C.L.E.A.R: An Intelligent Iot-Based Autonomous Rover For Landmine Detection And Recognition

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Abstract- *There exists a considerable risk posed to human personnel in the process of conducting field inspections and identifying mines. In order to counteract such issues, the proposed work introduces CLEAR (Counter Landmine Exploration and Recognition Rover), which is a portable and remotely controlled robot that can be employed in dangerous locations for investigating the terrain and detecting metal objects. The robot is supposed to minimize human presence near possible explosive areas by being cheap in implementation and easy to deploy. The robot uses a pulse-induction sensing technique placed under the vehicle for detecting any underground metallic anomalies. An STM32F411CEU6 microcontroller manages all actions of the platform, such as sensor acquisition, motor control, wireless transmission, and detection processing. In addition, a web-based dashboard has been designed to display telemetry data and detect positions on the digital map interface. The experiment was carried out using buried metallic objects. The proposed system has shown high performance in detecting buried metallic objects with low latency. Positioning tags based on the GNSS technology have been used to mark detected objects. The whole system has been put together within the budget of less than USD 100, which means that it is possible to build an affordable robotic system to assist with landmine awareness.*

Keywords: Embedded Robotics, GNSS Tracking, IoT Monitoring, Landmine Awareness, Pulse-Induction Detector, Remote Rover, Unmanned Ground Vehicle, Wireless Telemetry.

I. INTRODUCTION

Nevertheless, in some areas of the world, there are still explosive devices hidden beneath the Earth's surface, which pose a threat to the population even many years after the end of military operations. For such individuals, agricultural activities, walking along roads and reconstruction of settlements become extremely risky actions. According to the data provided by the International Campaign to Ban Landmines, there are millions of landmines that have not yet been detonated in different countries of the world [1].

Speaking about the process of landmine detection, it is necessary to point out that the current technology of doing so implies manual detection of mines with the help of metal detectors and probes. This process is extremely time-consuming and risky for demining professionals. There are also machines that may be used for cleaning territories of mines, but the utilization of this machinery is rather ineffective due to the lack of manoeuvrability in limited space.

This will facilitate the rover moving in small places because of its compact nature when compared with bulky mechanical machines. Besides detecting the presence of objects, the system will also store their coordinates and transmit the information to the monitoring dashboard via wireless transmission.

Several researchers have utilized robots in mine detection and exploration of hazardous regions [2][4]. However, the issue with the majority of the robotic systems is that they use highly expensive processors or even sophisticated software or special hardware that may not be economically viable. Some robotic systems have proved to be efficient in object detection, but they neglect other important issues such as user-friendliness. The concept behind designing this robot is to develop a low-cost and user-friendly system.

Here comes the solution called CLEAR (Counter Landmine Exploration and Recognition Rover). To address the aforementioned issues, the following four decisions are made regarding the development of the system: (a) All computations are made on one USD 5 STM32F411 microcontroller instead of an expensive application processor; (b) The timing of firmware with a period of 50 ms enables simultaneous execution of all operations, such as metal detection, orientation measurement, GNSS data processing, and motor control; (c) No dependency browser-based dashboard is used instead of visualization software based on ROS; and (d) All system components can be purchased for less than USD 100, making the technology applicable for NGOs conducting de-mining in challenging conditions.

The rest of the paper is organized as follows. Section II considers CLEAR in the context of the literature. Section III describes the system architecture, while Section IV deals with the system hardware implementation. Section V covers the design of the firmware. Section VI addresses experimental results.

II. RELATED WORK

However, the field of study concerned with the deployment of robots in detecting and disarming mines has been around for several decades now. The primary objective of the early studies in this field was to minimize risks involved in the process of inspection and deactivation of mines through robotic systems. One of the most cited studies in the literature in this context is that of Mohamed Habib [2]. In this study, he classified the demining robots according to the type of locomotion and sensory systems used in them. These locomotion types may vary from wheeled, tracked to legged robots. Though wheeled robots tend to be more effective, tracked robots are suitable for rugged terrains.

