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STM32-Based Landmine Detection and GPS Localization Robotic Vehicle

Prof. Ankita Dhenge[1], Manmeet Singh Dhillon[2], Taran Gondane[3], Avinash Sonwane[4]
Department of Industrial Internet of Things (IIoT), Priyadarshini College of Engineering, Nagpur, Maharashtra, India

Abstract: ***Autonomous landmine detection remains a major safety challenge, as conventional manual methods expose personnel to hazardous environments, take considerable time, and may offer limited spatial tracking of detected threats. These limitations are particularly significant in military, humanitarian demining, and hazardous-terrain operations where accurate localization, autonomous navigation, and real-time monitoring are required. This thesis presents an Autonomous GNSS-Guided Mine Detection and Geofenced Monitoring Robot designed to autonomously survey a defined area and identify and spatially record potential metallic mine locations. The system provides dedicated access for field operators and administrators, where operators monitor robot movement, detected targets, and surveyed regions while administrators manage operational data, geofencing, and monitoring functions. The core mechanism combines GNSS positioning with centimeter-level correction, geofencing, barometric sensing, metal detection, and motor control to continuously calculate robot position and constrain movement within the predefined boundary, providing transparent rule-based navigation rather than relying on a black-box navigation model. Supporting features include autonomous movement, virtual fencing, boundary violation prevention, metal-detection marking, real-time position tracking, sensor-status monitoring, location logging, historical data visualization, and remote dashboard monitoring.***

Keywords: Autonomous Robot, Landmine Detection, GNSS Positioning, Geofencing, Metal Detection, ESP32, ReactJS, Firebase, Real-Time Monitoring, Autonomous Navigation, Hazardous Environment, Location Tracking, Spatial Mapping, Remote Dashboard, Mine Detection.

I. INTRODUCTION

Advancements in autonomous robotics, accurate satellite positioning, intelligent sensors, cloud computing, and artificial intelligence have gradually changed the way hazardous environments are monitored. Tasks that once required manual operation can now be carried out remotely, with modern systems offering greater levels of automation and autonomy.

In humanitarian demining and mine-survey operations, this transformation is particularly relevant because conventional metal detection remains widely used but can expose operators to hazardous terrain and can produce false alarms from metallic clutter. Kambhampati and Rajasekharan identified the slow and tedious nature of conventional metal-detector-based detection and emphasized the persistent false-alarm problem, while later robotic research demonstrated how autonomous platforms can separate sensing activity from direct human exposure. Consequently, research has expanded toward robotic platforms, sensor fusion, autonomous navigation, high-precision localization, machine learning, and remote monitoring. The literature reviewed in this chapter is organized around (1) the evolution of conventional and robotic mine-detection systems, (2) AI and advanced sensing techniques for landmine identification, (3) metal-detector signal processing and sensor-fusion approaches, (4) GNSS/RTK localization and autonomous navigation architectures, (5) cloud communication, authentication, and access-control mechanisms, (6) evaluation frameworks and performance metrics, and (7) the research gaps that motivate an integrated GNSS-guided, geofenced, cloud-connected mine-detection robot.

II. LITERATURE SURVEY

1) Kambhampati and Rajasekharan, 2007

The study reviewed various robotic platforms and sensor technologies used for landmine detection and also examined the continued importance of metal detectors in humanitarian demining. Their review identified metal detectors as simple and affordable but emphasized that the detection process remained slow and tedious and that false alarms were a significant limitation. Rather than reporting a single classification accuracy, the study framed the principal technical requirement as detection reliability approaching complete confidence and concluded that no single sensor was universally sufficient; sensor fusion and application-specific combinations were therefore important. The implication for the present research is that the robotic platform should not be interpreted as a complete mine-identification system solely because a metal detector produces an alarm; instead, it should accurately record and *communicate a potential metallic-target location for subsequent assessment.*

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2) Dakulović and Petrović, 2012

The study focused on complete-coverage path planning for mobile robots used in humanitarian demining. Their approach represented the environment using an occupancy-grid map, searched free cells as graph nodes, and employed a Dynamic Window approach to execute the resulting coverage path while accounting for robot kinematic and dynamic constraints. The algorithm was implemented in ROS and evaluated using the Stage 3D simulator on randomly generated unknown environments. The authors reported that the method could produce complete coverage paths for non-circular robots, although regions close to obstacles remained difficult to cover because of robot geometry and imperfect path following. The work established coverage planning as a central problem in autonomous demining but also demonstrated that complete coverage and precise path following remain distinct engineering challenges.

