware System Diagram

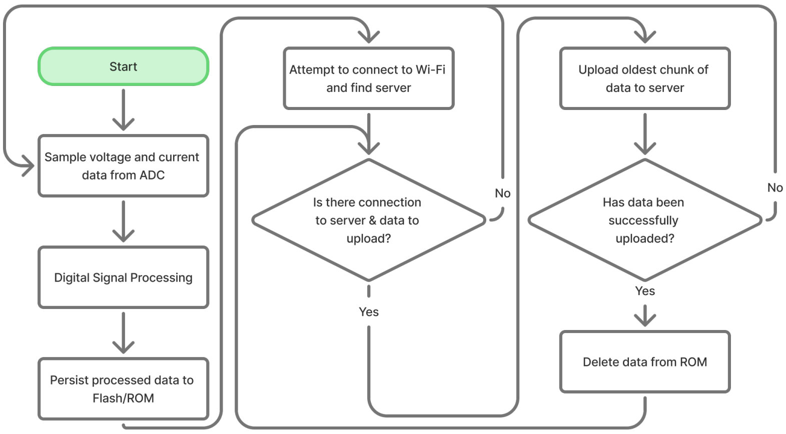

Start
Sample voltage and current data from ADC
Digital Signal Processing
Persist processed data to Flash/ROM
Attempt to connect to Wi-Fi and find server
Is there connection to server & data to upload?
No
Yes
Upload oldest chunk of data to server
Has data been successfully uploaded?
No
Yes
Delete data from ROM

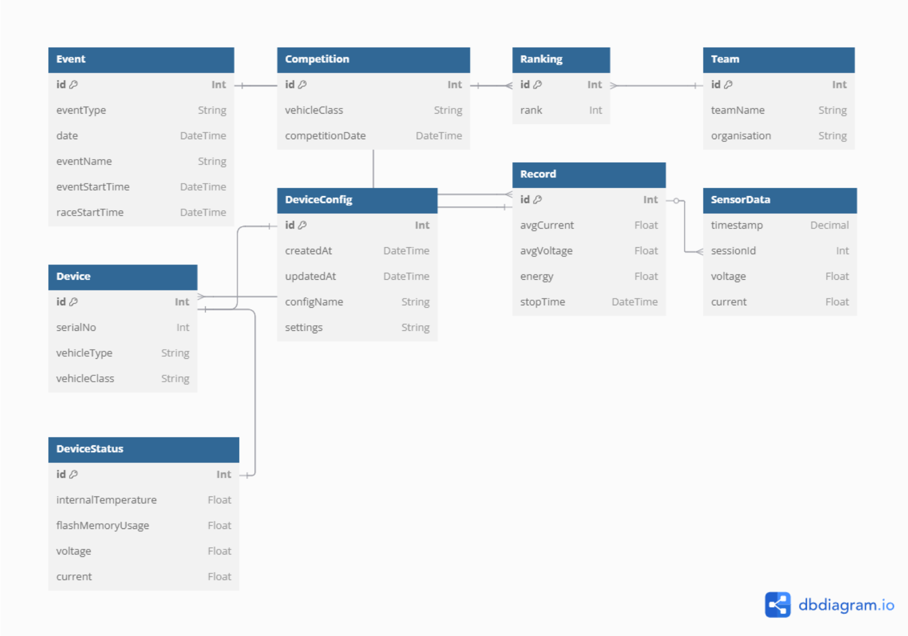
Figure 6: Firmware system architecture showing flow and key components.

Software

Tools & Technologies

- Frontend: Next.js + Tailwind
- Component Library: ShadCN
- Backend: Next.js + Prisma
- Database: PostgreSQL, Prisma builtin adapter available (Figure 7).

Database Schema



Event	
id	Int
eventType	String
date	DateTime
eventName	String
eventStartTime	DateTime
raceStartTime	DateTime

Competition	
id	Int
vehicleClass	String
competitionDate	DateTime

Ranking	
id	Int
rank	Int

Team	
id	Int
teamName	String
organisation	String

DeviceConfig	
id	Int
createdAt	DateTime
updatedAt	DateTime
configName	String
settings	String

Record	
id	Int
avgCurrent	Float
avgVoltage	Float
energy	Float
stopTime	DateTime

SensorData	
timestamp	Decimal
sessionId	Int
voltage	Float
current	Float

Device	
id	Int
serialNo	Int
vehicleType	String
vehicleClass	String

DeviceStatus	
id	Int
internalTemperature	Float
flashMemoryUsage	Float
voltage	Float
current	Float

Figure 7: Database schema showing relationships between competitions, teams, events, and ECU data.