Amongst the different sensing techniques available for detecting mines, one of the most common and popular sensing techniques used is that of pulse induction metal detectors. Pulse induction involves sending a magnetic pulse through the coil into the soil, which then detects any conductive materials in the vicinity through an electromagnetic pulse. As opposed to other sensing techniques based on waves, pulse induction technology is highly effective in detecting metal objects in soils filled with minerals, and is impervious to external magnetic fields [3]. However, one major drawback of metal detection technology is its inability to detect plastic mines containing very small quantities of metals. This problem has been addressed in several attempts where metal detection technology has been combined with other sensing techniques such as GPR and hyperspectral imaging [4][5].

The second important feature of robotic mine clearance devices concerns the ability to detect and provide precise coordinates of the discovered objects. Based on the results of the research in the MINBOT project [6] and the study of Acar et al. [7], the use of advanced methods of location has been implemented in order to achieve high precision in identifying the target objects. In most cases, the differential GNSS technology was applied in order to ensure high precision (down to centimetre level). In the case of the developed CLEAR robot, the less expensive device, i.e., the NEO-6M GPS module, was chosen, and the meter precision was considered enough for the localization of suspicious areas during the initial stage of inspection.

In relation to monitoring the performance of robots, the previous approaches applied the ROS-based visualization tools such as RViz. Though they were quite efficient, they required the installation of Linux systems and other configurations. The developed CLEAR robot utilizes a more convenient method of monitoring that is based on the HTTP protocol. This means that there is no need for any special software and configuration of the robot's software framework since the monitoring can be done through a web browser.

III. SYSTEM ARCHITECTURE

STM32F411CEU6 Black Pill is the main CPU used in the rover. The rover uses three hardware UARTs of STM32 to receive GNSS NMEA data via UART1 (with DMA) and transmit MSP telemetry frames via UART2. The sensors are connected to the rover via I2C bus 1; PI coil is connected to the analog input PC0 and is also measured using internal 12-bit successive approximation ADC. Motor torque is created by using the L298N dual H-bridge, where its enable pins are connected to the hardware PWM signals generated by the STM32 timers TIM1 and TIM2.

The ESP8266 NodeMCU is responsible for communication with the rover via UART3, which is a Wi-Fi gateway only and transmits the JSON strings received from the STM32 CPU to the dashboard server via local access point network. The operator command source is a portable device that consists of Arduino Nano along with the compatible NRF24L01 radio module; the NRF24L01 SPI interface of the rover receives messages from Arduino and sends them to the STM32 firmware.

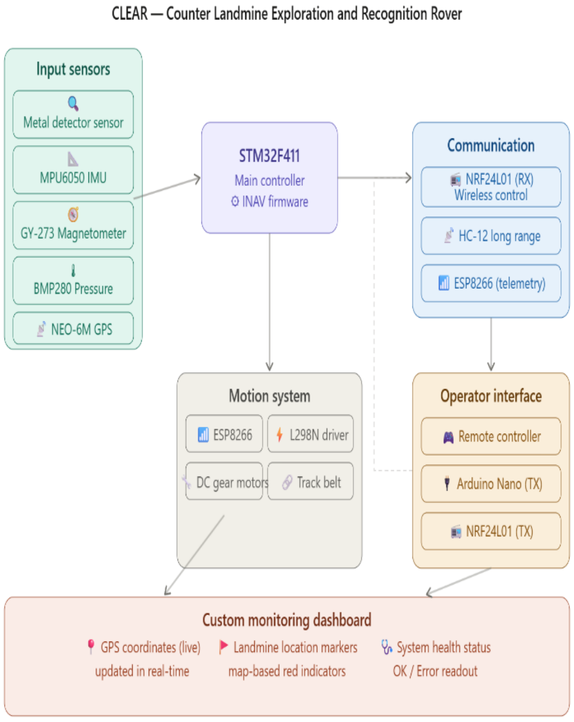


Fig. 1. CLEAR functional block diagram: sensor cluster (PI coil, MPU-6050, QMC5883L, BMP280, NEO-6M), STM32F411 processing core, NRF24L01 primary and HC-12 backup radio links, ESP8266 Wi-Fi gateway, L298N motor stage, and browser-hosted operator dashboard.