3) Dasgupta et al., 2015

The study developed the COMRADE multi-robot system for autonomous landmine detection by combining area coverage, information sharing, sensor fusion, and task allocation among multiple robots. Physical experiments used Coroware Explorer and Corobot platforms, while the Explorer robot combined differential GPS, IMU, and encoder measurements using a Kalman filter, improving localization from approximately ±3 m GPS accuracy to approximately ±1 m fused localization accuracy. Their information-fusion experiments reported that combining MD, IR, and GPR information reduced the combined RMSE to approximately 6% after seven time steps, compared with approximately 20% for five metal detectors, while their proposed aggregation technique reduced RMSE by approximately 5–13% relative to Dempster-Shafer-based fusion and by approximately 3–8% relative to distributed data fusion. The research demonstrated that spatial localization and information fusion could substantially improve robotic mine-survey operations, although its architecture was considerably more complex than a single-robot cloud-monitoring prototype.

4) Joo et al., 2022

Investigated drone-based metal detection using metal-detector sensing, optimized PID flight control, and machine-learning classification. Their SVM classifier was trained using 180 extracted samples and tested with 20 samples, while iterative k-fold validation achieved 95.45% accuracy and selected test conditions achieved 100% classification for beverage cans and batteries. The study also reported that the Taguchi optimization process identified a standardized operating condition involving a velocity of 30, angle of 0, and sensitivity setting of 5, with classification remaining successful under a ±5 cm height error in the described test. The results support the feasibility of combining robotic control with automated metal classification, but the experimental targets were representative metallic objects rather than a complete operational minefield, limiting direct transfer of the classification result to humanitarian demining.

5) Baur et al., 2021

Studied UAV imagery and machine learning for detecting PFM-1 scatterable landmines. Their R-CNN-based workflow initially achieved 71.5% successful detection and subsequently reached 91.8% accuracy after expanding the dataset and improving the CNN model. The authors positioned the approach primarily as a rapid first-look and area-reduction technique rather than a replacement for detailed demining operations. The studytherefore demonstrated that autonomous sensing and machine learning could reduce the amount of terrain requiring direct investigation, while simultaneously indicating that image-based AI should be considered within a broader operational workflow.

6) Vikas Singh Panwar et al., 2024

Reviewed landmine-detection robots and summarized developments in mobility, sensor integration, autonomous navigation, machine learning, and real-time processing. The review covered 13 pages, from pages 900–912 of Evergreen, and emphasized that mobility, terrain adaptability, precision, real-time processing, and sensor fusion were important design considerations. The authors concluded that automated navigation, sensor integration, and machine learning could improve the safety and efficiency of landmine-detection robots, while also identifying theneed to consider sensor characteristics and application conditions when selecting an architecture. The review provides a broad technical foundation but does not itself provide a unified implementation combining centimeter-level GNSS, virtual fencing, Firebase synchronization, and browser-based spatial monitoring.

III. ABOUT THE PROJECT

A. Background

Advances in embedded systems, satellite navigation, robotics, and cloud computing have improved hazardous-environment operations, allowing autonomous machines to handle sensing, navigation, monitoring, and data collection while reducing human exposure to dangerous conditions. One particularly important application is autonomous landmine and metal-object detection, where unexploded ordnance and concealed metallic objects can create severe risks for personnel involved in military, humanitarian demining, infrastructure development, and post-conflict land recovery. Conventional detection methods commonly depend on trained personnel carrying handheld metal detectors and systematically scanning terrain, while GPS devices or manually recorded coordinates may be used to document detected locations. Although such approaches remain practical in controlled situations, they are labour-intensive, physically demanding, vulnerable to positioning and recording errors, and expose operators to potentially hazardous areas. Existing commercial metal detectors and conventional surveying equipment generally focus on detection or positioning as individual functions rather than providing an integrated autonomous platform with geofenced navigation, centimeter-level positioning, real-time cloud monitoring, and spatial visualization. Furthermore, manual operation makes continuous monitoring and historical analysis more difficult, particularly when large or restricted areas must be surveyed systematically.