User Workflow

The system implements an intuitive, step-by-step workflow that guides race officials through the process of creating competitions, registering teams, and collecting data (Figure 8).

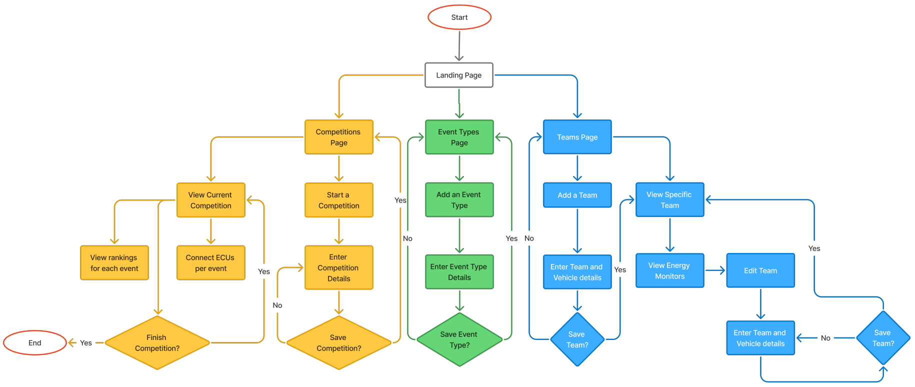
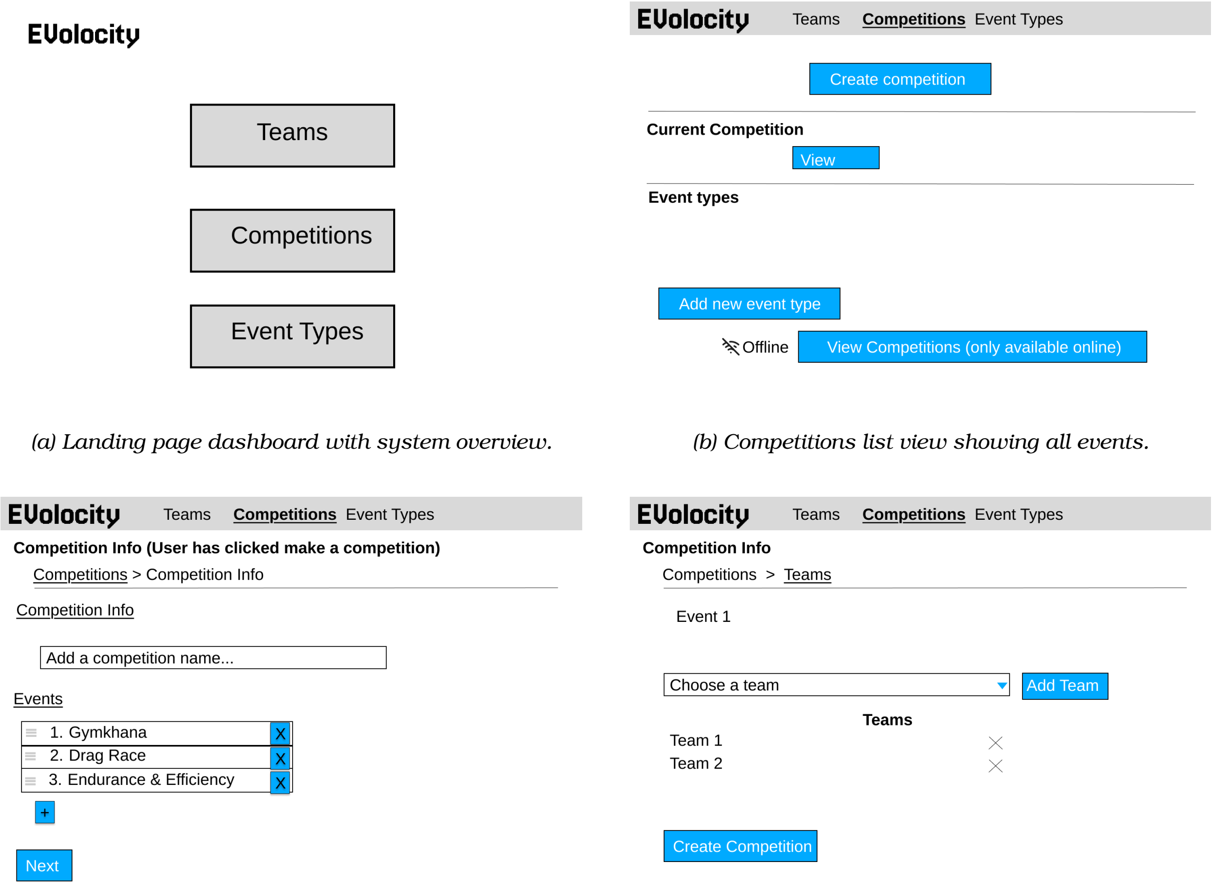


