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Design of a Wireless-Controlled Mobile Robot for Geo-Tag Metal Detection

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Abstract: Hidden metallic hazards such as unexploded ordnance are typically located with handheld detectors, which expose operators to risk, provide limited coverage, and leave sparse digital records. High-end robotic and geophysical solutions exist but are expensive, complex, and often over-specified for small team use, while many low-cost builds lack mapping and cloud telemetry. This project proposes a low-cost, teleoperated metal-detection robot that fuses electromagnetic sensing, differential-drive mobility, and cloud Internet of Things. An ESP32-S3 governs an L298N motor driver and a servo-swept search coil repurposed from a handheld detector; a NEO-8 Global Positioning System module provides geolocation; Blynk Cloud supplies bidirectional control and visualization. A segmented 4-cell Li-ion power architecture with fixed-output buck converters isolates noisy and sensitive rails. Field trials demonstrated reliable teleoperation over Wi-Fi, coin detection at about 2 cm, larger targets at 6 cm, and roughly 480 min of run time. The results show an accessible, cloud-connected pathway to geotagged metal search that improves operator safety and recordkeeping using commodity hardware.

Keywords: Unmanned Ground Vehicle (UGV), robotic metal detection, automatic metal detection, geotagging

1. Introduction

Metal detection and removal of hazardous metallic objects, such as unexploded ordnance and landmines, is a critical challenge in civilian and military applications. Traditional handheld metal detectors require close human involvement, which can be a dangerous activity in high-risk contexts. Automation of this task, through, for example, mobile robotics, has emerged as a promising solution to improve safety and efficiency. According to international monitoring reports, more than 110 million landmines remain buried in 68 countries [1]. Beyond landmines, metal detection is important in applications like archeological exploration, infrastructure maintenance in locating buried pipes and cables, and security screening [2]. A mobile robot equipped with metal-detection capability can address these needs by (i) scanning terrains autonomously or via remote control, (ii) detecting metal objects, and (iii) pinpointing their locations without risking human lives.

The convergence of several technological advances has made such a robotic platform feasible. Improvements in *electromagnetic induction* (EMI) sensors enable the detection of metals by induced eddy currents and secondary magnetic fields [3]. Low-cost microcontrollers with wireless connectivity, such as the ESP32, and the *Internet of Things* (IoT) paradigm enable remote operation, data logging, and real-time alerts. Precise positioning systems, such as the *Global Positioning System* (GPS), and mapping software, including *Geographic Information System* (GIS)

and Google Maps, enable the spatial recording of detection events for visualization.

Effective development of a mobile metal-detecting robot requires understanding and integration of knowledge from multiple domains. Key domains include metal-detection technologies, existing robotic platforms for metal detection, methods for spatial data collection and mapping, IoT technologies for remote robot operation and data logging, power supply architectures for mobile robots, and rapid prototyping via 3D design and printing.

1.1. Metal detection

Metal detectors generally operate on the principle of EMI, where a time-varying magnetic field induced by a coil penetrates the ground and interacts with conductive objects [4]. The fundamental theory involves *Faraday's law* of induction and *Lenz's law* of EMI, such that eddy currents oppose the change in magnetic flux, effectively altering the impedance of the coil circuit [5]. EMI can also be explained using a *Colpitts oscillator circuit*, where the detection principle is based on the resonance of an LC circuit, whose frequency is given by:

$$F = \frac{1}{2 \cdot \pi \sqrt{L \cdot C}} \quad (1)$$

where L is the coil inductance and C is the tank capacitance. When a conductive or ferromagnetic object approaches, the inductance changes by ΔL (r , σ , μ), where r is the distance, σ is the object's electrical conductivity, and μ is its magnetic permeability. This produces a corresponding frequency shift ΔF , which is directly proportional to the relative change in inductance. In

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practice, the system uses a *Beat Frequency Oscillator* method, where a reference oscillator and the detection oscillator are mixed, converting small frequency shifts into audible tones or numeric values [6].

1.2. Robotic platforms for metal detection

Robotic platforms for metal detection vary widely in their locomotion configurations, each offering distinct advantages and limitations depending on the intended application and operating environment. Common configurations include wheel designs, tracked systems, or legged robots. Two-wheeled robots often employ a differential-drive mechanism, providing high maneuverability, but they may struggle with stability on uneven terrain [7]. Four-wheeled robots are a popular choice for mobile detection systems due to their inherent stability, straightforward control dynamics, and balance between speed and load-bearing capacity [8]. However, their added mechanical complexity and weight can result in higher power consumption and increased cost [9, 10]. Legged robots present the advantage of navigating highly irregular environments where wheels or tracks are impractical [11].

1.3. Robotics kinematics and control

Focusing on a robotic device where the robot uses a differential drive (*i.e.*, two rear powered wheels and two free front wheels for enhanced stability), the kinematic model relates the speeds of the actuated wheels with the linear and angular motion of the robot. If V_l and V_r are the left and right wheel linear velocities, respectively, then the robot's forward velocity V and angular velocity ω are:

$$V = (V_l + V_r)/2 \quad (2)$$

$$\omega = (V_r - V_l)/L \quad (3)$$

where L is the distance between the two wheels. The Instantaneous Center of Rotation, which defines the point about which the robot is currently rotating, is located at a distance R from the midpoint between the wheels, namely:

$$R = \omega/2(V_l + V_r)/(V_r - V_l) \quad (4)$$

When the robot moves in a straight line, it holds $V_l = V_r$, $R \rightarrow \infty$ and $\omega = 0$. Similarly, when $V_l = -V_r$ and $R = 0$, then the robot rotates in place about its midpoint, as it is shown in Figure 1.

This model also allows controlling the robot via either open-loop commands or closed-loop, where, for example, remote-control signals from a joystick or an end-user interface can be straightforwardly translated into the two differential motor speeds and drive of the device [12].

1.4. Spatial data collection, processing, and visualization

A significant advantage of instrumenting a mobile metal detector with positioning technology is the ability to provide a spatial map of where metal objects are detected. GIS and digital mapping tools enable visualization of detected object locations over a real-world map [13]. Robotic systems can integrate GPS receivers where high accuracy can be reached with differential GPS techniques [14] as well as with *Real-Time Kinematic* positioning. A standard GPS module is adopted at this stage, where

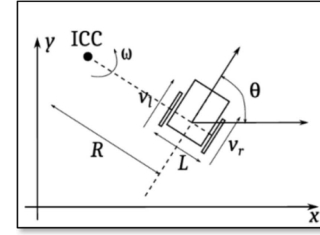


Figure 1
Differential-drive kinematics [12]

the robot's movements are monitored and GPS data are saved for further analysis [15–17]. Then a time-sequenced map of detections can be designed with additional such as, for example, the signal strength [18–22]. For deeper analysis, GIS software like QGIS or ArcGIS can be used, interpolating or marking cleared versus uncleared areas [23–25]. Advanced systems might also incorporate inertial navigation or visual odometry to augment GPS for better localization of detections [26].

1.5. IoT for navigation, remote control, data logging, and storage

The IoT joins distributed sensing and actuation nodes over standard internet protocols and is central to mobile robotics because it enables remote operation, telemetry, and cloud analytics.

Low-power microcontroller platforms with integrated Wi-Fi system—and often Bluetooth system as well—such as the ESP-class, Nordic, and similar *System on Chip* (SoC), provide sufficient computational capability, *General Purpose Input/Output* (GPIO) breadth, and real-time peripherals to read sensors, drive actuators, and also maintain a network stack [27, 28]. *Message Queuing Telemetry Transport* (MQTT) is widely adopted on these IoT systems because of its small header size, topic-based decoupling, and brokered delivery model. In this context, robots can easily publish their telemetry on hierarchical topics, while the subscribers and operators, dashboards, or storage services are consuming data asynchronously [29]. Low-code platforms such as Blynk, ThingsBoard, or Adafruit IO also offer device *Software Development Kits*, cloud back ends, and mobile or web-based dashboards which can be designed to interact with the end-user [3]. IoT robots typically operate as Wi-Fi stations on existing infrastructure when available, enabling internet reachability, or create local access points for direct operator connection in the field [30]. Alternatives include Bluetooth for short-range control and sub-GHz links such as LoRa for long-range, low-bit-rate telemetry with different characteristics in terms of range, throughput, latency, and energy consumption [31, 32]. Cloud databases and object stores provide long-term archiving, visualization, and multi-user access [33]. Robustness of communication can also be improved with the support of watchdogs, reconnect logic, and commands handling intermittent links [34].

1.6. Power supply

Power supply design is a crucial aspect of any mobile robotic system. The robot must carry an energy source that is sufficiently dense to allow reasonable operation time without being too heavy and provide the necessary voltages and currents to all components: motors, sensors, and computing units [35]. Rechargeable

Lithium-ion (Li-ion) batteries and related chemistries, such as Li-polymer, are the preferred choice for most mobile robots since they offer more energy per weight/volume and can supply high discharge currents for motor drivers [36]. A single Li-ion cell has a nominal voltage of around 3.7 V; therefore, cells and battery packs are combined to meet other voltage requirements [37–39]. Different subsystems often require different voltages: for example, the ESP32 and logic circuits typically run at 3.3 V, whereas sensors, such as the GPS module, run on 5 V or 3.3 V, and direct current motors might run on 6–12 V [40–42]. An LM2596 buck converter module can be used to drop a 12 V initial power supply down to, for example, 5 V. On-board regulators or smaller low-dropout regulators can produce 3.3 V for the microcontroller as well [43]. The system should also include either a battery protection module or use cells that have built-in protection [44]. Additionally, fuses or resettable polyfuses may be added to protect against short circuits. A common practice is to place electrolytic capacitors near motor drivers and logic inputs to absorb transients [45]. Motors should have flyback diodes, which the L298N includes internally, and maybe additional snubber circuits if needed to avoid large inductive kicks feeding back into the supply line [46].