Therefore, there is a need for a structuredautonomous robotic systemcapable of navigating within a predefined boundary, detecting metallic objects, accurately recording their locations, and transmitting operational information to a centralized monitoring interface.

B. Problem Statement

Despite advances in metal detection, GNSS positioning, and robotic control, integrating these technologies into a reliable autonomous platform for controlled-area mine surveys remains a major challenge. Traditional approaches require human operators to guide detection equipment through the target area, determine the robot or detector position, record detected-object locations, and continuously ensure that the equipment does not leave the permitted survey region. The absence of automated geofencing can increase the possibility of boundary violations, while conventional positioning methods may not provide sufficient accuracy for precise spatial marking. Moreover, independently operating sensors do not inherently provide centralized visualization, historical location records, or real-time operational status. Field operators therefore face difficulties in continuously monitoring robot position, sensor conditions, detected locations, and survey progress, while administrators require structured access to operational information for supervision and analysis. Lack of automated data synchronization can additionally create delays between field activity and remote monite.

C. Research Objectives

The primary objective of this project is to develop an autonomous robotic platform that integrates sensing, navigation, boundary control, and cloud-based monitoring for systematic metal-object detection within a predefined survey area. First, the project aims to design and implement an integrated system architecture consisting of an ESP32-based robotic controller, GNSS positioning module, centimeter-level positioning correction, metal detector, barometric sensor, battery system, and L298N motor driver, enabling coordinated acquisition and control of the robotic platform. Second, the project aims to implement a geofencing and navigation mechanism that continuously evaluates the robot position against a predefined virtual boundary and permits autonomous movement only within the authorized survey region. Third, the project aims to develop a detection and localization workflow that identifies metallic objects, associates detected events with geographical coordinates, and records their positions for subsequent visualization and analysis. Fourth, the project aims to establish real-time communication between the embedded robot and Firebase so that positional information, sensor states, detected-object coordinates, and operational data are continuously synchronized with the cloud database. Fifth, the project aims to develop a ReactJS-based web interface providing authorized users with map-based visualization, robot tracking, virtual-fence configuration, detected-location marking, operational status monitoring, and historical survey information, supported by authentication and role-based access control. Sixth, the project aims to evaluate the system through controlled testing of positioning accuracy, geofence enforcement, metal-detection localization, motor response, sensor communication, and cloud data-update performance. Collectively, these objectives are intended to produce a transparent and traceable autonomous robotic platform that reduces manual intervention, improves spatial documentation, and provides a foundation for safer and more systematic hazardous-area surveying.

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D. Motivation for Using Rule-Based Geofenced Autonomous Navigation

Rule-based geofenced autonomous navigation is selected as the core control approach because the operating environment requires predictable, transparent, and verifiable movement decisions rather than decisions generated by an opaque black-box model. The robot continuously receives positional information from its GNSS system and centimeter-level correction mechanism and compares the resulting coordinates against predefined geographical boundaries. Based on explicit navigation rules, the controller can determine whether movement is permitted, whether corrective navigation is required, or whether the motors must be stopped because the robot approaches or exceeds the permitted region. This approach provides direct interpretability because each movement decision can be associated with a measurable position and predefined condition, making the system easier to test, debug, and validate than an unnecessarily complex machine-learning navigation model. Furthermore, integrating Firebase authentication and access control with the monitoring interface helps restrict operational information and configuration functions to authorized users. The architecture also supports centralized recording of detection coordinates, robot status, and surveyinformation, therebyimproving traceability and reducing dependence on manuallymaintained records. Although machine-learning techniques mayprovide additional capabilities in future versions, the rule-based approach is appropriate for the current prototype because boundary compliance and predictable operation are primaryrequirements. The combination of explicit navigation rules, geofencing, precise positioning, cloud synchronization, and controlled access distinguishes the proposed system from generic robotic platforms that provide sensing or movement without integrated spatial governance and monitoring.