The movement of rovers can be managed with the help of L298N motor driver controlling the DC motors. The speed and direction control of the motors can be done by means of generating PWM control signals via STM32 timers. Further, ESP8266 NodeMCU module is used for communication between the microcontroller and the dashboard. The collected information on events and sensor data is transformed into JSON data packets and then transferred to the dashboard through the local Wi-Fi connection.

On the other hand, the control of the rover is done with the help of a remote control transmitter, which has been developed using Arduino Nano and NRF24L01 transceiver modules. The control signals from the rover are decoded by NRF24L01 transceiver module of the rover through the SPI interface. Apart from the main wireless connection, there is another wireless connection through HC-12 wireless module operating at a frequency of 433 MHz.

IV. HARDWARE DESIGN

A. Rover Chassis and Mechanical Layout

The design of the mechanical structure of the CLEAR rover was based on such criteria as compactness, stability, and simplicity in manufacturing. The chassis of the vehicle was fabricated from a 3 mm thick plate of ABS plastic in the shape of a rectangle with dimensions 280 mm x 180 mm. It was decided to use ABS material owing to its light weight and machinability. The rover was equipped with four geared DC motors with rubber wheels having a diameter of 65 mm. These motors were fixed at the corners of the chassis in the configuration of the skid-steer drive; consequently, it was possible to rotate the rover in any direction by changing the speed of motors positioned on opposite sides.

In order to enhance stability of the robot while moving on uneven terrain, the height of the rover was chosen as small as possible so that to keep the center of gravity near the ground surface. In this case, the tilt of the vehicle was avoided and its stability improved. The pulse-induction metal detecting coil was attached to the front part of the rover with an aluminum bracket.

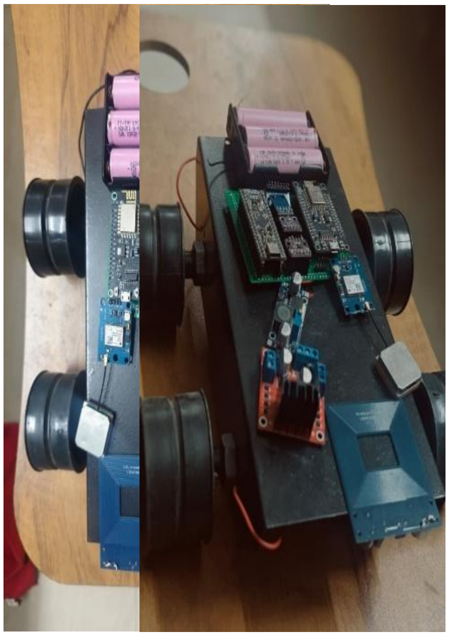


Fig. 2. CLEAR rover hardware prototype. Left: top-down view showing battery pack, microcontroller stack, and sensor modules. Right: angled perspective showing chassis structure and four-wheel drivetrain.

B. Component Selection and Rationale

Table I enumerates the principal electronic assemblies. We chose the STM32F411 for three specific reasons: (i) its 100 MHz Cortex-M4 core with single-precision hardware floating-point unit supports real-time DSP on sensor streams without software-emulated arithmetic; (ii) three physically independent UART peripherals eliminate the need for software UART or context-switching multiplexing overhead; and (iii) its unit price is well under USD 5 in typical online markets. The ESP8266 was selected purely for its integrated TCP/IP stack and 802.11 b/g/n radio — it performs no sensing or control computation.