1.7. Gap analysis

According to the literature, a number of previous works focused on a reduced set of aspects, such as designing robots with good metal detection but no mapping, or systems with proper data logging but no real-time connectivity. A gap in the integration of the different technologies seems missing in the current proposed solutions. Traditional mine detection robots often rely on proprietary or military-grade communication systems and may not utilize modern IoT platforms or open tools such as Google mapping for visualization.

By using IoT microcontrollers and Google Maps, we want to bring a modern twist to these applications to make these integrated technologies more accessible and user-friendly. Moreover, a design that remains low-cost and relatively simple yet achieves practical functionality through careful design and integration would best fit within such constraints. We also want to include circuit schematics, code, and Computer-Aided Design (CAD) designs since sharing these details will contribute to the

knowledge base, allowing others to replicate or build upon the work. By addressing these gaps, the proposed system will not only implement a specific solution, but it will also advance the understanding of how we can effectively combine metal sensing, robotics, IoT, and mapping synergistically.

This work aims to design, build, and validate a low-cost, teleoperated metal-detection robot that safely detects metallic targets, geotags them, and visualizes results in real time via a cloud interface, with the following main objectives:

- 1) Implement a 4-wheel differential-drive chassis controlled by an ESP32-S3 and L298N, with a front-mounted servo boom that carries the search coil ahead of the body to maintain consistent ground clearance and enable lateral sweep.
- 2) Interface the repurposed detector Printed Circuit Board (PCB) as an active-Low (LOW) digital input with confirm/hold filtering and automatic rearm; drive a buzzer and red LED on detection to provide immediate, unambiguous feedback.
- 3) Integrate a NEO-8 GPS and publish breadcrumbs at a fixed cadence; on detection, emit a synchronous V3 event paired to the current V0 location using a shared timestamp and longitude-first ordering map pins align with the track.
- 4) Use Blynk Cloud with virtual pins and a non-blocking firmware loop so driving, sensing, and publishing proceed concurrently over campus Wi-Fi.
- 5) Deploy a segmented supply based on a 4-cell Li-ion pack with fixed-output Mini560 Pro buck converters for clean rails to the ESP32, GPS, servo, and detector, while the L298N receives pack voltage directly; design and 3D-print a two-piece shell, motor pods, front wheel anchors, and a one-piece coil boom for serviceable assembly.
- 6) Quantify detection range on representative targets, mapping error against ground truth, joystick latency, runtime endurance, and basic terrain robustness; compare results with design targets and identify improvements for autonomy, sensing depth/discrimination, mobility, communications, and data handling.

Figure 2 displays an overview of the system. The paper is then organized into four sections that reflect distinct phases of the research process. Section 2 outlines the methodology, including the design principles of the robot. Section 3 presents the results

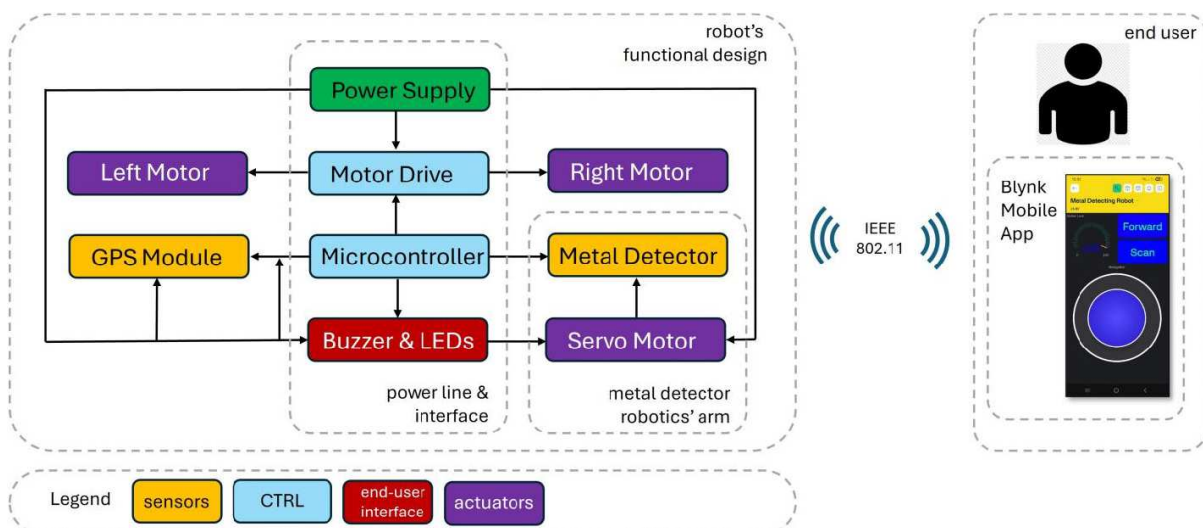


Figure 2
Hardware integration block diagram of the proposed robot's design

obtained from both simulation and practical experiments, accompanied by a thorough discussion. Finally, Section 4 concludes the study by summarizing the primary findings, contributions, and recommendations for further work.

2. Materials and Methods

This section describes the methodology followed in designing, building, and testing the mobile robot for metal detection.

2.1. System design

The system is broken down into subsystems, and each is designed and then integrated. *Phase 1*, the hardware platform, covers the mechatronic stack: the ESP32-based controller, the L298N motor driver with direct current (DC) gear motors, a servo-swept metal-detector head, and GPS, power regulation, and safety interlocks. *Phase 2*, software development, implements the embedded firmware and control logic. *Phase 3*, IoT development, delivers mobile and cloud interfaces through Blynk and MQTT, defines virtual pin mappings and message topics, configures map visualization and alerting, and establishes authentication and rate limits for reliable field links. *Phase 4*, data management and logging, integrates persistent telemetry capture and event records such as time, coordinates, and signal strength to a cloud database or broker for post-mission analysis and traceability.

These four phases are executed iteratively so that simulation and tests can suggest further revisions at each step and are then fused to deliver an end-to-end prototype.

Concerning the *metal detection*, the proposed design leverages an inductive coil-based detector due to its proven reliability and simplicity. Attention must be paid to the coil design size, number of turns, and geometry, as well as to the signal filtering, amplification, and thresholding to detect the tiny perturbations that are triggered by the metal targets [47]. A PCB is mounted inside the robot chassis, while its search coil, a copper winding 5 cm-long, 0.5 cm-radius graphite rod, is transferred into a custom front housing. From the supplier's specification, the sensitivity is about 5 cm to an RMB 1-yuan coin. Electrically, the detector PCB is powered from the robot's regulated 9 V rail from a buck converter, with a common ground. The board's native alarm output is leveraged as a digital detection signal: the node that

originally drove the detector's buzzer is routed to the ESP32 through a GPIO with a 10 k Ω pull-up to 3.3 V and a series 1N4007 diode, anode at the GPIO, cathode to the detector's buzzer negative pad (Figure 3). A compact active buzzer and a red LED on the robot are driven directly by GPIOs to reproduce an audible and a visual indication in parallel with digital logging.

2.2. Hardware integration

The robot is partitioned into four hardware main subsystems that meet at the ESP32-S3 controller. The electronics architecture is organized around an ESP32-S3 DevKitC-1. It coordinates sensing, actuation, and telemetry while keeping high-current drive physically separated from low-noise sensing. Table 1 summarizes the pin allocations. Remote teleoperation uses Blynk virtual pins V_1/V_2 joystick, V_0 track, and V_3 hit flag and therefore does not consume additional physical GPIOs.

Power is provided by a 4-cell Li-ion pack feeding a fused distribution node. Fixed-output Mini560 Pro buck converters create isolated rails: 5 V for the ESP32-S3 and indicators, 5 V for the sweep servo, and 9 V for the metal-detector board; the L298N motor driver receives the raw battery rail for maximum headroom. Pack voltage is monitored through a high-impedance divider and Resistor and Capacitor (RC) filter to an Analog-to-Digital Converter (ADC) channel on the ESP32, enabling low-battery warnings and controlled shutdown. The sensing subsystem comprises the metal-detector coil and its analog PCB, plus a NEO-8 class GPS module. The detector's digital alert output is read on a protected GPIO with a pull-up and series diode; the GPS connects to a dedicated Universal Asynchronous Receiver-Transmitter (UART) at 9600 baud. The actuation subsystem couples the ESP32-generated pulse width modulation (PWM) and direction lines to an L298N dual H-bridge that drives the left and right DC motors, while a separate PWM channel positions the front-mounted servo that sweeps the coil. A feedback subsystem provides operator cues: a green LED shows system and satellite-fix status, a red LED and active buzzer latch on metal hits, and both are driven directly from ESP32 GPIOs with appropriate current-limit resistors. Layout and wiring follow noise-aware practices. High-current motor paths are short and kept to one side of the chassis; logic and sensor looms are separated and twisted where possible; all grounds return to a single star point

