Autonomous Navigation Robot for Military Applications

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***Abstract*— The increasing need for safer battlefield monitoring and remote reconnaissance has motivated the development of compact robotic platforms that can operate effectively in hazardous military environments. This paper presents an autonomous ground-surveillance robot capable of switching seamlessly between autonomous navigation and manual teleoperation, ensuring mission continuity in unpredictable operational conditions. The proposed system is built around an ESP32 controller that integrates multiple sensing modules—including ultrasonic, infrared (IR), passive infrared (PIR), smoke detection, and a dedicated landmine detection sensor—to enable real-time obstacle avoidance, threat identification, and situational awareness. A multi-sensor fusion strategy enhances decision accuracy during autonomous movement, enabling the robot to detect intrusions, navigate around obstacles, and identify concealed explosive threats.**

For tactical visual intelligence, the robot employs an ESP32- CAM module that provides live video streaming to a remote operator, supporting surveillance, target assessment, and remote maneuverability. A laser firing module is incorporated for precision target indication and simulated engagement. The motion subsystem consists of an H-bridge motor driver and high-torque DC motors, enabling stable mobility across outdoor terrain.

Keywords- Autonomous UGV, multi-sensor fusion, ESP32, landmine detection, obstacle avoidance, intrusion detection, remote teleoperation, battlefield surveillance.

Introduction

Military surveillance operations frequently occur in high-risk environments where threats such as hidden explosives, hazardous gases, and hostile intruders place defense personnel in extreme danger. To minimize direct human exposure and enhance situational awareness, autonomous ground robots have emerged as effective tools for reconnaissance and threat assessment. These robotic platforms utilize onboard computing and diverse sensing technologies to detect obstacles, identify threats, and transmit real-time information to remote operators. Modern embedded systems such as the ESP32 and ESP32-CAM enable compact, energy-efficient robots capable of wireless communication and live video streaming, making them highly suitable for tactical deployment.

Recent advances in semi-autonomous robotic control demonstrate the importance of hybrid operation modes, where manual teleoperation can complement autonomous navigation when communication delay or sensing uncertainty affects performance. Research on delay-dependent and control- assisted teleoperation confirms that combining manual and autonomous modes significantly improves navigation stability under inconsistent network conditions, enabling safe operation in hazardous environments [3]. These results highlight the relevance of dual-mode robotic systems for defense applications where continuous mobility and responsiveness are critical.

Sensor-fusion frameworks have also become crucial in modern surveillance robots, as the integration of sensing modalities—such as PIR, ultrasonic, IR, and motion-tracking modules—improves detection accuracy and reduces ambiguity. Studies show that combining PIR and ultrasonic sensors enhances direction and distance estimation for moving subjects, offering improved reliability in real-time tracking applications [1]. Such findings support the strategic use of fused sensing for human detection and situational monitoring in military systems.

Parallel advancements in explosive and hazardous material detection show the importance of integrating specialized sensors with mobile robotic platforms. For example, controlled metal-detection mechanisms designed for mine-detection robots demonstrate significantly enhanced detection performance by maintaining optimal positioning relative to ground contours [2]. Additionally, systematic research into hazardous gas-detection systems emphasizes the need for autonomous sensing to ensure continuous monitoring and safety, particularly where chemical exposure risks are severe [4].

Motivated by these developments, this work presents an ESP32-based autonomous military surveillance robot equipped with a fused sensor suite including ultrasonic, IR, PIR, smoke, and landmine detection sensors. An ESP32-CAM module provides live video surveillance, and a laser unit is implemented for precise target marking and simulated engagement. The robot supports both autonomous navigation and wireless manual override, ensuring reliable operation during mission-critical conditions. Through sensor-fusion- based threat detection and hybrid control, the proposed platform delivers a practical, cost-efficient, and adaptable solution for modern defense surveillance and hazardous-zone assessment.

I. RELATED WORKS

A. The robot employs an ESP32-based control system that manages real-time sensing, motor coordination, and wireless supervision. A dedicated metal- detection module enhances the robot's capability to identify buried or concealed metallic objects, with the ESP32 handling signal conditioning and threshold analysis. Combined with auxiliary perception sensors and responsive actuation, the system ensures reliable navigation, rapid hazard detection, and safe manual override in complex environments[3].