Figure 8: User workflow showing the process of registering a team, creating a competition, and uploading data.

UI/UX Design

Our user interface is designed for simplicity and efficiency, with intuitive navigation and clear information presentation as seen in Figure 9 and Figure 10.



(a) Landing page dashboard with system overview.

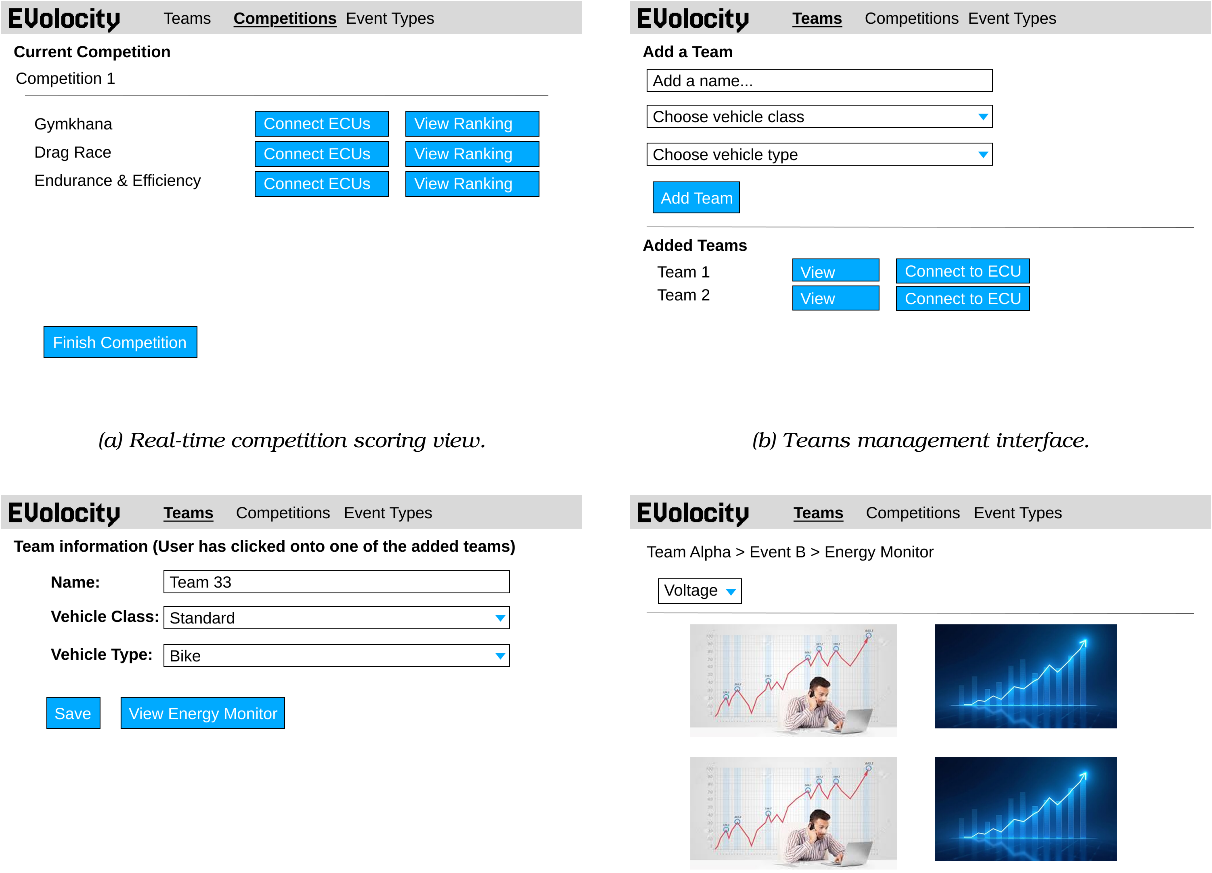
(b) Competitions list view showing all events.