TABLE I. CLEAR Electronic Component Inventory

Assembly	Part / Module	Primary Function
Main Processing Unit	STM32F411CEU6	Handles sensor processing, motor control, and real-time system operation
Wi-Fi Relay	ESP8266 NodeMCU	Sending HTTP POST to dashboard
Motor Stage	L298N Dual H-Bridge	Controls forward, reverse, and turning movement of DC motors
Search	PI Induction Coil	Detects buried metallic

Assembly	Part / Module	Primary Function
Coil		objects beneath the ground surface
Inertial Sensor	MPU-6050 (I2C)	Measures acceleration and angular motion along three axes
Compass	QMC5883L (I2C)	Provides magnetic heading and directional orientation
Barometer	BMP280 (I2C)	Measures atmospheric pressure, temperature, and estimated altitude
GNSS Receiver	NEO-6M (UART)	Provides geographic location and navigation data
Primary RF	NRF24L01 (SPI)	Used for short-range wireless rover control
Backup RF	HC-12 433 MHz	Provides backup communication during signal loss or long-range operation
Ground Controller	Arduino Nano+NRF24	Sends steering and movement commands to the rover
Energy Storage	3S Li-Po 5500 mAh	Supplies 11.1 V power to the complete system
Power Regulation	Buck 5 V + LM2596	Generates stable supply voltages for logic and sensor modules

C. Power Architecture

The power supply part of the rover is comprised of the Li-Po battery pack, including three batteries, supplying 11.1 V of voltage and having a capacity of 5500 mAh. The use of one energy source in the rover will facilitate the simplification of the power supply part as well as the reduction in the number of wires necessary for the use within the rover. It should be mentioned that the chosen battery provides adequate voltage and current for the functioning of all the electronic devices of the rover.

To ensure sufficient voltage for the majority of electronic devices installed in the rover, the buck converter was applied to the power supply system of the rover. As a result, 5V of voltage is supplied for the STM32 microcontroller, ESP8266 Wi-Fi module, NRF24L01 radio modules, and sensors.

However, the voltage needed for the GNSS receiver was less than the one needed for all other components. To avoid damaging the circuit due to overvoltage, an additional power regulation stage using LM2596 power regulator was included, and hence 1.5 volts were supplied to the GNSS receiver.

Furthermore, connecting the L298N motor driver to the power line of the 11.1 V battery ensured the right voltage supply to the DC motors for maintaining constant torque generation. Connecting the motors directly to the battery avoided poor performance due to the reduction in the battery voltage during operation. The electrical scheme of the rover is shown in Fig. 3.

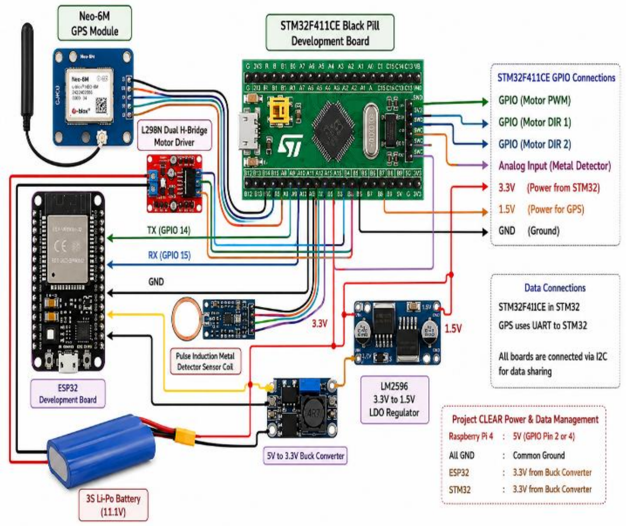


Fig. 3. Detailed wiring diagram showing power-rail routing, GPIO assignments between STM32F411 and all peripheral assemblies, L298N input connections, and antenna placements for the NRF24L01 and HC-12 modules.