B. The paper describes a navigation approach that uses PIR sensors to detect human or object motion and ultrasonic sensors to measure distances for obstacle awareness. PIR data helps identify movement direction, while ultrasonic readings refine spatial understanding through multiple distance reflections. Together, these sensors provide a lightweight, low- cost method for reliable indoor navigation without requiring complex systems like LiDAR[1].

C. The paper explains how modern gas sensors are designed to measure different gases more accurately and quickly. It describes improved sensing materials, better signal-processing methods, and the use of simple machine-learning models to make readings more reliable. The paper also highlights techniques like automatic calibration and combining multiple sensors to get cleaner, more stable gas- detection results in real environments[4].

D. The paper studies how to control mobile robots when network delay keeps changing. It introduces two assist modes that let the robot drive itself briefly when the delay is high or the operator's control is unstable. A new method using RGB-D camera data helps detect obstacles and stay on the route. Tests in a tunnel-like track show these assist modes make driving smoother, faster, and safer than manual control[2].

II. BACKGROUND

In this section, we first explain the ESP32 controller and then the different sensors used in this project

A. Overview of ESP32

The ESP32 is a compact, low-power microcontroller combining processing power, wireless connectivity, and versatile interfaces. It reads sensor inputs, processes data, and communicates through Wi-Fi or Bluetooth, making it suitable for automation, IoT applications, and autonomous robotic systems requiring reliable real-time control.

Its dual-core processor allows parallel execution of tasks. One core can manage sensor readings and control logic, while the other handles communication or background functions. This structure ensures smooth operation without delays, especially in robots requiring continuous sensing, decision- making, and remote monitoring.

The ESP32 integrates Wi-Fi and Bluetooth, enabling wireless data exchange and remote control. Through these modules, it can stream sensor information, receive commands, and connect to mobile devices or cloud platforms, supporting applications like live surveillance, autonomous navigation, and smart environmental monitoring.

A wide range of interfaces—ADC, PWM, UART, SPI, I2C, and GPIO—allows the ESP32 to connect with actuators and sensors. It collects real-time data from modules like ultrasonic, PIR, IR, or gas sensors and generates appropriate outputs for motors or alarms.

The ESP32 operates using an internal scheduler that manages simultaneous tasks efficiently. It balances sensing, processing, communication, and actuation without performance drops. This enables stable operation in complex robotic systems where both manual control and autonomous functions must run continuously.

B. ESP32 Architecture

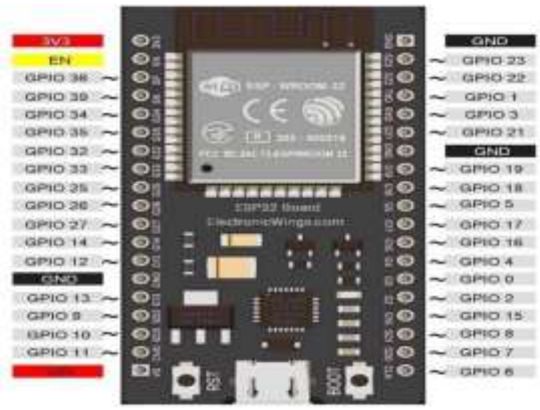

Fig 2.1: Esp microcontroller

- The ESP32 architecture centers on the ESP-WROOM-32 module, containing the dual-core processor, memory, and wireless communication hardware.
- GPIO pins around the module support digital I/O, ADC, PWM, communication buses, and sensor or actuator interfacing.
- Built-in Wi-Fi and Bluetooth radios enable wireless communication for control, monitoring, and data transmission.
- Power rails like 3.3V, VIN, and multiple GND pins supply stable power to the microcontroller and connected peripherals.
- Dedicated EN, RESET, and BOOT buttons manage startup, flashing, and system reset operations.
- USB interface and onboard regulators handle programming, serial communication, and stable voltage regulation for the entire board.

C. Sensor Specifications

1. Navigation and Obstacle Detection Sensors

The robot relies on a combination of ultrasonic and infrared sensing for reliable spatial perception. The ultrasonic module performs long-range distance estimation by transmitting a 40 kHz acoustic burst and calculating echo-return time with microsecond accuracy. This enables detection of walls, objects, and terrain irregularities within its forward path. Complementing this, the IR obstacle sensor provides fast short-range feedback by analyzing variations in reflected infrared intensity. Because IR detection is minimally affected by surface texture at close distances, it helps the robot negotiate tight indoor spaces and react to sudden obstacles. Together, these two sensors form a hybrid navigation layer that enhances obstacle avoidance, path correction, and safe autonomous maneuvering.