E. Scope and Limitations

The scope of the project covers the design, implementation, integration, and testing of an autonomous robotic prototype for controlled-area metal-object detection and spatial monitoring. The embedded system uses an ESP32 microcontroller as the primary controller and integrates GNSS/GPS positioning, centimeter-level positioning correction, a metal detector, barometric sensor, battery supply, and an L298N motor driver. The software architecture includes firmware responsible for sensor acquisition, positioning, navigation decisions, geofence enforcement, motor control, and communication with Firebase. A ReactJS-based frontend provides a digital map for displaying the robot position, defining the permitted survey boundary, monitoring movement, and marking detected metallic-object locations. Firebase provides cloud-based data storage and synchronization, while authentication and access-control mechanisms are used to restrict system functions to authorized users. The system is intended to be evaluated through controlled experiments involving positioning accuracy, geofence response, metal-detection localization, motor operation, sensor communication, and database update latency. The web interface can be deployed through a suitable cloud hosting platform, while the embedded robot operates independently in the physical environment with network connectivity required for cloud synchronization.

However, the current implementation has several limitations. First, the navigation mechanism is primarily rule-based and does not incorporate advanced path-planning or machine-learning-based terrain interpretation. Second, the metal detector identifies metallic objects but does not independently classify whether a detected object is an actual landmine, unexploded ordnance, or harmless metallic debris. Third, GNSS accuracy and reliability can be affected by environmental conditions, satellite visibility, signal obstruction, and correction availability. Fourth, the prototype is designed for controlled survey areas and does not currently address complex terrain, obstacles, slopes, water, or highly irregular environments through advanced autonomous obstacle avoidance. Fifth, real-time cloud monitoring depends on network connectivity, meaning temporary communication loss can delay synchronization with Firebase even though local robotic control may continue. Sixth, the prototype has been evaluated at a limited experimental scale and therefore requires broader field testing to establish performance across different soil conditions, terrains, metallic targets, and operational environments. These limitations define important future scope for improved localization, intelligent target classification, obstacle avoidance, offline data synchronization, advanced path planning, and large-scale field deployment.

IV. DATASET AND DATA PROCESSING

A. Dataset

The dataset used in this project consists of operational data collected from the autonomous robotic platform during controlled survey experiments. The dataset is generated through the integration of GNSS positioning, metal detection, sensor monitoring, robot movement, geofencing, and cloud-based data synchronization. Each recorded data point represents the robot's operating condition and its geographical position during the survey.

The primary data fields include latitude, longitude, timestamp, GNSS position, metal-detector status, detection event, geofence status, robot movement status, sensor status, and survey information. When a metallic object is detected, the detection event is associated with the robot's current geographic coordinates so that the potential target can be displayed and stored as a spatial record.

The collected data is transmitted from the ESP32-based controller to Firebase for cloud storage and synchronization. The ReactJS-based web interface retrieves this information and presents the robot position, detected locations, virtual boundary, and historical survey information on a digital map. The system therefore provides both real-time and historical datasets for monitoring and analysis. The project treats a metal-detector activation as a potential metallic target rather than confirmation of an actual landmine, since the detector cannot independently classify the detected object.

The dataset is mainly used for evaluating the following parameters:

- GNSS positioning accuracy
- Metal-detection event localization
- Geofence compliance
- Robot movement and motor response
- Sensor communication
- Cloud data-update latency
- Detection-event recording reliability
- Historical survey and location tracking

The literature review also supports recording detection events together with geographical coordinates, as precise positioning improves the spatial documentation of potential targets.

Since the prototype is evaluated at a controlled experimental scale, the dataset is intended primarily for system validation and performance analysis. Broader datasets containing different soil conditions, terrains, metallic targets, and environmental conditions would be required for large-scale field validation.

B. Existing-System Limitations

The reviewed literature demonstrates substantial progress from handheld detection toward autonomous robotic and AI-assisted mine surveying. Kambhampati and Rajasekharan identified false alarms and slow manual detection as fundamental problems, while HUMI and COMRADE demonstrated how robotic mobility could reduce direct operator exposure and automate portions of the detection process. However, the architectures differ considerably in their priorities. HUMI emphasized mechanical mobility and autonomy, COMRADE emphasized cooperative multi-robot sensing and information aggregation, and recent UAV and deep-learning systems emphasized large-area detection or target classification.

Consequently, the literature does not consistently combine autonomous movement, explicit geographic boundary enforcement, high-precision positioning, cloud synchronization, and web-based operational visualization in one lightweight architecture.