EVolocity
Teams
Competitions
Event Types
Competition Info (User has clicked make a competition)
Competitions > Competition Info
Competition Info
Add a competition name...
Events
1. Gymkhana
X
2. Drag Race
X
3. Endurance & Efficiency
X
+
Next

(c) Competition details with team assignments.

(d) Event configuration with scoring parameters.

Figure 9: Web interface showing competition management features with clean, functional design.



Name: Team 33

Vehicle Class: Standard

Vehicle Type: Bike

(a) Real-time competition scoring view.

(b) Teams management interface.

(c) Team detail view with member information.

(d) Energy monitoring dashboard for a team.

Figure 10: Team management and energy monitoring interfaces.

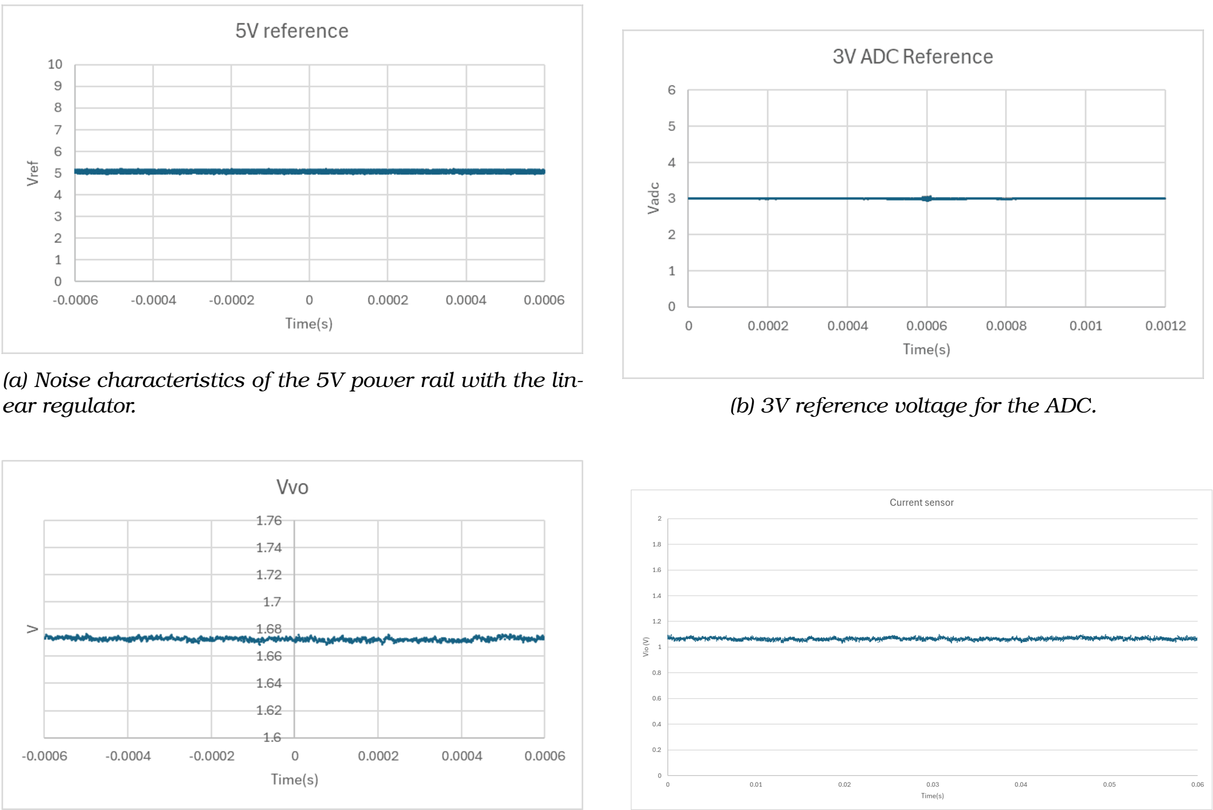
Initial Testing Plan

The testing plan will be divided into three main phases: hardware, firmware, and software testing.