2. Motion and Presence Detection Sensors

The PIR sensor contributes to situational awareness by identifying movement within the robot's surroundings. It uses dual pyroelectric elements that respond to differential changes in infrared energy emitted by living bodies. When a warm object moves across its detection field, the sensor generates a stable digital output that can trigger behavioral routines such as switching to surveillance mode, activating the camera, or logging environmental activity. This low-power detection mechanism enhances the robot's responsiveness in human-interactive or security-focused applications.

3. Environmental Monitoring Sensors

MQ-series gas sensors allow the robot to evaluate air quality and detect hazardous gases during field operation. Their semiconductor sensing surface changes resistance when exposed to gases such as methane, LPG, smoke, or CO. This resistance shift is converted into an analog signal proportional to gas concentration, enabling continuous real-time monitoring. These sensors are particularly valuable in confined spaces, industrial zones, and emergency-response environments where early detection of toxic gas accumulation can prevent critical failures and ensure operational safety.

4. Electromagnetic Detection Sensors

The metal detector module expands the robot's sensing capabilities by identifying metallic objects hidden beneath or near the surface. It operates by generating an oscillating electromagnetic field using an induction coil. When metal enters this field, induced eddy currents alter the oscillation frequency or amplitude, producing a distinct electrical signature. This enables the robot to detect buried metal, hidden utilities, or metallic debris, making it useful for search, security scanning, and mine-detection tasks.

5. Vision and Targeting Sensors

The ESP32-CAM module provides the robot with visual intelligence by capturing image frames through the OV2640 sensor and streaming them over Wi-Fi. Its onboard JPEG compression and PSRAM buffering support real-time video transmission with minimal latency, enabling remote inspection and visual navigation assistance. Alongside vision processing, a low-power laser module offers precise targeting capability. The narrow, collimated beam helps mark reference points, align the robot's orientation, or indicate the direction of interest during manual control. This combination of imaging and pointing technologies enhances both situational awareness and user interaction with the robotic platform.

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 01 | Jan - 2026 SJIF Rating: 8.586 ISSN: 2582-3930

Table 2.2 Sensor specifications

Sensor	Model	Operating Voltage	Detection Range	Output Type	Power Consumption	Key Features
Harmful Gas Sensor	MQ-135	5V DC	Sensitive to CO2, CO, NH3, NOx	Analog	90 mA	High sensitivity, long life
Mine Sensor	Metal Detector	5V DC	2–5 cm	Digital / Analog	20–40 mA	Detects metals, adjustable
PIR Sensor	HC-SR501	5–12V DC	3–7 m	Digital	65 µA	Adjustable delay/sensitivity
IR Obstacle Sensor	IR Module	3.3–5V DC	2–30 cm	Digital	15 mA	Adjustable distance
Ultrasonic Sensor	HC-SR04	5V DC	2–400 cm	Trigger/Echo	15 mA	Accurate distance sensing

III. METHODOLOGY

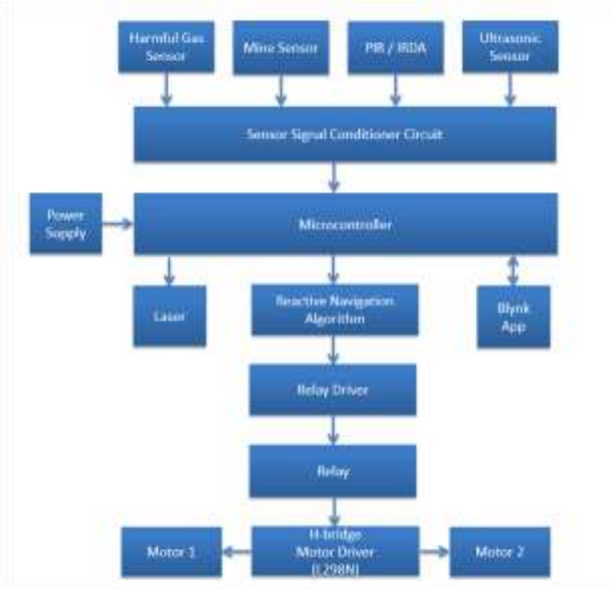

Fig 3.1 Block diagram of the model

The development of the autonomous ground robot followed a modular design strategy, integrating sensing, perception, actuation and communication subsystems into a compact mobile platform. The system was required to operate in hybrid mode—capable of autonomous navigation while also providing manual operator access through wireless control. To meet this requirement, the robot architecture employed an ESP32-based microcontroller for processing, data acquisition, and wireless connectivity. The design emphasized real-time response, low power consumption, and seamless switching between autonomous and operator-driven modes.