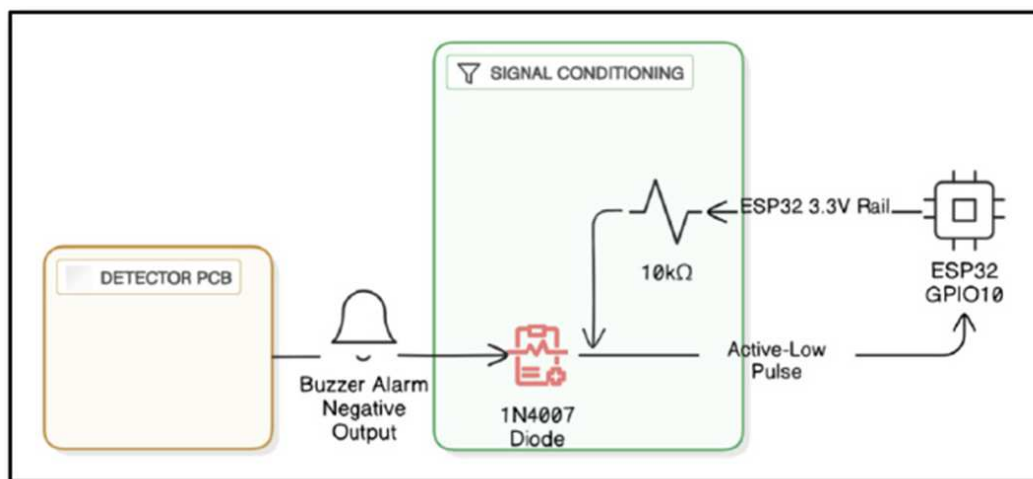


Figure 3
The metal-detector signal to the ESP32 conditioning

Table 1
ESP32 pin allocations

Component/function	GPIO address	Notes/description
L298N – ENA (left motor speed)	G14	PWM enable for the left motor
L298N – IN1 (left dir <i>A</i>)	G21	Direction input <i>A</i> for left <i>H</i> -bridge channel
L298N – IN2 (left dir <i>B</i>)	G35	Direction input <i>B</i> for left <i>H</i> -bridge channel
L298N – IN3 (right dir <i>A</i>)	G36	Direction input <i>A</i> for right <i>H</i> -bridge channel
L298N – IN4 (right dir <i>B</i>)	G37	Direction input <i>B</i> for right <i>H</i> -bridge channel
L298N – ENB (right motor speed)	G38	PWM enable for right motor.
Sweep servo (coil scanner)	G42	Standard servo PWM signal.
Metal-detector input (active-LOW)	G10	From the detector buzzer negative pad
Buzzer (active)	G8	HIGH = ON.
Green LED – Power/GPS state	G1	Solid at boot, blinks on GPS fix.
Red LED – Metal detection status	G2	Lights on confirmed detection
GPS RX → Module Tx	G12	Receive-only UART from NEO-8 <i>M</i>

near the battery negative. The detector coil is mounted in a lightweight, open-bottom housing ahead of the chassis to minimize magnetic coupling to the motors, and the GPS antenna is placed with a clear sky view. This partitioned design yields a robust, EMI-tolerant platform while keeping interfaces simple and serviceable.

2.3. The firmware

The adopted firmware targets ESP32-S3 DevKitC-1 under the Arduino framework and is organized into modules for configuration, sensing, actuation, GPS parsing, and IoT telemetry. Core dependencies are *ESP32Servo* for the sweep actuator, *TinyGPS++* for National Marine Electronics Association parsing, and Blynk for teleoperation and map visualization. Figure 4 shows the flow chart of the events in the firmware. A compact logging layer timestamps key state transitions on Serial at 115200 baud for reproducible diagnostics.

Configuration lives in a dedicated header, so trials do not require code edits. It captures the designed pin mapping, Blynk template token, Eduroam credentials, virtual pin assignments: V_1 for throttle, V_2 for turn, V_0 for location, and V_3 for metal hit; telemetry cadences of every 5 s for track points and detector filter constants for sample interval, confirm window, and hold time.

The calibration is performed in different stages: servo end-points are set to the mechanical sweep range used in the build at a range of 23°–161° with neutral aligned to the housing cup; the metal-detector baseline is then captured on startup; forward stride of approximately 95 mm between sweeps is characterized by fixed PWM dwell and measured displacement; a GPS “fix-OK” guard is required together with a minimum number of visible satellites before any map update.

Integration and field testing follow a bottom-up path using isolated sketches for LEDs, buzzer, servo, motor directions, detector input active-LOW via 10 kΩ + diode, and GPS RX-only on GPIO12. The full application then exercises the scan–step–sense state machine while maintaining Blynk. Timestamp alignment for map overlays is enforced by batching V_0 (lon, lat) and $V_3 = 1$ in a single *beginGroup()*/*endGroup()* on each confirmed hit; routine tracking sends only V_0 every 5 s. Watchdogs reassert Wi-Fi/Blynk without blocking, motors idle on stale joystick, and telemetry is rate-limited to keep bandwidth predictable. The result is a

repeatable path from build to bench to outdoor trials with traceable parameters, aligned timestamps, and logs that map directly to the evaluation framework.

2.4. IoT system

The robot adopts a layered IoT architecture that separates the edge device, the communication fabric, the cloud service, and the client interfaces while remaining lightweight for an ESP32-S3 microcontroller. Figure 5 below depicts the layered nature of the IoT architecture.

Edge Layer – The ESP32-S3 aggregates local services for positioning, metal detection, mobility control, and annunciation. Peripherals are abstracted behind stable device application programming interfaces, so sensing and actuation remain deterministic under variable links.

Connectivity and Security – The ESP32-S3 is provisioned on the university Eduroam network using WPA2-Enterprise credentials stored outside source control and loaded at build time; the device boots in station mode, delays motor enable, and establishes a Transport Layer Security-secured session to Blynk Cloud. The Blynk communication runs over encrypted Transmission Control Protocol with certificate validation. Payloads are compact:

- V_1 and V_2 carry signed integers in the range minus 255 to plus 255 for throttle and turn.
- V_0 carries location as longitude followed by latitude.
- V_3 carries an integer of one only when a metal hit is confirmed.

Blynk Cloud – The robot is registered under a single Blynk template. The template defines virtual pins and widget bindings used by both the mobile app and the web console:

- V_0 Location track uses the location data type and stores longitude and then latitude. Retention is enabled, so tracks can be reviewed.
- V_1 and V_2 are integer streams used by the joystick.
- V_3 MetalHit is an integer event stream used for overlays and callouts.

Operations on Blynk Clients – The web console is the primary place for monitoring and administration. It shows device online status, last contact, and stream charts. Operators can export V_0

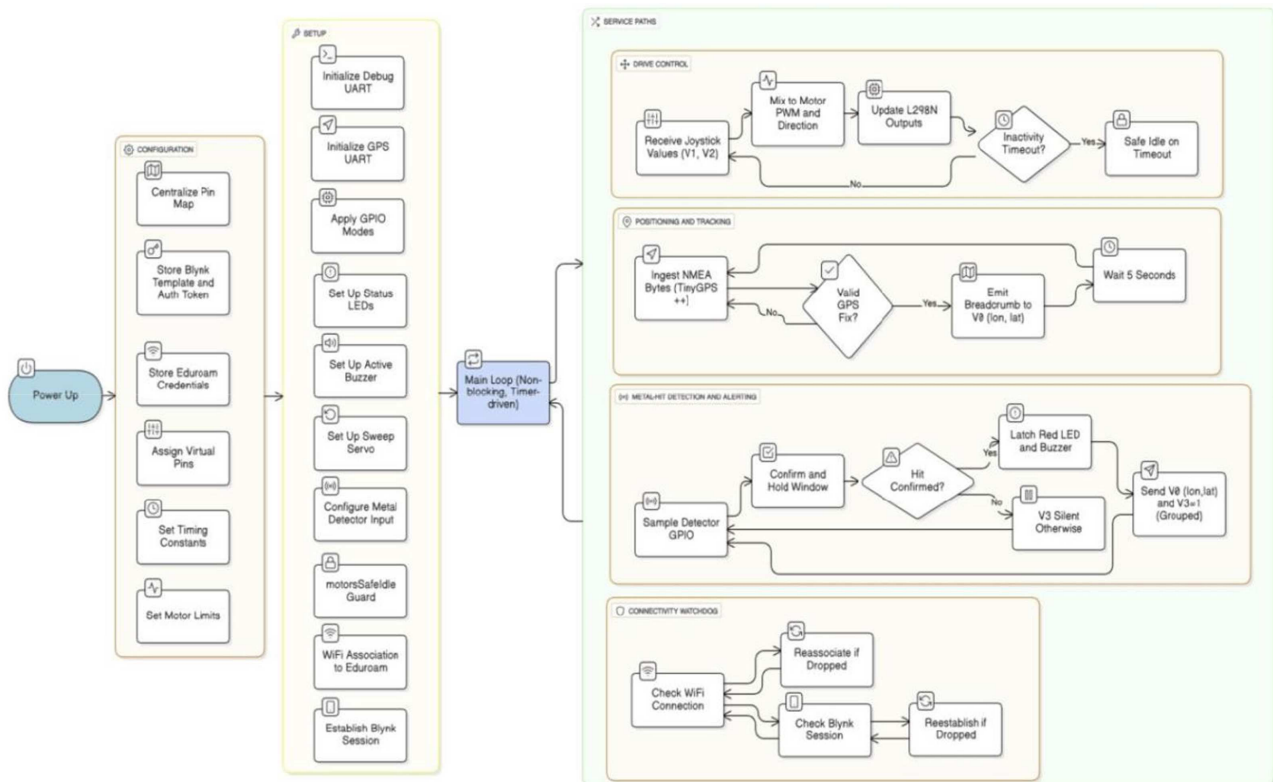


Figure 4
The firmware architecture

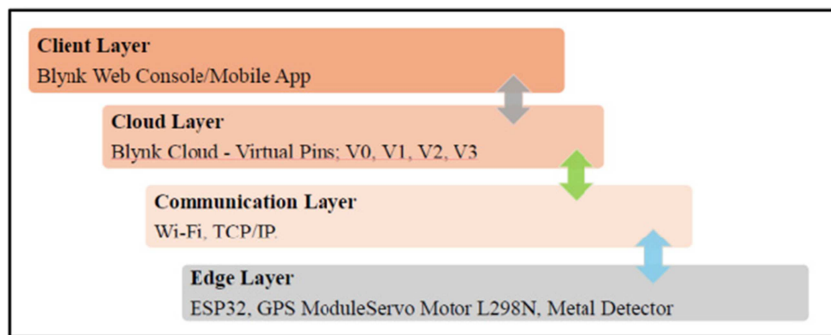


Figure 5
The IoT Layered Architecture

and V_3 to comma-separated values for analysis and can adjust width- get visualization, such as track thickness, point direction arrows, and overlay color. Figure 6 shows the visualization of the spots of detection of metals on the Blynk web console map widget.

The Blynk mobile app client provides a user-friendly and interactive control panel for operating the robot (Figure 7). Two large control buttons, labeled *Forward* and *Scan*, enable the user to toggle between continuous forward drive and activation of the servo coil sweeping mode for metal detection, respectively. A joystick widget is placed centrally in the interface, allowing manual navigation of the robot in all directions. When the forward mode is activated, the joystick serves as an override for steering or reversing.