For simulation, LTSpice will be used for simulating the expected values and LD1117 regulator was used in testing to provide a stable stepped down 5V DC voltage to the system. From our testing results in Figure 11, we can see that this regulator has some noise, to mitigate this we have used smoothing capacitors to reduce the noise. A small decoupling capacitor in uF range could be used to further reduce the noise.

From testing (Figure 11), we can see that we have successfully implemented a stable 3V ADC reference with minimal noise which may be used as an alternative to the internal reference voltage generated by the SMPS onboard the RPi.

As for our sensing circuitry, the LM324 opamp was used to minimise the costs whilst still providing good functionality. However, this comes at the cost of added noise to the output of the opamp which we can clearly observe in the test results. The characteristics of the opamp such as a relatively high input offset voltage (5 mV), and input bias current (40 uA) all contribute to noise. In addition, Johnson noise is introduced by the resistors in the amplifier. The combined thermal noise from R1 to R4 can add noise to the output. In practical testing, Vvo was higher than the simulated output. This is mainly due to the shunt resistor tolerance differences. Ideally, we want a 0.1 Ω shunt resistor, but practically this is closer to 0.3 Ω. The increased shunt resistance caused an increase in Vvo.



(a) Noise characteristics of the 5V power rail with the linear regulator.

(b) 3V reference voltage for the ADC.

(c) Voltage as probed at the Vvo pin.

(d) Noise characteristics of the current sensing circuit.

Figure 11: Oscilloscope measurements of various circuit components.

Conclusion

Our wireless data collection system directly addresses EVolocity's need for efficient performance data retrieval from competition vehicles. The proposed solution integrates:

- An affordable custom PCB with precise voltage and current sensing circuitry, validated through comprehensive testing
- Firmware optimized for reliable data collection, storage, and transmission in race conditions
- A user-friendly web interface enabling officials to manage competitions and analyze performance metrics

Through extensive collaboration between hardware, firmware, and software teams, we've developed an affordable and technically viable solution that can be implemented within the specified timeline. By eliminating manual data collection processes, this system will enhance the competition experience for both organizers and participants by providing real-time access to critical performance data while reducing operational overhead.

References

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Appendices

Appendix A: Deliverables and Milestones

Table 2: Project milestones and deliverables with their due dates and current status.