A. Sensor Suite Integration and Calibration

A multi-sensor configuration was selected to enhance situational awareness. The PIR sensor served as the primary motion detector, triggering immediate scanning behavior. Ultrasonic and IR sensors provided short-range distance estimation and obstacle detection, enabling safe mobility in cluttered environments. A gas sensor and a metal detector module were included to expand the robot's environmental monitoring capability. Each module was individually characterized to determine operational thresholds, noise behavior, and optimal sampling intervals. Calibration trials were performed in controlled settings to establish reference values for detecting motion, hazardous gases, metallic objects, and proximity variations.

B. Perception and Event-Driven Response Mechanism

The robot employed an event-driven perception model, where sensor activations controlled the system's behavioral transitions. When the PIR module detected motion, the controller activated the camera and oriented a low-power laser pointer toward the region of interest using a pan-tilt mechanism. This laser acted solely as a visual indicator for marking detected activity, ensuring safe operation. The camera provided real-time imagery to the operator over Wi-Fi for confirmation. Concurrently, ultrasonic and IR sensors validated whether obstacles were present in that direction, reducing false alarms and preventing hazardous movement.

C. Navigation and Motor Control Architecture

Autonomous mobility was achieved using a differential motor system driven through an L298N motor driver. The ESP32 generated PWM signals for speed and direction control while simultaneously receiving sensor feedback. A reactive navigation algorithm was implemented, enabling the robot to avoid obstacles and maintain stable motion. In manual mode, control commands received from the operator interface over Wi-Fi temporarily overrode the autonomous decisions. This layered control approach ensured that human supervision remained available during critical tasks.

D. Communication, Teleoperation, and Safety Protocols

The ESP32 provided dual-function wireless connectivity: (1) streaming camera output to the operator, and (2) receiving manual navigation commands. A lightweight control interface allowed the operator to switch between autonomous and teleoperated modes without interrupting sensing functions. Safety protocols were integrated into the firmware, including laser-activation limits, obstacle-proximity warnings, and emergency motor shutdown capability. All events—such as motion detection, sensor alerts, and manual overrides—were logged for analysis and validation.

E. Power Management and Hardware Assembly

The robot was powered by a rechargeable lithium-ion battery pack arranged to supply separate power lines for motors and components. This isolation reduced electrical noise and improved microcontroller stability. The hardware components were securely mounted on a wooden chassis, providing mechanical stability for sensors and ensuring consistent alignment. Power distribution circuits were tested for load behavior, thermal stability, and runtime capacity to verify that the system could sustain extended field operation.

F. System Testing, Validation, and Performance Evaluation

The complete system underwent multi-stage testing, beginning with bench-level verification of each sensor and actuator. Integration testing ensured that sensor fusion and event-driven responses behaved as intended during real-time operation. Field trials were conducted indoors and outdoors, measuring detection accuracy, robot response time, communication latency, and stability under manual override. Performance metrics such as motion-detection precision, obstacle-avoidance success rate, and battery endurance were analyzed to validate the overall system effectiveness. Observed limitations—such as sensor noise, lightingdependent camera performance, and uneven ground behavior—were documented for future improvement.