Data flow – The device posts a breadcrumb to V_0 every 5 s during motion. On detection, the firmware sends V_0 and V_3

together, sharing the same timestamp, which allows the console to align the callout with the correct breadcrumb on the polyline. Rate limits of the firmware cap the breadcrumb cadence and suppress repeated V_3 alerts within a short time.

2.5. Power system

The power system has been designed around a 18650 four-cell Li-ion battery pack in series, 14.8 V nominal and 16.8 V at full charge, with a capacity of 20000 mAh, giving about 296 Wh of stored energy. The pack feeds a small power-distribution block through a master toggle switch.

A built-in *Battery Management System* provides balancing, over-current, and over-voltage cut-off (Figure 8). From the distribution block, the pack is converted into clean rails generated

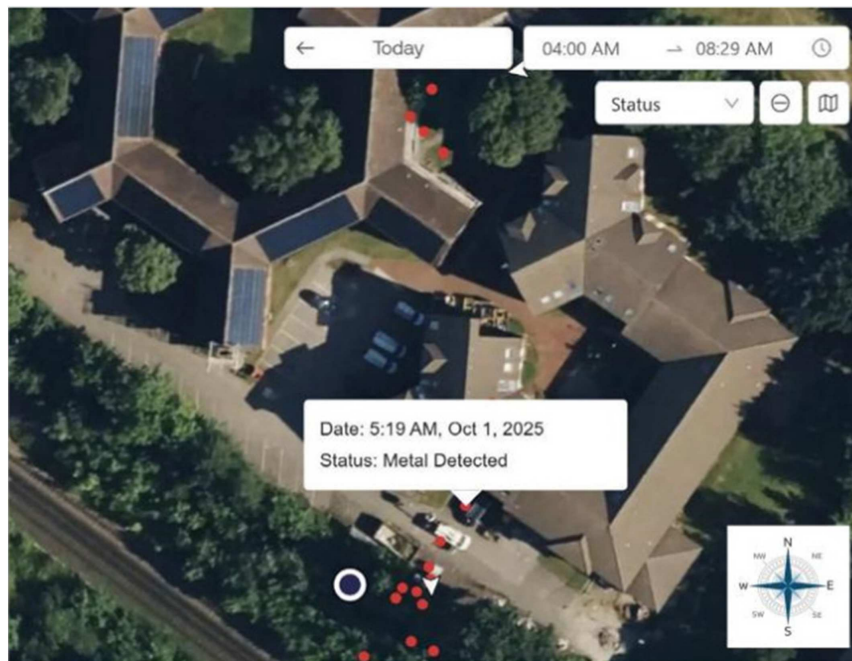


Figure 6
Visualization of metal-detected spots on the map widget of the Blynk web console

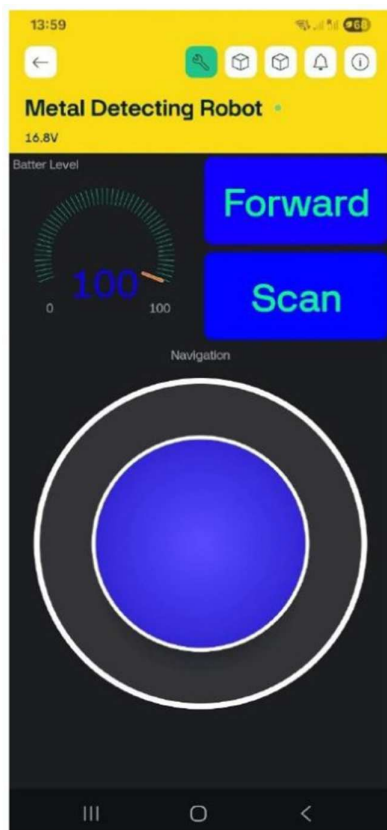


Figure 7
The Blynk Mobile app interface showing the joystick and map widget

by a dedicated Mini560 Pro fixed-output buck converter for each electrical system, providing electrical isolation and well-regulated supplies. A 5 V Mini560 Pro powers the ESP32-S3 board, another 5 V unit feeds the sweep servo, a 9 V unit powers the metal-detector PCB, and finally a 3.3 V unit supplies the GPS module. The L298N motor driver is directly fed from the distribution block at 14.8 V to provide good motor torque (Figure 8).

With a typical cruise power of 20-30 W for the drivetrain and 3-5 W for control and sensors, the usable energy of roughly 80% of the pack yields 6–10 hours of mixed operation. The separation of noisy actuators from sensitive electronics ensures stable supplies, predictable motor torque, clean GPS reception, and reliable metal-detector performance, while leaving headroom to add sensors or a second servo without rework.

2.6. 3D modeling

The robot platform was modeled in SketchUp 2025 as a 2-piece rectangular enclosure with a continuous rounded nose, defined by an overall envelope of 24.8 cm length, 15 cm width, and 7 cm height with 1.5 mm wall thickness, and a front nose radius of 7.86 cm (Figure 9, top panels). It consists mainly of robot cases and chassis. The other components are the left and right mudguards; front and rear rims; electronics support frames for the motor driver and buck converters, ESP32-S3, GPS, and detector PCB; search-coil housing and boom; front wheel anchor bosses; and rear motor housing, which are fitted to the chassis.

Robot Case – The case is a rectangular shell blended to the rounded nose with side faces carrying 360 ventilation perforations of 0.075 cm radius each. The top deck integrates: a central Wi-Fi slot $4.8 \times 0.9 \times 0.1$ cm aligned to the ESP32-S3 antenna with an internal 2.2×0.15 cm pigtail channel deepened by 0.05 cm, two status LED apertures of 0.25 cm radius, a 1.8 cm square for the