V. SOFTWARE ARCHITECTURE

A. Firmware Structure and Scheduling

The following are the tools used to develop the firmware for the CLEAR rover: C programming language, STM32CubeHAL library, and ARM GCC compiler. While developing the firmware, emphasis was put on ensuring that the firmware was compact, stable, and real-time. Instead of implementing an advanced operating system, all the important operations are done periodically.

To make sure that maintaining and debugging the firmware would be easier, several layers were created according to functionality. Thus, the first layer is responsible for all interactions with the sensors and hardware modules. The second layer is responsible for processing inputs and converting sensor values into physical measurements. The third layer deals with rover movement and decision-making, whereas the fourth layer is responsible for telemetry and dashboard communication. To minimize the risk of conflict within the process of updating the shared data structure used by various parts of the rover, it was decided to update the shared data structure once during each cycle.

Several other safety measures were taken to improve stability in the outdoor environment. Specifically, all of the sensor data is checked against acceptable values at the beginning of the process, and if the value is higher than the acceptable one, the corresponding measurement is rejected. Communications through GNSS are carried out through DMA-based serial reception, which means that data collection will be constant and no interruptions in the main control loop will occur. Finally, to prevent unintentional movements, the motors are stopped in case no valid packets are received from the controller within some time interval.

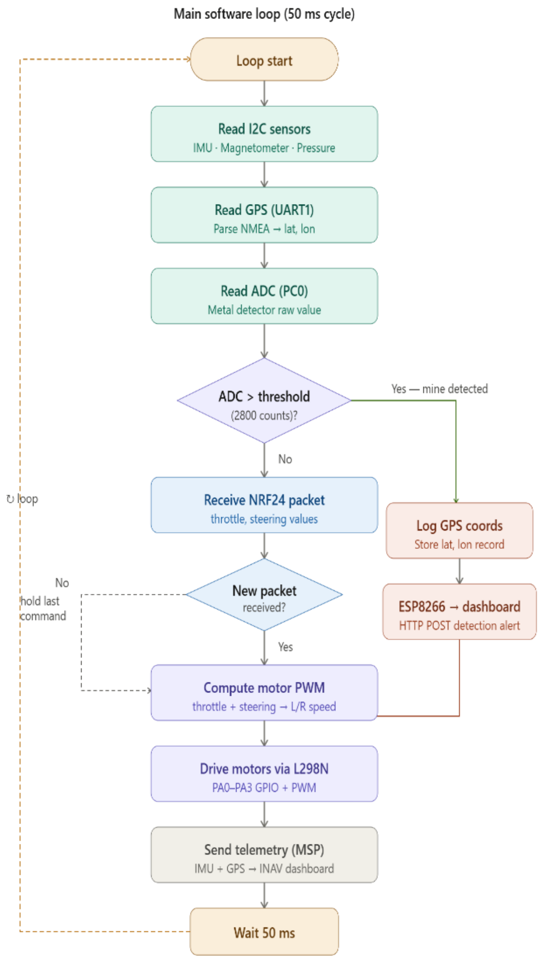


Fig. 4. Firmware tick-flow (50 ms period): I2C burst read → GNSS buffer parse → ADC conversion → threshold evaluation → NRF24L01 packet decode → PWM mix → L298N update → MSP telemetry transmit.

In order to operate the rover correctly during each 50 ms cycle iteration, there are several operations necessary. The first one is to read all sensor data through the I2C bus, including inertial, magnetic, and atmospheric sensors. Another operation is to read GNSS buffer for obtaining data about rover position, including latitude, longitude, altitude, and time. Then, the rover reads an analog output signal of the pulse induction metal detector via the internal ADC of the STM32.

After receiving the signal, it compares its sample to the threshold, which helps find metallic objects underground. In case the threshold is exceeded, the GPS coordinates and the object found are defined. While performing those operations, the rover receives commands concerning steering and throttle control through the NRF24L01 wireless receiver. After receiving the commands, the speed of each motor is calculated to move the rover in any direction using the differential drive mechanism.