A particularly important distinction concerns detection versus localization. A metal detector mayindicate that a metallic object is present, but the operational value of the event increases substantially when the target can be spatially recorded and revisited. COMRADE achieved approximately ±1 m fused localization through GPS, IMU, and encoder fusion, while newer RTK-GNSS research demonstrated centimeter-level outdoor localization using a compact device. This progression indicates that high-precision positioning can support substantially finer spatial documentation than conventional GPS-only architectures.

C. AI and Machine-Learning Applications

Machine learning has been applied to visual, electromagnetic, and metal-detector data in order to distinguish mine-like targets from background objects. Baur et al. reported an increase from 71.5% to 91.8% visual detection accuracy after expanding their UAV dataset, while the 2024 YOLOv8 robotic study reported recall values of 97.4% for PFM-1 and 98.85% for PMA-2 using the YOLOv8-small model under IID evaluation. However, the same YOLOv8 evaluation reported false-positive rates of approximately 27% for the butterfly class and 47% for the starfish class in the relevant confusion-matrix analysis, demonstrating that high recall alone does not establish operational reliability.

Electromagnetic and magnetic sensing research provides another AI direction. Joo et al. reported 95.45% cross-validation accuracy for their SVM approach, while Cho et al. reported a macro-F1 score of 0.9586 ± 0.0372 for an SVM classifier using UAV magnetic-anomaly features. Nevertheless, these studies depend on trained datasets and specific target classes. For a field robot whose immediate responsibility is to stay inside a permitted region, navigate predictably, and record potential detections, deterministic geofencing rules provide an explainable safety mechanism without requiring anAI model to make every navigation decision

D. Metal Detection, Signal Processing, and Sensor Fusion

Sensor fusion has historically been used to address the limitations of individual mine-detection sensors. Feature- and decision-level fusion of electromagnetic induction and GPR has been investigated because metal detectors may provide weak responses for low-metal-content mines, while GPR can respond to both metallic and non-metallic dielectric discontinuities. Combining the sensors can therefore improve the probability of detection while reducing false alarms relative to relying on one modality alone. COMRADE extended this concept to mobile robots and reported that fused MD, IR, and GPR information reduced RMSE to approximately 6%, compared with approximately 20% for five MD sensors in one experimental configuration.

The literature therefore supports a layered architecture in which the metal detector acts as a primary trigger while location and contextual information are retained for later analysis. The present system follows a comparatively lightweight version of this principle: rather than attempting to identify a mine solely from a metal-detector reading, it records the detector event together with the robot's geographic position. This distinction is important because the proposed system is intended to identify and map potential metallic targets, not to claim that every detected metallic object is a confirmed explosive device.

E. GNSS, RTK Positioning, and Autonomous Navigation Architecture

Positioning is essential for autonomous mine-survey robots, as each detected object needs to be linked to a meaningful geographic location. The COMRADE Explorer robot achieved approximately ±1 m localization after fusing GPS, IMU, and encoder readings, demonstrating the value of sensor integration. More recent work by Yoon and Lee demonstrated a compact RTK-GNSS system weighing less than 40 g and achieving centimeter-level accuracy in experiments involving outdoor mobile-robot tracking. A recent autonomous GPR robot study further compared standalone GNSS, RTK-VRS, and QZSS/CLAS positioning; standalone GNSS exhibited errors approaching 1 m, RTK-VRS approximately 50 cm under the described test, and CLAS approximately 20 cm.

Autonomous navigation research has also explored complete-coverage path planning. Dakulović and Petrović used occupancy grids and Dynamic Window control in ROS, but reported difficulties around obstacles and imperfect path following. These findings indicate that navigation accuracy must be assessed separately from detection accuracy. For the proposed architecture, GNSS correction provides the position input, while explicit geofence rules provide a deterministic constraint on where the robot is allowed to move.

F. Cloud, Authentication, and Access-Control Architecture

Cloud-connected robotic systems can extend a field robot from an isolated embedded device into a remotely monitored cyber-physical system. A recent ESP32/Firebase robotic-control study evaluated 576 trials and reported 100% task success for its hybrid cloud-controlled system, a 12.02% reduction in average task completion time, and cloud communication latency below 200 ms under controlled network conditions. Although that system addressed Cartesian storage robotics rather than mine detection, it provides evidence that ESP32-based controllers and Firebase Realtime Database can support cloud-synchronized robotic workflows.