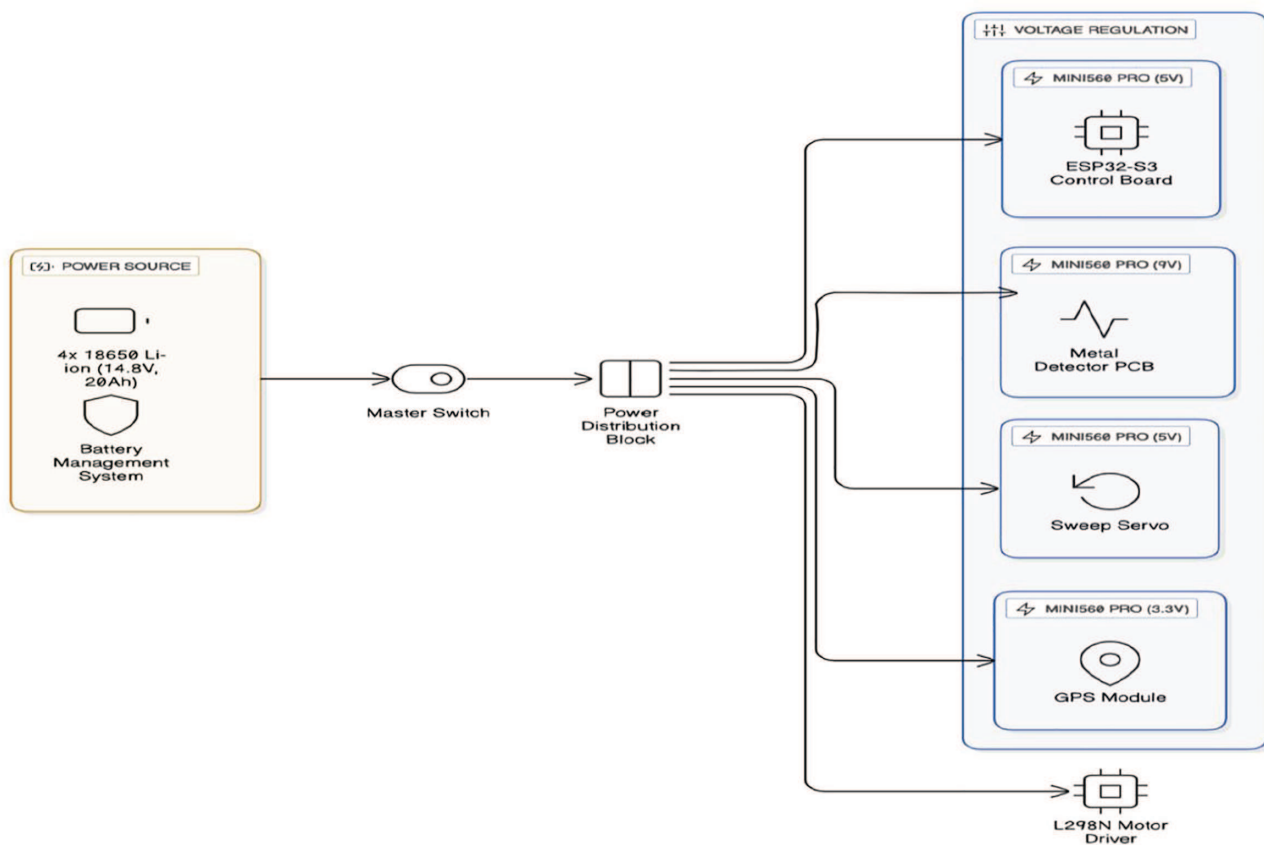


Figure 8
The power system's architecture

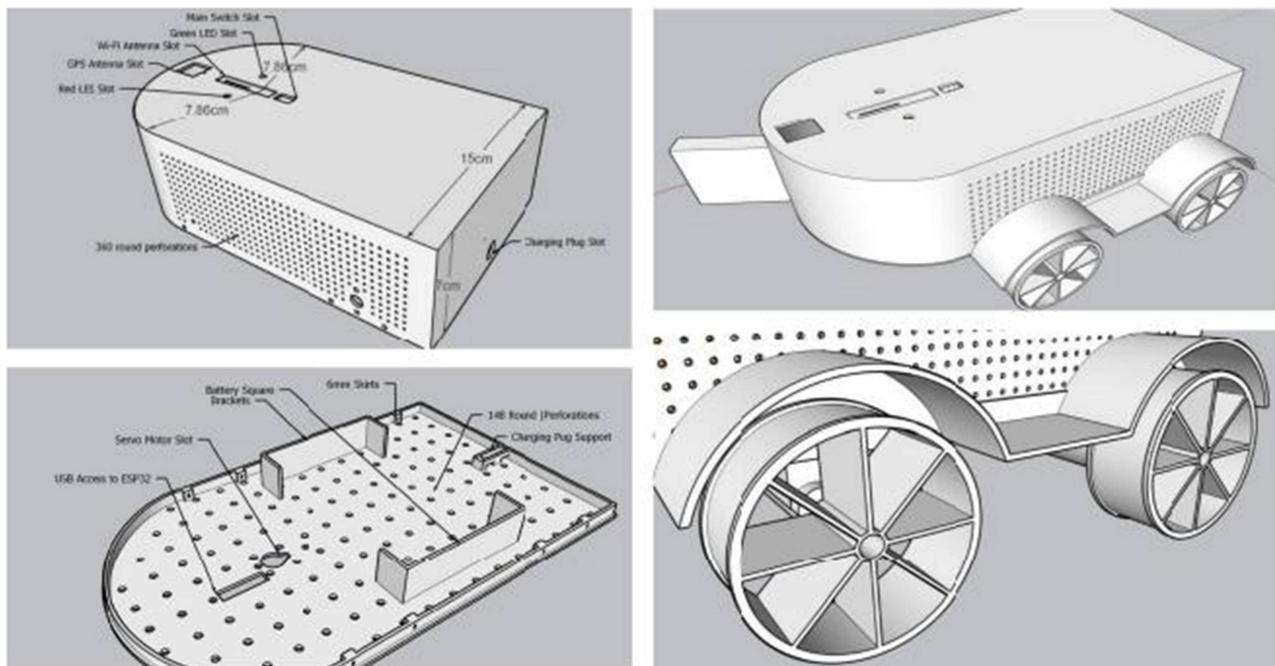


Figure 9
Modeling of the robot platform in SketchUp 2025: case (top left panel), main robot design (top right panel), chassis (bottom left panel), and design of the mudguard and rims (bottom right panel)

GPS patch, and a 6.05 mm rear DC-jack opening (Figure 9, top left panel).

Chassis – The chassis is the internal mounting plane and service surface. Inner skirts rise 0.6 cm to nest inside the shell for a stiff, dust-resistant joint. A uniform grid of 148 round perforations with a radius of 0.175 cm is meant to provide ventilation and a repeatable anchor pattern for screws and standoffs (Figure 9, top left panel). At mid-chassis, two square brackets capture the support pack laterally and longitudinally. Each bracket measures $1.6 \times 7.4 \times 2$ cm and 0.15 cm in wall thickness, with the pair spaced 11.4 cm apart. Four rectangular slots (1.0×0.55 cm) allow two tie wraps to secure the pack against vertical movement.

Mud Guards – On each side of the platform, a paired mud-guard assembly is attached with an outer radius of 4 cm, inner radius of 3.67 cm, and a guard width of 3 cm, bridged by a flat web that ties the front and rear guards together to increase lateral stiffness (Figure 9, bottom left panel). Walls are 1.5 mm thick with a small trailing lip to resist flex.

Rims – The rim is a lightweight, spoked wheel with a 2.8 cm radius and 2.4 cm width. Rear rims use a *D*-shaped hub keyed for the motor's *D*-shaft. Front rims use a round hub of 0.165 cm radius to spin freely on an M3 screw (Figure 10, bottom right panel).

Electronics Support – Electronics parametric support frames are modeled as discrete components (Figure 10). Rear frames seat the motor driver and the dedicated buck converters, placing high-current hardware near the motor terminations. Front frames carry the ESP32 controller, the GPS module, and the MPU-6500 to separate sensitive electronics and to shorten critical cable runs.

The search-coil housing – The search-coil housing is a one-piece forward boom that protects the coil, carries it ahead of the chassis, and provides a rigid servo anchor for sweeping (Figure 11). At the rear, a circular cup seats the servo round adaptor; from there, the arm transitions into a lightweight open-bottom *U*-channel to cut mass while side webs and a few short ribs maintain torsional stiffness. The front coil bay is open underneath

to avoid disturbing the field, with a minimal perimeter frame that supports only the ends of the copper winding wrapped in a 5 cm-long, 0.5 cm-diameter graphite rod, retained by non-metallic clips or two small screws. This open, stiff, and lightweight construction preserves coil *Q* and sensitivity, reduces servo load, and yields smooth, wide-angle sweep performance.

The front wheel mounts – The front wheels mount on short, gusseted bosses keyed into the chassis hole grid; each boss has a precision M3 through-bore with counterbore for the head and nyloc below, so the wheel runs on the shoulder, not threads, giving low-wobble, low-wear support.

Rear Motors Brackets – The rear motors sit inside cylindrical housings that act as both guards and structural beams: a fixed inner cradle with anti-rotation ribs locates the gearbox, and a two-screw outer half-shell clamps the can for quick service. A slotted output window aligns with the wheel plane, ventilation ribs aid cooling, and built-in cable channels with tie points provide strain relief. Together, these features give accurate alignment, strong load paths, easy maintenance, and good protection with minimal weight.

2.7. System manufacturing

The models of each component of the robot housing authored in SketchUp were exported to PrusaSlicer in STereoLithography (STL) file formats and printed on an Original Prusa i3 MK3S (Figure 12). The components are printed using Galaxy Silver Polylactic Acid filament at a speed of 0.20 mm and an infill of 15%.

Robot Case and Chassis – Prints met the specified size; heat-set inserts at standoffs provide repeatable assembly. The top deck includes a long central slot aligned with the ESP32-S3 Wi-Fi antenna, a rectangular aperture for the power switch, a square opening for the GPS patch antenna, and two round apertures for the status LEDs. Two DC gearmotors and four multi-spoke rims

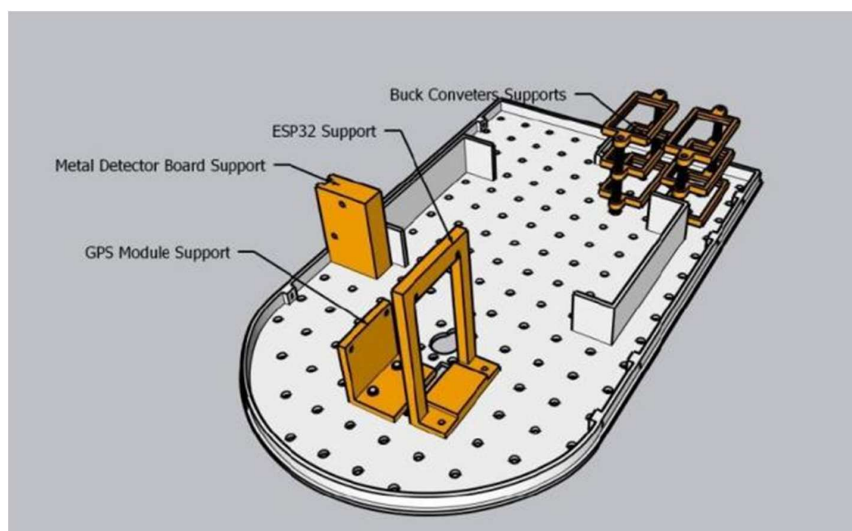


Figure 10
Design of the support for the electronics (in orange color)