B. Detection and Geo-Tagging Workflow

For every instance of detecting the existence of the metal object, the firmware will generate a data packet which will contain all the necessary data regarding such an occurrence. In particular, this data packet will consist of the latitude and longitude values gathered from the GNSS module, the UTC timestamped value, and the sensor reading received from the pulse induction detector. All the data packets will be stored in JSON format and sent from the STM32 controller to the ESP8266 module using the UART method.

The role of ESP8266 will be that of a wireless communication module, which will connect the rover to the monitoring dashboard. More specifically, the ESP8266 module will send the JSON data to the server of the dashboard using the HTTP POST method in the local Wi-Fi network. The server will receive this data and send the real-time notifications to all the users of the dashboard through the WebSocket protocol. The new position can be shown automatically on the map interface of the operator.

From the experiment carried out in normal Wi-Fi conditions on campus, the overall time taken for the detection of the metallic object and the time taken for it to appear on the monitor screen was 320 milliseconds. This was quite fast and allowed real-time monitoring of the situation by the rover.

C. Operator Dashboard Design

A light-weight web dashboard has been designed for the CLEAR rover, which could be run on any laptop/PC within the local network. All components of the interface have been integrated into a single HTML page and operated alongside the Node.js server, providing real-time communication between client and server applications.

The digital map has been developed with the help of the Leaflet.js framework and OpenStreetMap service. Upon detection of a new object by the rover, its geographical position is marked on the map using markers. Clicking on the respective marker allows getting additional information about the object, including geographic coordinates, detection time, and sensor data.

The telemetry data might have also been retrieved via the telemetry dashboard interface. In addition to the aforementioned, there were parts of the environmental data that had the following parameters: temperature, atmospheric pressure, and altitude calculated from atmospheric pressure with the help of the BMP280 sensor. Moreover, there was a part with the magnetic field and heading information retrieved with the QMC5883L sensor. There was motion data with acceleration and rotations around each axis obtained with the MPU-6050 sensor as well.

Lastly, there was implemented the notification system that will notify the operator of the detected mines and metallic objects by the rover. The banner notifying the operator of their presence will change to the much more noticeable banner saying "MINE DETECTED" in red letters, remaining on-screen until the operator dismisses it. In addition, there is an option to save all notifications in CSV files locally on the computer.

VI. EXPERIMENTAL RESULTS

A. Test Environments and Procedures

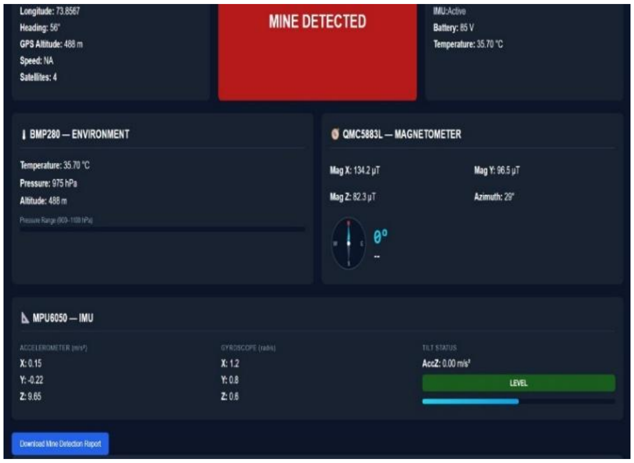
Performance of the CLEAR rover was evaluated based on the data obtained through the series of tests performed under controlled conditions. The tests were carried out in two distinct environments. First, the tests were performed in the laboratory of the university on a flat concrete surface. The reason why this environment was chosen for testing is because it would allow for testing the performance of the electronics without any hindrance like an uneven surface or soil. In the second series of tests, tests were performed in compacted laterite soil within the AISSMS campus.