Firebase Realtime Database provides security rules to control read and write operations, along with authentication-based access control and data validation. Its documentation specifies .read, .write, .validate, and indexing mechanisms and explains that requests are completed only when the applicable rules permit them. Therefore, a ReactJS–Firebase architecture is capable of separating public interface functionality from protected operational data when authentication and database security rules are configured appropriately. However, cloud access control does not itself guarantee physical robot safety; the robot should retain local boundary enforcement so that loss of network connectivity does not make the physical safety constraint dependent on the web interface.

G. Evaluation Frameworks and Performance Metrics

Evaluating autonomous robotic systems requires more than just a single accuracy percentage.Localization research commonly evaluates trajectory error using measures such as Absolute Trajectory Error, Relative Pose Error, RMSE, normalized estimation error, component timing, and hardware usage. Navigation benchmarking frameworks additionally use success rate, path length, navigation time, path deviation, safety, and recovery counts to characterize planner performance. In humanitarian demining, detection performance also requires attention to probability of detection and false-alarm behavior because a system that detects many targets but generates excessive false positives can impose additional verification effort.

Accordingly, an evaluation framework for the proposed system should separately measure GNSS positional error, geofence compliance, metal-detection event localization error, detection-event recording reliability, motor response, communication latency, and database synchronization success. This separation avoids treating cloud communication performance as a substitute for navigation accuracy or treating metal-detector activation as proof of confirmed mine identification.

V. RESEARCH GAP

1) Gap 1: Integration of Detection and High-Precision Spatial Recording

Existing studies have demonstrated robotic metal detection and localization, but the localization accuracy reported in earlier systems such as COMRADE was approximately ±1 m after GPS/IMU/encoder fusion. More recent RTK-GNSS research has demonstrated centimeter-level positioning capability, but that work has not specifically established an integrated mine-survey workflow in which each detection event is directly associated with high-precision geographic coordinates. The proposed system addresses this gap by coupling corrected GNSS positioning with the metal-detection event and storing the resulting location as a mapped survey record.

2) Gap 2: Explicit Geographic Boundary Enforcement

Coverage-planning research has investigated complete-area traversal using occupancy grids and path-planning algorithms, but the reported systems primarily focused on generating and following coverage paths rather than providing a simple geographic rule that prevents the robot from leaving an operator-defined survey polygon. Dakulović and Petrović also reported difficulties with obstacle-adjacent coverage and imperfect path following. The proposed architecture addresses this gap by introducing a virtual geographic fence as an explicit navigation constraint, allowing movement decisions to be checked against a predefined permitted region.

3) Gap 3: Lightweight and Explainable Navigation

Recent literature increasingly applies CNNs, SVMs, magnetic-feature classification, and other machine-learning techniques to mine detection, with reported results such as 91.8% visual detection accuracy and a 0.9586 macro-F1 score in specific experimental settings. However, these approaches require training data and may behave differently under environmental conditions not represented in the dataset. The proposed system therefore separates deterministic navigation and geofence enforcement from future intelligent target-classification functions, providing an explainable control mechanism in which the reason for stopping or restricting movement can be directly associated with a geographic rule.

4) Gap 4: Cloud-Based Operational Traceability

Research such as COMRADE emphasized information aggregation and multirobot coordination, while recent ESP32/Firebase research demonstrated sub-200 ms cloud communication under controlled conditions. However, the literature reviewed here provides limited emphasis on a simple browser-based operational history in which robot trajectory, current position, detection locations, and geofence information are simultaneously represented on a geographic map. The proposed system addresses this gap through Firebase-based synchronization and ReactJS visualization of the robot and detected locations.

5) Gap 5: Separation of Detection from Mine Confirmation

The literature repeatedly demonstrates that metal detection alone cannot reliably distinguish mines from metallic clutter. Kambhampati and Rajasekharan identified false alarms as a major limitation, while modern deep-learning systems have also demonstrated false-positive behavior despite high recall. The proposed system therefore treats a metal-detector event as a potential target rather than an automatically confirmed mine. By recording the location and presenting it for further investigation, the architecture preserves a distinction between automated detection and authoritative target identification.