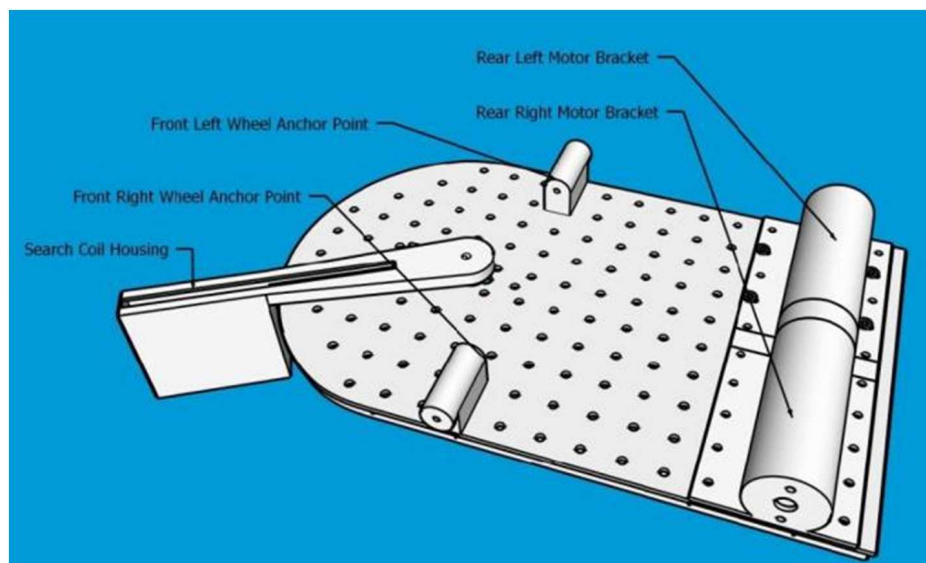


Figure 11
The rear motor brackets, front wheel mounts, and search-coil housing

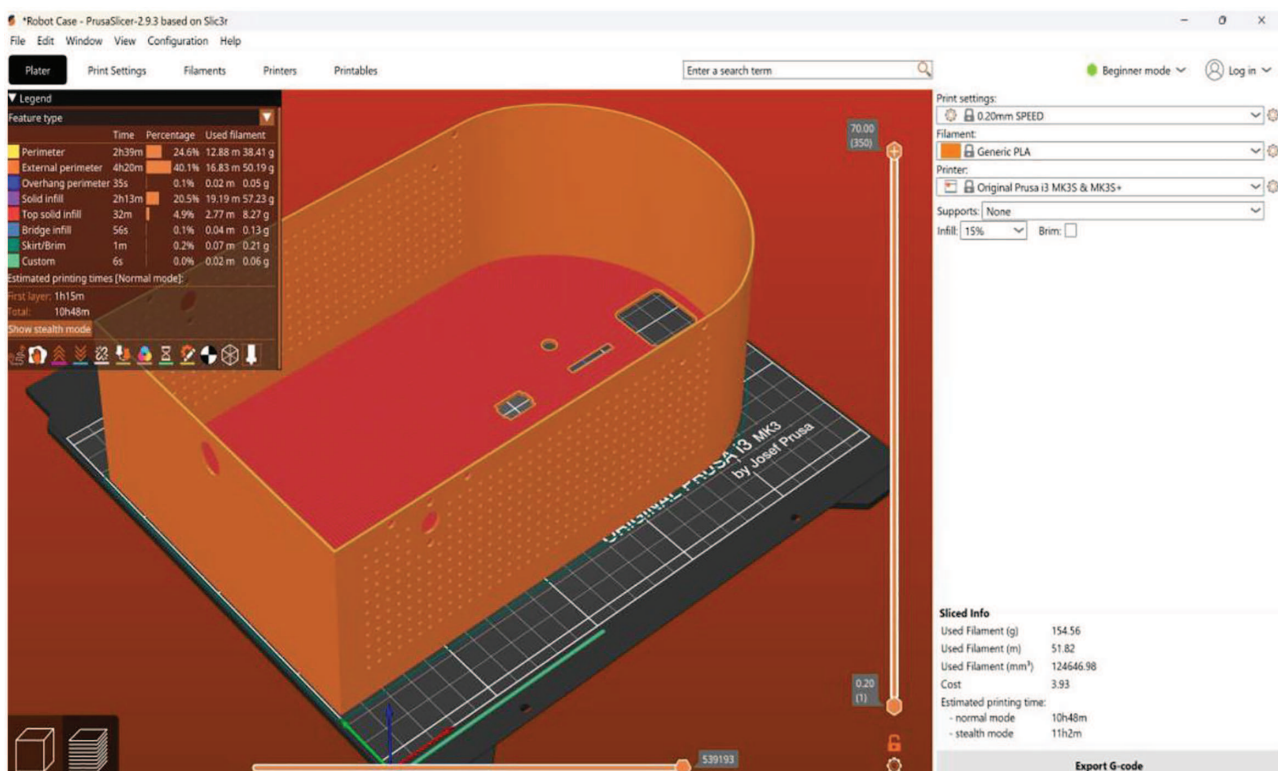


Figure 12
Slicing of the 3D models with the PrusaSlicer software before printing

with a 2.8 cm radius are positioned for a low center of mass and predictable differential-drive tracking (Figure 13, top panel).

The rear motor Brackets – The rear motor brackets are printed as paired side pods that act as both guards and structural beams (Figure 13, bottom left panel). Each pod forms a half-round cradle tied into the chassis rail with filleted feet and short gussets, and a removable outer half-shell secured by two screws clamps the motor can for quick service.

Front Wheel Mounts – The front wheels mount in Figure 13 (bottom left panel) are printed bosses keyed into the chassis hole grid. Each boss has a precision through-bore for an M3 shoulder bolt axle with a shallow counterbore for the fastener head, and triangular side gussets spread cornering and impact loads into the deck.

Electronics Mounts – Electronics mounts, as shown in Figure 13 (bottom right panel), are printed as modular frames

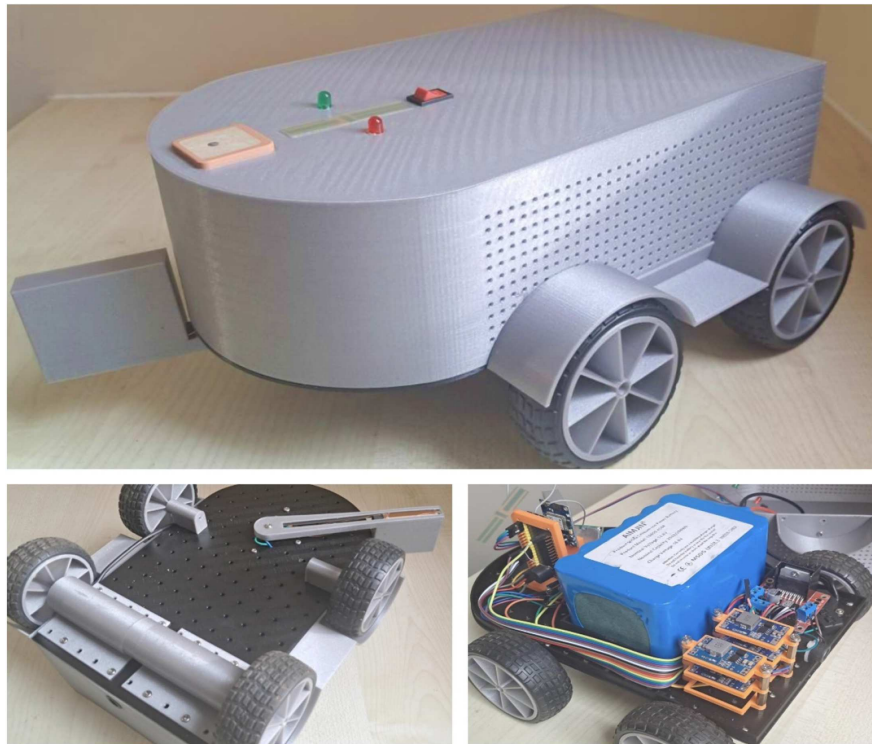


Figure 13

The overall system after the 3D manufacturing of all the parts, the integration of all the electronics, and the assembly: integrated system (top panel), rear motor bracket, front wheel mounts, and search-coil housing (bottom left panel), 4S6P Li-ion battery with the electronics and their modular supports (bottom right panel)

that locate and protect the boards while enforcing clean cable paths. A rear cross-frame carries the motor driver and the fixed-output Mini560 Pro buck converters with standoffs for airflow and channels for VM, 5 V, 9 V, and 3.3 V runs.

Mechanical Integration and Wiring – Mechanical integration followed the intended load path and service layout. Two DC gear motors and four multi-spoke wheels were positioned to achieve a low center of mass and predictable differential-drive tracking. The servo-driven sensor arm was mounted at the rounded nose so the metal-detector coil could sweep laterally near ground level without interference from the bodywork.

2.8. Preliminary tests

Testing began with simple, observable bring-up checks. Power-on verified rail presence at the distribution block with a multimeter and a clean boot signaled by the green status LED. A minimal sketch toggled the green LED, the red metal-hit LED, and the active buzzer. The sweep servo was exercised across its operating range to confirm smooth travel and clearance at the rounded nose. A motor jog test drove both wheels forward on a flat surface to confirm direction, braking response, and the approximate 95 mm stride between sweeps. Sensing and connectivity were validated with straightforward exercises. The metal-detector active-low input was watched on the serial monitor while passing small metallic items under the coil to confirm debounced thresholding, the brief alert latch, and automatic resume when clear. The GPS was powered outdoors to first fix, then observed updating coordinates at one Hertz. With Blynk online over Eduroam, the map widget showed five-second breadcrumbs on V_0 and confirmed metal hits raised V_3 with a

marker aligned to the matching breadcrumb. A brief low-battery check verified the firmware's safe-halt behavior. These simple tests established readiness for extended runs without additional instrumentation.

Validation against objectives

Metal detection and alerting – The repurposed pin-pointer PCB, read as an active-LOW digital input on the ESP32-S3, reliably detects small and medium metallic targets at close range. The firmware's confirm-and-hold filter eliminates spurious hits; each confirmed event latches the red LED and active buzzer briefly and resumes scanning when clear.

Geotagging and mapping – Every hit is published as a batched pair to Blynk (V_0 location in longitude, latitude, and $V_3 = 1$) with a shared timestamp, so callouts align exactly with the breadcrumb trail. Routine tracking posts V_0 every five seconds, producing a continuous path in the map widget suitable for post-run coverage review.

Remote operation and telemetry – Over Eduroam WPA2-Enterprise, the robot remained responsive to the Blynk joystick (V_1 throttle, V_2 turn). A command-loss watchdog idles the motors on stale updates, and connectivity retries maintain the session without disrupting control.

Power sufficiency and stability – The 20,000 mAh 4S pack with fixed-output Mini560 Pro rails powered the drivetrain, ESP32, GPS, servo, and detector without brownouts or overheating. Mixed driving and scanning matched expectations; after roughly one hour of continuous testing, remaining capacity was around half, consistent with the estimated runtime envelope.

Mechanical robustness and mobility – The printed chassis, motor pods, and wheel mounts withstood repeated starts, stops,

and mild uneven ground (short grass, shallow slopes) with no structural failures. The servo-mounted coil swept cleanly at the rounded nose; occasional snagging in dense grass suggests a minor future tweak to coil standoff or a thin skid lip.

Safety and housekeeping – Green LED behavior matched the state: solid at boot, blinking with a GPS fix. Low-battery simulation triggered a safe halt. Startup and smoke tests confirmed deterministic bring-up: rails present, clean boot, GPS fix acquisition, joystick response, and timely map updates.

Experimental Data Collected

Logged data include metal-hit counts with confirm-and-hold filtering, rejected transients, and per-target detection distances; GPS breadcrumbs on V_0 at 5 s cadence and paired V_0 plus V_3 markers for confirmed hits with shared timestamps; positional error against tape-measured or handheld GPS references; end-to-end control latency during Blynk teleoperation on Eduroam; pack voltage over time for endurance profiling; and notes on link stability and electromagnetic susceptibility.

Detection metrics – For each run, the firmware logged total metal hits on V_3 , de-duplicated events, and rejected transients from the confirm-and-hold filter. False positives were counted by cross-checking V_3 spikes against operator notes and stationary coil intervals.

Detection range – With the repurposed pin-pointer coil at a fixed sweep height, maximum detection distance was recorded for small coins, screws, and larger steel offcuts. Results are reported as mean and range across passes to capture variability from posture and soil.