During the course of the experiment, two different kinds of metals were used as the targets for testing. The metals selected included a mild steel circular disk with a diameter of 50 mm and oxygen-free copper plate with dimensions 80 mm x 80 mm. The targets were buried in the soil at various depths starting from 0 mm all the way to 80 mm at 10 mm increments. The tests were repeated several times at each depth to ensure accuracy. Sixty tests were carried out at each depth.

The data collected from the rover was transferred to the dashboard using the ESP8266 module after connecting the rover to the Wi-Fi network of the university. Access to the dashboard was made using the consumer laptop throughout the experiments. If positioning occurred outdoors, data collection was performedonly after a stable connection was made between the GNSS module and at least four satellites.

B. Dashboard Screenshot Analysis

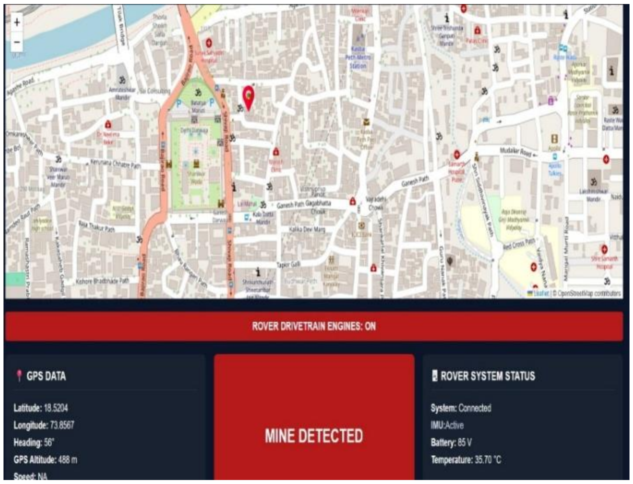
Figures 5 and 6 present dashboard snapshots captured during the outdoor testing phase of the CLEAR rover on the AISSMS campus in Pune, Maharashtra. These screenshots were taken while the rover was actively moving across the test area and transmitting live sensor and detection data to the monitoring interface in real time.



Longitude: 73.8567
Heading: 56°
GPS Altitude: 488 m
Speed: NA
Satellites: 4
IMU:Active
Battery: 85 V
Temperature: 35.70 °C
Temperature: 35.70 °C
Pressure: 975 hPa
Altitude: 488 m
Pressure Range (900-1100 hPa)
Mag X: 134.2 µT
Mag Y: 96.5 µT
Mag Z: 82.3 µT
Azimuth: 29°
X: 0.15
Y: -0.22
Z: 9.65
X: 1.2
Y: 0.8
Z: 0.6
AccZ: 0.00 m/s²

Fig. 5. Dashboard sensor panel during outdoor trial: MINE DETECTED banner active; BMP280: 35.70°C, 975 hPa, 488 m; QMC5883L magnetic vector; MPU-6050 six-axis data; LEVEL tilt label.

Figure 5 represents the screen display of sensors while detecting any metal objects. During the time period when the object was detected, the screen displayed the environmental information detected by BMP280. This includes ambient temperature 35.70°C, atmospheric pressure 975 hPa, and altitude 488 m. Additionally, the alert light was on as the pulse induction sensor detected the presence of metal objects during the movement of the rover.



GPS DATA

Latitude: 18.5204
Longitude: 73.8567
Heading: 56°
GPS Altitude: 488 m
Speed: NA

ROVER SYSTEM STATUS

System: Connected
IMU: Active
Battery: 85 V
Temperature: 35.70 °C

Fig. 6. Dashboard map panel: detection pin at 18.5204° N, 73.8567° E; GNSS sidebar shows 56° heading, 488 m MSL, 4-sat fix, 85% charge, 35.70°C.

Figure 6 represents the map interface of the dashboard. The map interface displays the location of the detected object using the visual marker pin on the background of the OpenStreetMap. The detected object was located somewhere near the Shaniwar Wada area in Pune. Other telemetry information that can be viewed from the map interface includes 4 satellites, magnetic heading 56°, 85% battery life, and ambient temperature 35.70°C.