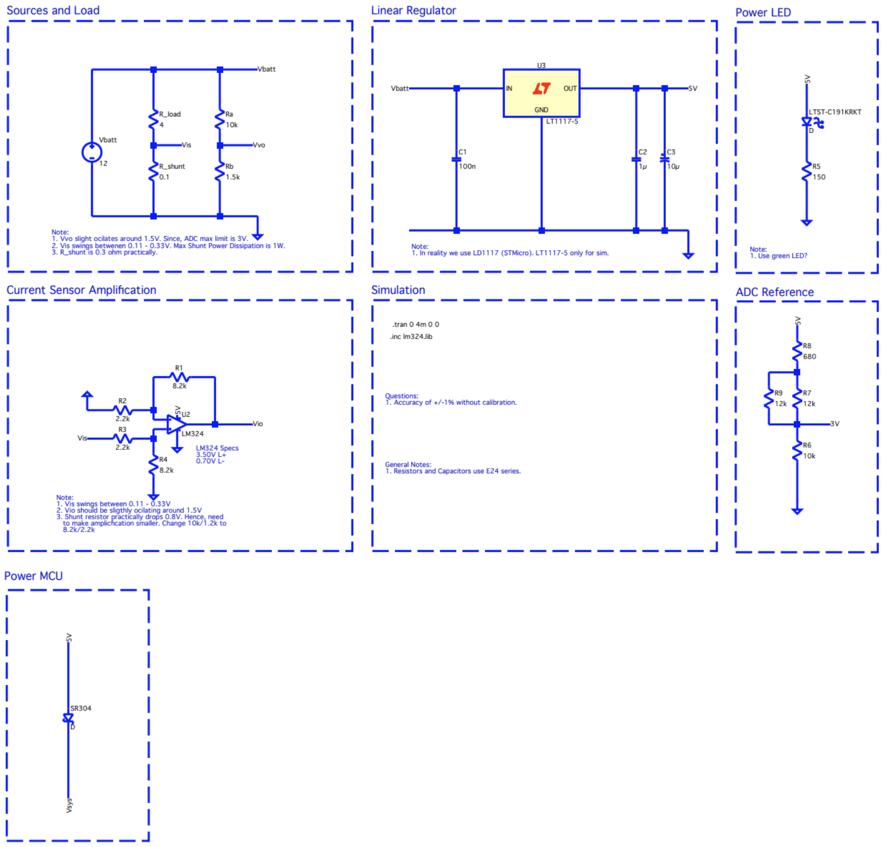
Item	Due Date	Status
Risk Analaysis	14th March 2025	Submitted
PCB Submission	11th April 2025	Submitted
Project Proposal	14th April 2025	Done
Final Report	23rd May 2025	Upcoming
Demonstration	26th May 2025	Upcoming

Appendix B: Task Breakdown

Table 3: Breakdown of project tasks and responsibilities assigned to team members by discipline.

Discipline	Task	Assigned To
Hardware	Implementation & verification	V
Hardware	PCB design	A & T
Hardware	Soldering & assembly	A
Hardware	Testing & prototyping	J
Hardware	Demo with RPi Pico W	A & J & V
Firmware	ADC implementation & sampling	S
Firmware	Data validation & error checking	S & T
Firmware	Flash memory storage & implementation	T
Firmware	Wi-Fi connection	P & T
Firmware	HTTP(S) data transmission	P
Firmware	Ensure successful data transfer	P
Software	Backend - Database & Schema	Z
Software	Backend - Server & API setup	J
Software	Frontend - Teams & Energy Monitor pages	C
Software	Frontend - Competitions & Events pages	C

Appendix C: LTSpice Schematic



Note:
1. Vvo slight ocilates around 1.5V. Since, ADC max limit is 3V.
2. Vis swings betwenen 0.11 - 0.33V. Max Shunt Power Dissipation is 1W.
3. R_shunt is 0.3 ohm practically.

Note:
1. In reality we use LD1117 (STMicro). LT1117-5 only for sim.

Note:
1. Use green LED?

Note:
1. Vis swings between 0.11 - 0.33V
2. Vio should be sligthly ocilating around 1.5V
3. Shunt resistor practically drops 0.8V. Hence, need to make amplicfication smaller. Change 10k/1.2k to 8.2k/2.2k

Questions:
1. Accuracy of +/-1% without calibration.

General Notes:
1. Resistors and Capacitors use E24 series.

Figure 12: LTSpice schematic of the circuit.