Position accuracy – Each V_0 breadcrumb (*lon*, *lat*) was compared to tape-measured ground points. Errors were on the order of a few meters, consistent with open-sky GPS and the observed Horizontal Dilution of Precision during trials. Event markers shared timestamps with their paired breadcrumbs, so the alignment error reflects GPS only.

Control and link latency – Round-trip control delay was estimated from joystick command to wheel motion, yielding typical values in the 100–200 ms band. Background Internet Control Message Protocol to the device gateway showed approximately 20 ms median network latency on Eduroam.

Tracking cadence and event timing – Breadcrumbs were emitted every 5 s under a valid fix; metal hits sent an immediate batched $V_0 + V_3$ with a common timestamp. The console export confirmed one-to-one alignment between callouts and track points.

Power profile – Pack voltage was sampled periodically to produce a discharge curve under mixed driving and scanning. The 20,000 mAh 4S pack sustained continuous operation without brownouts; the slope matched expectations from the estimated 23–35 W average load.

These datasets underpin the results section, where detection performance, geospatial accuracy, responsiveness, and endurance are analyzed against the project objectives.

3. Results and Discussion

This Section reports empirical results for the mobile, IoT-enabled metal-detection robot and interprets them against the project objectives: reliable detection and alerting, geotagged mapping, responsive remote control, stable power, and robust field behavior.

Tests were structured to validate detection performance, mapping accuracy, geotagging, teleoperation responsiveness, endurance, and robustness. Metrics include detection distance

for representative targets, position error of geotagged events, command latency during remote control on Eduroam (*i.e.*, the Institutional Wi-Fi network), energy usage over extended runs, and susceptibility to electromagnetic interference. Data were logged through five-second breadcrumbs on V_0 and event markers on V_3 with shared timestamps, providing a consistent basis for analysis across all trials.

3.1. Metal detection's performance

Bench and outdoor trials assessed sensitivity and range using representative targets placed beneath the coil at controlled heights. A small coin of approximately 2.3 cm in diameter of copper–nickel alloy produced clear hits up to about 2 cm below the coil. A 6 cm steel nail produced intermittent but detectable responses at about 3.5 cm. A 10×10 cm aluminum plate triggered strong responses at about 5 cm.

A simulated mine surrogate with a metallic casing of about 15 cm diameter was consistently detected at about 6 cm. The graph in Figure 14 plots maximum detection depth [cm] against increasing target surface area.

3.2. Mapping accuracy and geotagging

Detection positions were compared against ground truth measured independently. The average error of detection coordinates relative to the true positions was about 2.3 m, with all events within 3 m. This dispersion is consistent with open-sky civilian GPS performance and the observed dilution of precision during trials. Because V_3 and V_0 are emitted together with a shared timestamp, the console pins callouts to the corresponding breadcrumb; any offset is dominated by GPS error rather than timing or batching.

3.3. Remote control and telemetry

Teleoperation using the Blynk joystick on V_1 for throttle and V_2 for turn was stable over the campus Wi-Fi network with WPA2 Enterprise. The command-loss watchdog reliably idled motors if joystick updates stalled. End-to-end control latency from app action to wheel motion was typically between 100 and 200 ms, which felt responsive for low-speed scanning.

In a direct access point test with the ESP32 acting as a hotspot, reliable control range in open space was about 15 m; beyond this distance, occasional drops occurred, as expected for 2.4 GHz links. Figure 15 shows received signal strength [dBm] versus distance on a log-scaled *x*-axis, with sparse sample points and a smooth Length of Stay (LOS) trend line.

3.4. Tracking cadence and event timing

With a valid GPS fix, breadcrumbs on V_0 were emitted every five seconds; each confirmed hit sent an immediate grouped V_0 and V_3 so the metal callout appears exactly on a breadcrumb.

Console exports verified one-to-one pairing and consistent timestamps. When GPS was unavailable, the firmware suppressed event posting to avoid orphan markers. In this context, timestamp discipline and batching yield clean overlays without post-processing, supporting accurate visual narratives of search paths and detections.

3.5. Power and endurance

With a cell Li-ion pack of 20000 mAh with fixed-output Mini560 Pro buck converters supplying the rails, the longest

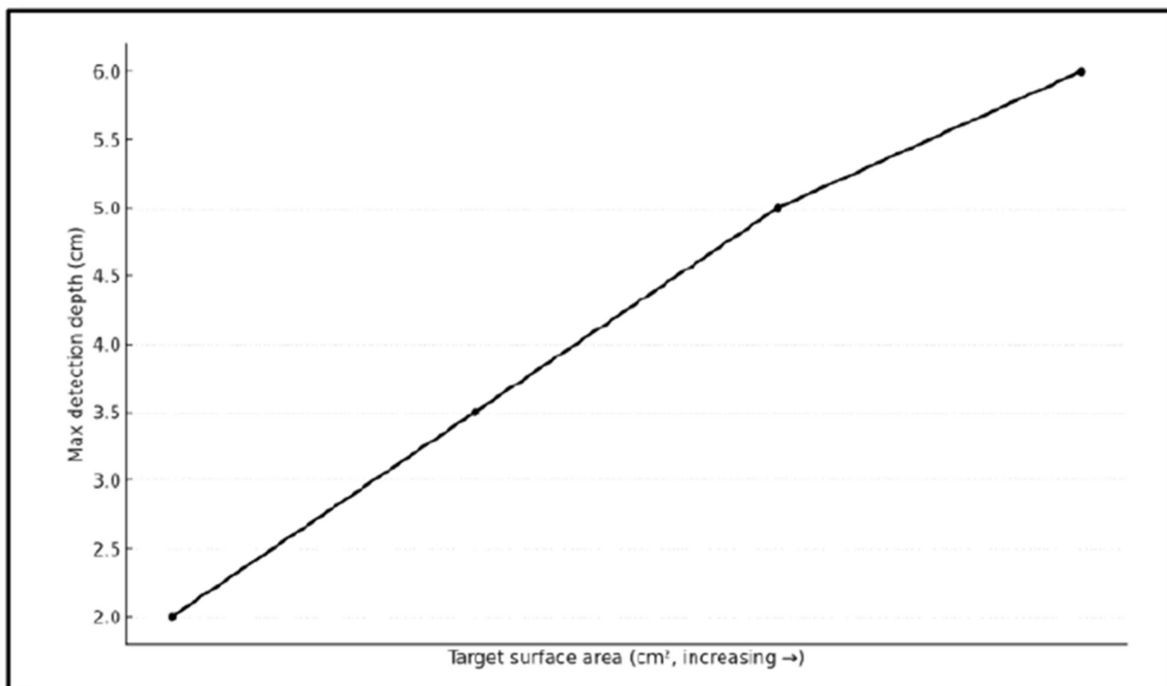


Figure 14
The maximum detection depth [cm] versus the target surface area [cm2]

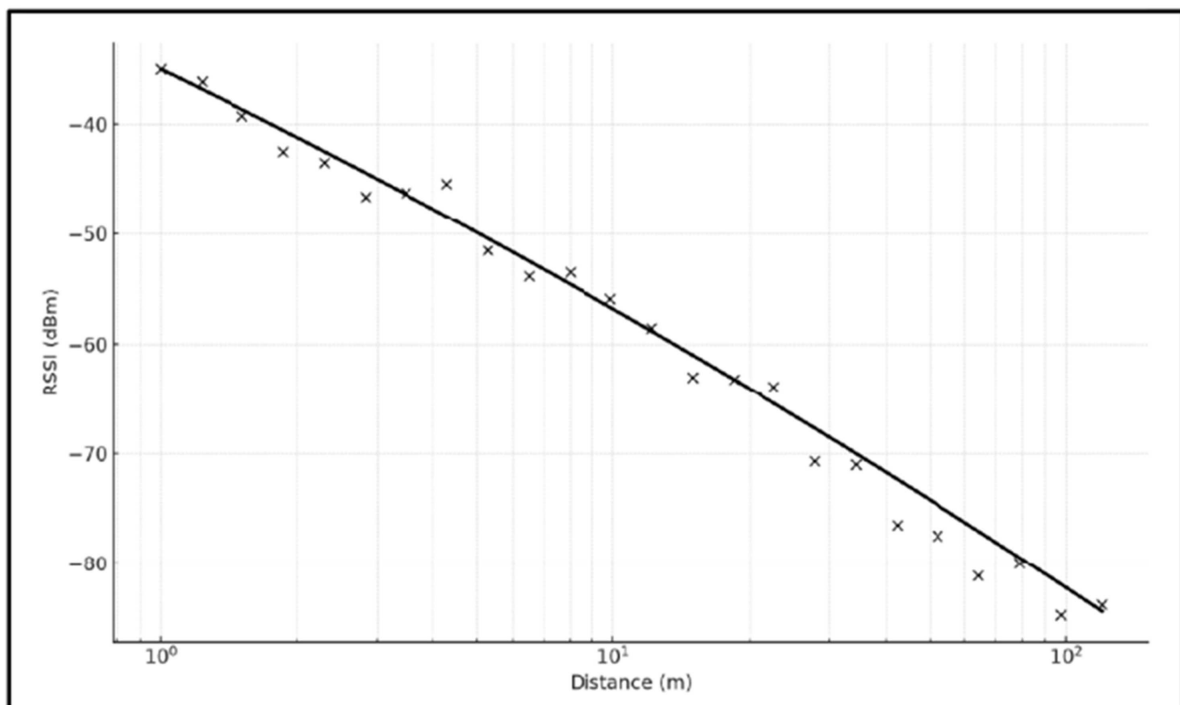


Figure 15
Signal's strength[dBm] versus distance [m]

continuous trial of about 60 min of mixed scanning and motion, the pack voltage decreased from about 16.1 V to about 15.7 V.

Figure 16 shows a non-linear discharge curve starting around 16.1 V and descending smoothly to the 12 V recharge threshold after 8 h, with no brownouts or thermal stress.

3.6. Mechanical robustness and electromagnetic compatibility

The printed chassis, pods, and mounts withstood repeated starts, stops, and mild uneven ground. On short grass and shallow slopes near five degrees, motion remained stable; in taller grass, the coil occasionally snagged, and wheels could slip, which is consistent with small, wheeled platforms.