IV. IMPLEMENTATION

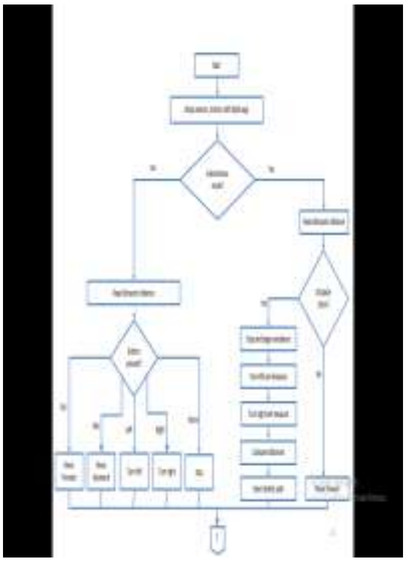

Fig 4.1 Navigation technique flowchart

This flowchart shows how the robot decides between manual and autonomous movement. After startup, it initializes sensors and motors using the Blynk app, then checks whether autonomous mode is enabled. In manual mode, it continuously reads ultrasonic distance and checks which control button is pressed—forward, backward, left, right, or none—and moves the robot accordingly. In autonomous mode, it reads ultrasonic distance to detect obstacles; if nothing is within 20 cm, it simply moves forward. If an obstacle is detected, the robot stops and performs obstacle avoidance by turning left and right to measure distances, comparing the two readings, and selecting the direction with more clearance before continuing forward.

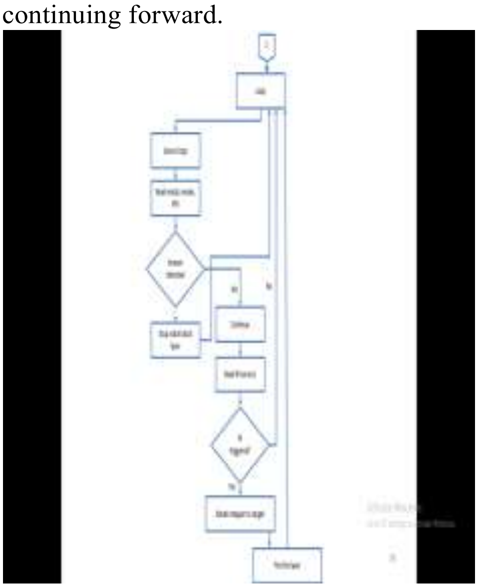

Fig 4.2 Sensor operation flowchart

This flowchart describes the robot's continuous sensing and targeting process. Inside the main loop, the robot repeatedly reads metal, smoke, and PIR sensors to determine if a human is detected; if yes, the robot stops and blocks the laser for safety. If no human is detected, it continues to read the IR sensors to check for a specific target trigger. When the IR sensor is activated, the robot commands a stepper motor to rotate the laser mechanism toward the detected position and then fires the laser. After completing the action, the system returns to the main loop and continues monitoring all sensors in real time.

V. RESULTS

The robot was tested in indoor and semi-outdoor conditions to assess navigation performance, sensor accuracy, and communication stability. Autonomous movement remained stable, and obstacle avoidance worked reliably using ultrasonic and IR sensors, enabling smooth path correction during trials.

The PIR sensor accurately detected human motion, triggering camera activation and laser alignment without false responses, while the metal detector identified objects within 3–5 cm and the gas sensor responded correctly to smoke exposure, validating threat-monitoring functionality.

Live video streaming through the ESP32-CAM remained smooth with low latency, supporting continuous remote surveillance. Manual override mode engaged instantly when activated, confirming reliable autonomous-to-manual switching without disruption.

Overall, the system demonstrated dependable sensing, steady mobility, and efficient communication, proving its suitability as a compact and low-cost platform for defense surveillance and hazardous-zone assessment.

Fig 5.1 Autonomous Navigation robot model

Fig 5.2 Output of the model

V. CONCLUSION AND FUTURE WORK

This work developed a compact unmanned ground robot capable of both autonomous and manual operation for military surveillance applications. The integrated multi-sensor suite, including ultrasonic, IR, PIR, gas, metal detection sensors and ESP32-CAM, enabled reliable obstacle avoidance, hazard recognition, and real-time visual monitoring. Experimental testing confirmed stable navigation, accurate sensing responses, smooth video streaming, and fast manual override switching,
demonstrating the system's effectiveness as a low-cost UGV platform for reconnaissance and perimeter monitoring in high-risk environments.

Future enhancements will focus on improving outdoor navigation using GPS or SLAM, implementing lightweight AI models for advanced object and motion recognition, and extending wireless communication range. Additional development will target better terrain adaptability, long- duration power support, and alternative control interfaces such as gesture or voice commands. These upgrades aim to transform the prototype into a more robust and versatile robotic system suitable for broader defense and emergency- response deployment.

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