Appendix D: Altium Schematic

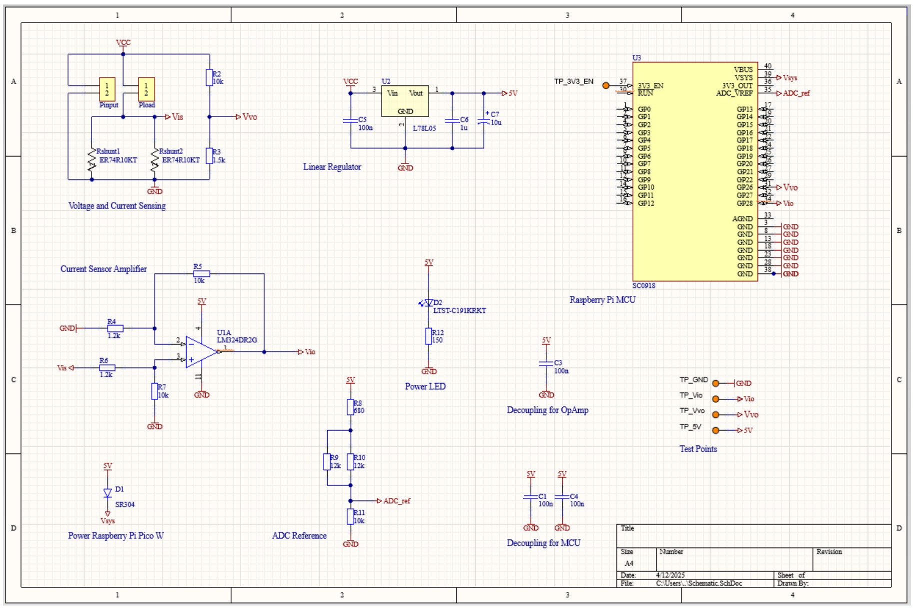


Figure 13: Altium schematic of the circuit.

Appendix E: PCB Bottom Layout

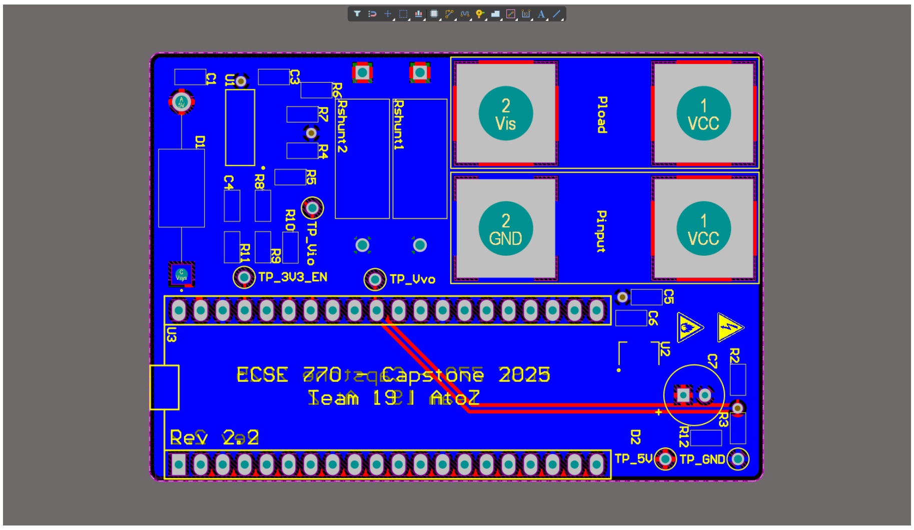


Figure 14: Bottom layer of PCB layout of the circuit.

Appendix F: PCB Render

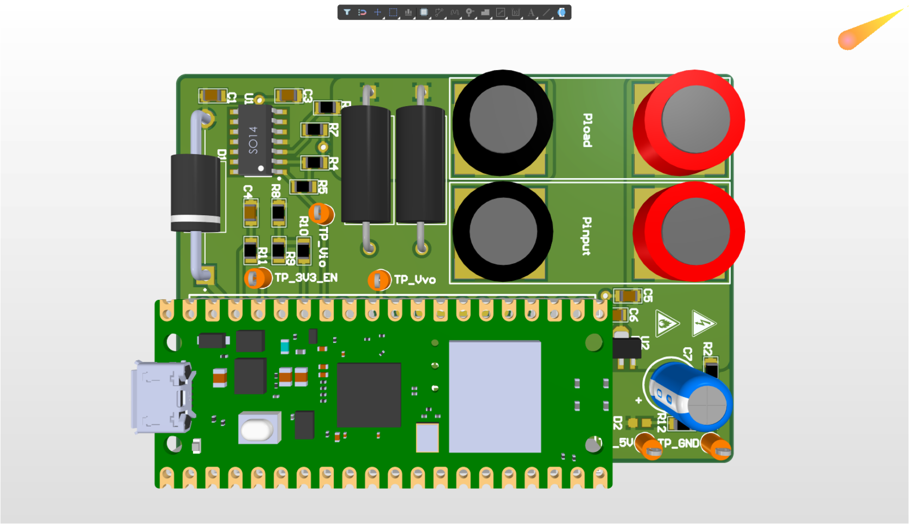


Figure 15: Altium 3D view of PCB layout of the circuit.