Tests with motors at full speed and no nearby metal produced no false hits; Wi-Fi activity did not perturb the detector, likely due to frequency separation and physical layout.

3.7. Discussion

The discussion interprets the measured performance against the project objectives and examines the trade-offs revealed by testing. It considers how detection ranges, map accuracy, link responsiveness, and endurance support the intended use, and where constraints such as shallow depth, terrain sensitivity, and limited range affect outcomes.

Goal satisfaction – Results support the primary thesis goals. The robot detects and alerts small and medium metallic targets with brief and conspicuous buzzer and LED indications and automatically resumes when clear. Shared timestamp batching places callouts exactly on the track, enabling straightforward

after-action review of coverage and finds. Teleoperation through Blynk was responsive; the watchdog and reconnect logic preserved safe behavior under link variability.

Capability relative to expectations and handheld detectors – The detection envelope of about 3 cm for coin-scale objects and about 6 cm for larger metallic bodies aligns with expectations for a compact induction balance coil driven by a low-power board. Professional handheld systems, particularly pulse induction detectors with larger coils, can exceed these depths, especially for large metallic masses.

Usability, safety, and range – Smartphone-based control offers low entry cost and rapid deployment. The two-second inactive watchdog and default idle state at power-on provide guardrails against runaways. For larger areas or obstructed radio environments, radio alternatives such as sub-gigahertz links, repeaters, or cellular data would extend standoff distance. A dual link strategy could combine a high bandwidth primary path with a robust low-rate fallback for emergency stop and rearming. Cyber hardening of credentials and tokens, and mutual authentication are advisable for deployments beyond these preliminary trials.

Mapping quality and operator workflow – Five-second breadcrumbs produce readable paths without overloading the link; instantaneous grouped V_0 and V_3 on hits ensure visual coherence. Suppressing events when the GPS is invalid avoids misleading markers.

System economics and accessibility – The proposed set-up demonstrates that commodity modules, including ESP32 S3, L298N, GPS, and fixed-output buck converters, plus a mobile-first cloud, yield a complete detection to map pipeline. This lowers barriers in community and humanitarian contexts where

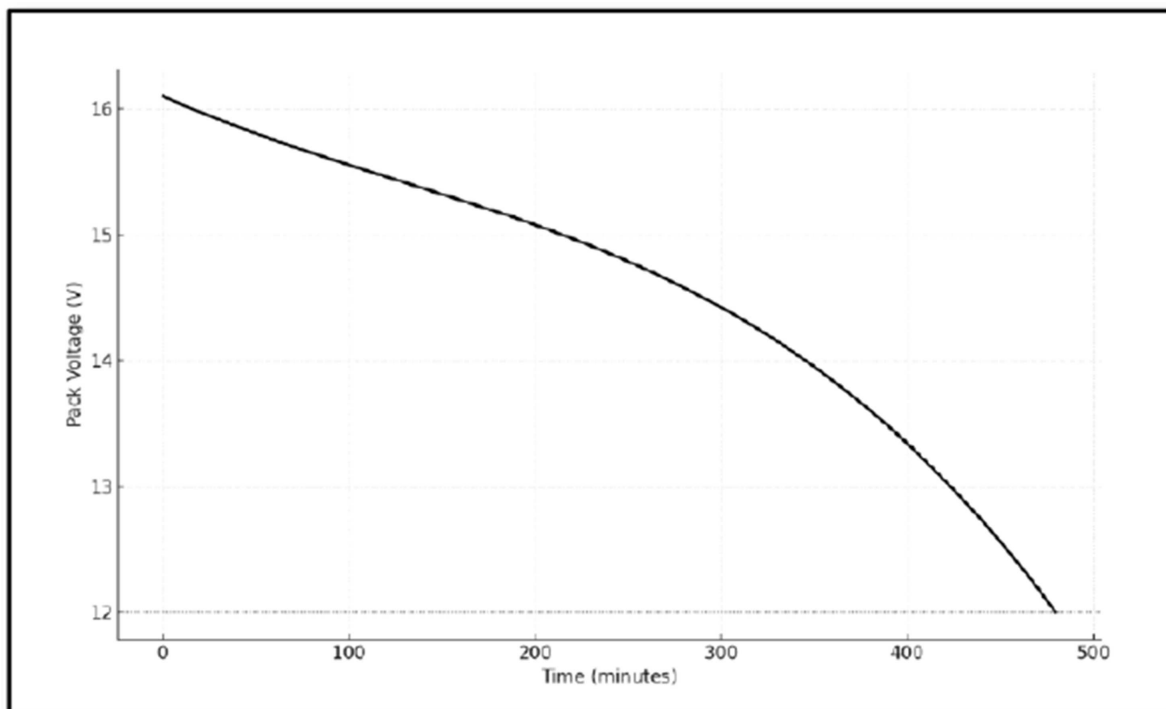


Figure 16
Curve of discharge, i.e., voltage [V] versus time [min]

budget and logistics constrain equipment acquisition, and it supports local fabrication and maintenance.

3.8. Limitations

This section summarizes the principal constraints observed during testing and how they affect suitability for real use.

Autonomy – Navigation and coverage are fully teleoperated; efficiency and repeatability depend on operator skill. Autonomous patterns, such as a lawnmower or snake, and obstacle avoidance would increase throughput and consistency.

Terrain envelope – Performance degrades in dense vegetation, sand, and steep grades; the coil can snag, and traction diminishes. Larger wheels, suspension or tracks, and a skid lip or compliant coil mount would improve passage.

Depth and discrimination – The current coil and electronics emphasize shallow detection and cannot classify targets. Pulse induction hardware, multi-frequency coils, or fusing a magnetometer could add depth and cues for triage. Ground-penetrating radar is possible, but it increases cost and complexity.

Endurance ceiling – Approximately one and a half hours of continuous runtime suits short sorties; larger batteries or quick swap trays extend operations but affect mass and handling.

Communications – Wi-Fi range is modest and environment dependent; link loss is mitigated by watchdogs but not eliminated. Long-range radios or cellular backhaul would be preferable for expansive sites.

Ruggedization – The prototype is not weather-sealed; the coil and electronics would need environmental protection and shock mitigation for harsh duty.

Comparative perspective – Within the landscape of small ground robots for sensing, this system occupies a practical middle ground. It is slower than aerial platforms but mechanically simpler and able to maintain constant coil height. It is less capable in depth than premium handheld pulse induction systems but adds objective geotagging and shareable telemetry. Prior robotic mine sensing efforts often required base station laptops and bespoke interfaces; the mobile-first cloud approach here provides a similar or better operator experience with far less infrastructure. The distinctive contribution is the timestamp-aligned detection to the map pipeline implemented on a low-cost edge platform. Grouped V_0 and V_3 updates, governed rates, and fail-safe controls deliver a coherent and reproducible record of where alerts occurred and how the platform moved.

4. Conclusion and Future Work

This section synthesizes what the project achieved, what the experiments revealed, and what should come next. It restates the core contributions of the mobile metal-detection robot, relates measured performance to the original objectives, and highlights the practical value of the detect map alert pipeline. It then sets out focused avenues for improvement in autonomy, sensing depth and discrimination, mobility and ruggedness, communications, and data workflow so the prototype can mature into a dependable field tool.

The project delivered a mobile metal-detection robot that integrates electromagnetic sensing, embedded control, cloud-connected telemetry, and map-based visualization.

Metal Detection's Performance – Bench tests and outdoor trials confirmed reliable detection and alerting. Coin-scale targets were detected at shallow depth, and larger metallic bodies were detected at greater distances. A confirm-and-hold filter with rearm

logic suppressed chatter so each validated event produced one audible and visual alert, after which scanning resumed automatically. This met the requirement to surface detections promptly and unambiguously for the operator.

Geotagging and Data Integrity – The geotagging pipeline produced map-aligned records of motion and detections. GPS breadcrumbs were published to virtual pin V_0 every 5 s in longitude followed by latitude. Field checks against ground references indicated position errors of a few meters with an average near 2 m, consistent with open-sky GPS performance and sufficient to guide a human operator to the vicinity of a detection.

Teleoperation and Network Behavior – Remote control through the Blynk mobile application was responsive over the Wi-Fi Eduroam network. Joystick updates on V_1 for throttle and V_2 for turn were serviced without blocking, and a command-loss watchdog idled the motors if updates stalled. End-to-end latency from user input to wheel motion was typically within a few hundred milliseconds, which was adequate for slow scanning.

Power and Mechanical Reliability – The power subsystem enabled continuous scanning without brownouts or abnormal heating. Extended mixed-use runs showed a practical endurance close to one and a half hours before recharge or battery swap.

Overall Performance – The system met the objectives of detecting metal, mapping detections, enabling safe teleoperation, and sustaining stable operation. It provides an end-to-end detection map alert pipeline that is accessible to operators using commodity hardware and a cloud service. This approach enhances safety by allowing the operator to work at a standoff and improves documentation by creating a permanent geospatial record of events.

This work demonstrates that a compact ground robot can deliver a coherent end-to-end pathway from sensing to decision support using widely available components. The system detects metallic targets in the shallow depth band relevant to many practical hazards, associates each detection with a geographic coordinate, and shares that information instantly with a remote operator. The mapping function converts a transient discovery into a durable record that supports verification and follow-up. The integration of embedded control, communication, and visualization was achieved without specialized base stations or proprietary interfaces, which lowers barriers for adoption in resource-constrained contexts.

The central contribution is a disciplined data design that keeps sensing, control, and mapping synchronized. By publishing breadcrumbs at a steady cadence and emitting detection markers in atomic lockstep with position, the system produces a trustworthy geospatial narrative of where the robot went and what it found. That narrative is accessible to any authorized device and exportable for archival and analysis. The approach is reproducible, economical, and adaptable, which makes it a promising foundation for future fieldable tools.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding Author upon reasonable request.

Author Contribution Statement

Brian Kaduma: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Visualization. **Emanuele Lindo Secco:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration.

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