C. Quantitative Results

TABLE II. Measured System Performance Indices

Performance Index	**Measured Value**	**Test Condition**
ADC Trip Level	> 2800 counts	Calibrated pre-trial
Position Accuracy	2.8 m mean radial	4-sat NEO-6M fix
Command Latency	< 50 ms	NRF24L01 at 2 Mbps
Firmware Loop Rate	20 Hz (50 ms)	Controlled using SysTick timing
Field Temperature	35.7 °C	Outdoor reading from BMP280 sensor
Battery Supply Voltage	11.1 V nominal	Battery charge approximately 85% at test start
Telemetry Mode	Event-driven POST	ESP8266 to dashboard
Inertial Sensor Update Rate	20 Hz	MPU-6050 communication over I2C

Indeed, it is evident that in spite of the circumstances, as soon as the metal objects were buried at a depth of 50 mm in the soil, the pulse induction sensor coil was able to surpass the threshold level of 2800 ADC counts. Therefore, it can be claimed that the rover would be able to detect metal objects at the necessary depth. If the depth exceeded 60 mm, the efficiency of detection decreased.

In order to verify whether the rover would trigger its alarm in vain, the rover was checked without any metal objects buried in the ground at a distance of five meters from the rover. Indeed, there were no cases of false alarms. The coordinates recorded for all the detections were done along with the geographic location using the GNSS system. The average difference between the two was 2.8 meters, while the standard deviation was 0.6 meters.

VII. DISCUSSION AND FUTURE WORK

First of all, it was shown that the project CLEAR successfully fulfilled its main objective that is the creation of the working mine surveying rover with low-cost components for demining organizations with limited budget possibilities. In addition, there are three problems that need to be solved in the following project.

Firstly, wheeled motion can be used only in case if the rover operates on compact surfaces; however, sandy ground, wet soil, and rocky precipices prevent the rover from functioning because of the current chassis structure. Replacing the existing four wheels with the continuous rubber tracks will greatly enhance the rover's performance.

Secondly, the current threshold is a fixed scalar number that is set only once in laboratory conditions, however, the level of noise in soils with high content of iron oxide and magnetite increases and, therefore, it becomes hard to detect shallow mines. The use of the adaptive threshold depending on the rolling mean and standard deviation of ADC readings will solve the problem automatically.

Lastly, the current communication system can be applied only if the rover is close to the portable Wi-Fi hotspot, and therefore, installing the 4G LTE module, such as SIM7600-series, will allow operating the rover remotely.

VIII. CONCLUSION

The design and implementation of the CLEAR remote-controlled rover that is used for early detection and surveys of hazardous regions such as landmine fields are discussed in this paper. In this particular case, the following equipment has been used in one economical hardware platform which includes pulse induction metal detector, inertial sensor, environmental sensor, GPS localization, wireless communication system, and web-based monitoring system.

The role of STM32F411 microcontroller in the sensing, communication, and control of the activities carried out by the device on regular basis at the frequency of 20 Hz is described in this study. Based on the findings of the experiments conducted, the proposed rover was capable of detecting the metallic items hidden underground at the specific detection threshold value while identifying their position with an average error of 2.8 meters. No communication delay was observed exceeding 50 milliseconds during the wireless communication process.

One of the key objectives of this project is related to the issue of usability and user-friendly interaction with the system. To make this objective true, the dashboard-based interface was designed. This interface is a lightweight browser-based interface which does not require any robotics infrastructure at all.

Thus, as it follows from the results of this project, it is possible to design a mine awareness robotic assistance system using inexpensive embedded hardware. Moreover, this project may be used as a foundation for creating numerous other systems in the future. To provide the opportunity to future researchers of working on these issues, the hardware schematics, firmware, and dashboard application source code will be made publicly available under the open-source license.

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