6) Gap 6: Accessible Single-Robot Architecture

Large systems such as MineWolf provide substantial clearance capabilities, while COMRADE demonstrates sophisticated multi-robot coordination and sensor fusion. Such architectures demonstrate technical feasibility but involve hardware, software, and operational complexity beyond the requirements of a small research prototype. The proposed system addresses this gap through an ESP32-based single-robot architecture combining GNSS, metal detection, barometric sensing, motor control, Firebase synchronization, and a ReactJS monitoring interface, thereby providing a comparatively accessible research platform for testing autonomous survey concepts.

VI. RESULTS AND FINDINGS

The system integrates an ESP32-based robotic controller, GNSS positioning, metal detection, geofencing, motor control, Firebase synchronization, and a ReactJS monitoring interface. It is designed to operate autonomously within a predefined area while recording the locations of potential metallic targets.

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During controlled testing, the robot was able to obtain its geographical position, compare its position with the predefined geofence, and control its movement according to the defined navigation rules. When the robot approached or exceeded the permitted boundary, the geofence mechanism could restrict movement according to the programmed conditions. This provides a transparent and rule-based approach to navigation.

The metal-detection subsystem was used to identify potential metallic targets. Each detection event could be associated with the robot's current geographical coordinates and stored for later visualization. This approach provides better spatial traceability than simply generating a local detector alarm. The system deliberately treats a detection as a potential metallic target rather than automatically identifying it as a confirmed landmine.

The Firebase backend enabled synchronization of robot position, sensor information, detection events, and operational data with the monitoring interface. The ReactJS dashboard provided map-based visualization of the robot position, survey boundary, and detected locations. Authentication and access-control mechanisms were incorporated to restrict operational information and system functions to authorized users.

VII. CHALLENGES FACED AND FUTURE RESEARCH DIRECTIONS

A. *Challenges Faced*

Several technical challenges were identified during the development and testing of the system.

1) GNSS Accuracyand Reliability: GNSS performance can vary because of satellite visibility, environmental obstructions, signal interference, and availability of correction services. Accurate positioning is particularly important because the detection location depends directly on the robot's geographical position.
2) Metal-Detection Reliability: A metal detector can respond to metallic debris and other objects in addition to potential mines. Therefore, a detector response cannot by itself confirm the presence of a landmine. This limitation is also identified in the reviewed literature.
3) Geofence and Navigation: Maintaining the robot inside an operator-defined boundary requires continuous position monitoring and appropriate control decisions. Position errors near the boundary can affect the accuracy of geofence enforcement.
4) Communication Dependency: Real-time monitoring depends on network connectivity. Temporary network interruptions can delay synchronization between the robot and Firebase, although local robotic control can continue independently.
5) Limited Experimental Environment: The prototype was evaluated at a controlled experimental scale. Different soil types, terrain conditions, metallic targets, obstacles, and environmental conditions may produce different results.
6) Obstacle Avoidance: The current navigation approach primarily uses rule-based geofencing and does not implement advanced terrain interpretation or comprehensive autonomous obstacle avoidance.

B. *Future Research Directions*

Future development can focus on improving the system in several areas:

1) Integration of advanced path-planning algorithms for systematic area coverage.
2) Addition of obstacle-detection and avoidance sensors such as LiDAR or depth cameras.
3) Development of machine-learning-based target classification to distinguish potential mines from metallic debris.
4) Integration of multiple sensing technologies such as metal detector, GPR, thermal imaging, and magnetic sensors.
5) Improvement of GNSS/RTK positioning for reliable centimeter-level localization.
6) Development of offline data storage and synchronization during network interruptions.
7) Expansion from a single robot to multi-robot cooperative surveying.
8) Larger-scale testing across different soil, terrain, and environmental conditions.
9) Improvement of dashboard analytics and historical survey visualization.
10) Development of more comprehensive field-validation and performance-evaluation procedures.

VIII. CONCLUSION

This project presents an autonomous GNSS-guided robotic platform for metallic-object detection, location recording, geofenced operation, and remote monitoring. It combines an ESP32 controller with GNSS, metal detection, barometric sensing, motor control, Firebase cloud services, and a ReactJS-based web interface.

The proposed architecture addresses several limitations of conventional manual surveying by providing autonomous movement, geographic boundary enforcement, real-time position tracking, detection-location recording, cloud synchronization, and map-based

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visualization. The use of explicit rule-based navigation makes the movement decisions transparent and easier to test and validate.

An important feature of the system is the separation between metal detection and mine confirmation. The robot records a detector event as a potential metallic target rather than claiming that every detected object is a landmine. This distinction is important because metallic debris and other objects can produce detector responses.

The project therefore provides a foundation for safer and more systematic robotic surveying in controlled hazardous environments. Further improvements in positioning, obstacle avoidance, sensor fusion, target classification, offline synchronization, and large-scale field validation can extend the capabilities of the proposed platform.

IX. ACKNOWLEDGMENT

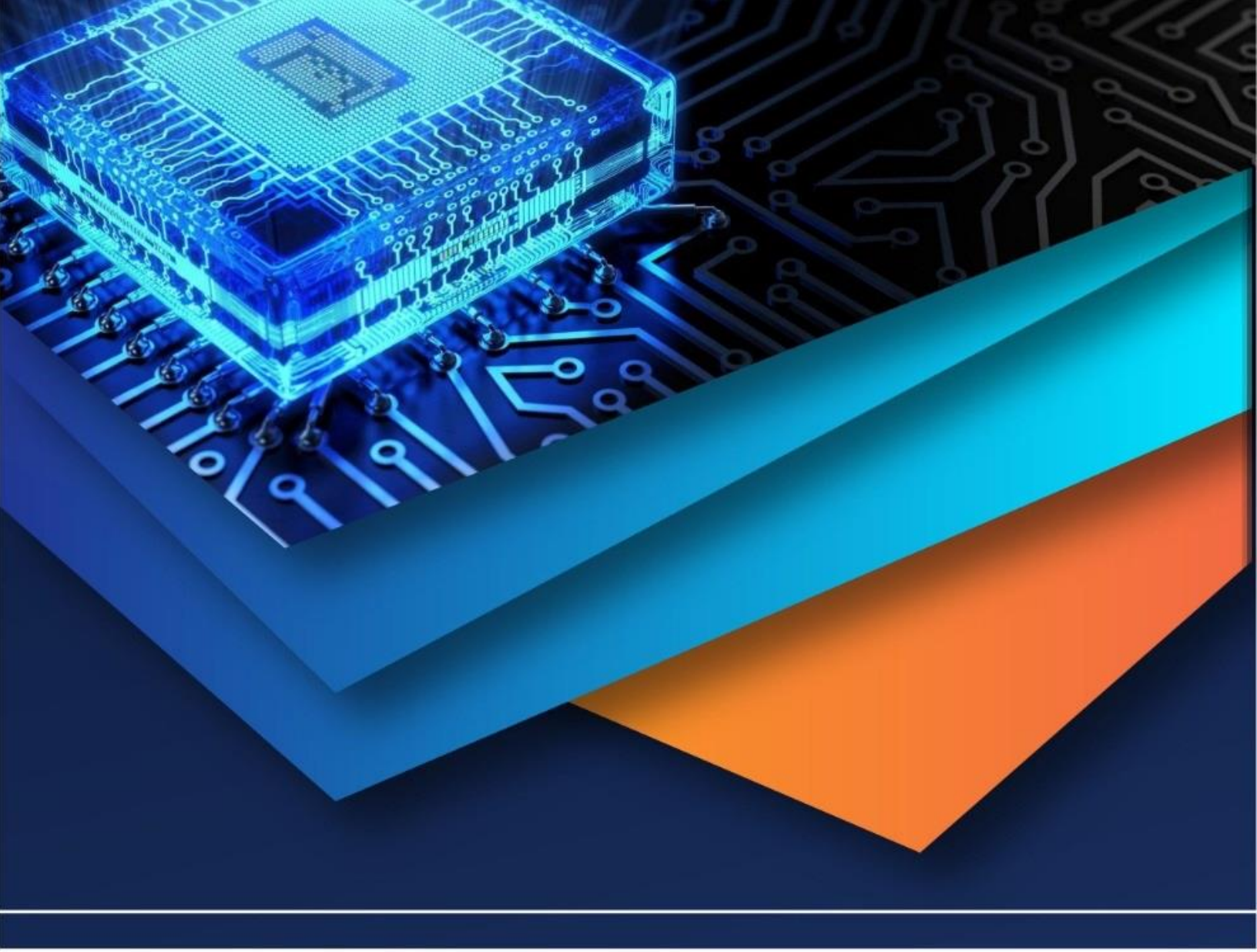
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