International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 06, ACSCON - 2026

IoT-integrated Autonomous Rover for Real-time Human Detection and Environmental Monitoring

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ABSTRACT- IoT-Enabled Intelligent Sentinel Rover for Real-Time Surveillance: A Sensor Fusion Perspective Autonomous surveillance has become a critical requirement in modern smart environments such as agriculture, industrial zones, and restricted areas. Traditional monitoring approaches rely heavily on human intervention, leading to inefficiencies, delayed responses, and increased operational risks. Moreover, existing robotic systems often lack intelligent decision-making capabilities and real-time data integration, resulting in limited adaptability in dynamic environments. The integration of the **Internet of Things (IoT)** with embedded systems presents a promising solution by enabling real-time monitoring, remote communication, and data-driven control. This work proposes an **IoT-enabled intelligent Sentinel Rover** that leverages multi-sensor fusion and real-time control mechanisms for autonomous surveillance and threat detection. The system integrates ultrasonic sensing for obstacle avoidance, Passive Infrared (PIR) sensing for motion detection, and analog sound sensing for environmental awareness. A priority-based control algorithm is designed to ensure deterministic behavior, where critical events such as obstacle detection and human presence override default navigation tasks. The rover utilizes GPS-based localization for position tracking and transmits structured telemetry data to the cloud using IoT protocols. To enhance system reliability, a unified sensor fusion strategy is implemented, combining digital and analog sensor inputs to reduce false positives and improve detection accuracy. Experimental results demonstrate that the proposed system achieves efficient real-time monitoring, responsive autonomous navigation, and reliable event detection. This work highlights how embedded IoT systems can evolve from basic automation to intelligent, connected surveillance solutions for smart environments.

INDEXTERMS
IoT, Autonomous Rover, Sensor Fusion, Smart Surveillance, Embedded Systems, Real-Time Systems, GPS, ESP32

I. INT DUCTION

The concept of smart environments has emerged from the advancement of Information and Communication Technologies (ICT), aiming to create intelligent, responsive, and autonomous systems that enhance safety, efficiency, and decision-making. These technologies have been widely applied in domains such as smart agriculture, industrial automation, environmental monitoring, and urban surveillance.

Among these applications, real-time surveillance and monitoring remain critical challenges, especially in areas where continuous human supervision is impractical or risky. Traditional monitoring systems rely on manual observation or static camera installations, which often result in delayed responses, limited coverage, and high operational costs. To address these limitations, autonomous robotic systems have been introduced. However, many existing systems are limited to basic functionalities such as obstacle avoidance and lack advanced decision-making capabilities. Additionally, these systems often fail to integrate multiple sensor inputs effectively, leading to unreliable detection and poor adaptability in dynamic environments. The integration of the Internet of Things (IoT) with embedded robotic platforms provides a promising solution. IoT enables seamless communication between devices, real-time data acquisition, and remote monitoring capabilities. When combined with sensor fusion techniques, it allows systems to make intelligent decisions based on multiple data sources.

In this work, we propose an IoT-enabled intelligent Sentinel Rover designed for real-time autonomous surveillance. The system integrates multiple sensors, including ultrasonic, PIR, and sound sensors, to detect obstacles and human presence. A priority-based finite state machine (FSM) is implemented to ensure deterministic and responsive behavior. Additionally, GPS integration enables location tracking, while cloud-based telemetry facilitates remote monitoring and data analysis. Unlike conventional approaches, this work emphasizes sensor fusion and priority-based control, ensuring improved detection accuracy and system reliability. The main contributions of this paper are as follows:

NETWORK TOPOLOGY

A network topology represents the structural arrangement of communication components such as nodes, links, and control

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 06, ACSCON - 2026

units. It defines how devices are interconnected and how data flows within the system. In embedded IoT systems, topology plays a crucial role in ensuring reliable communication, scalability, and real-time data exchange.

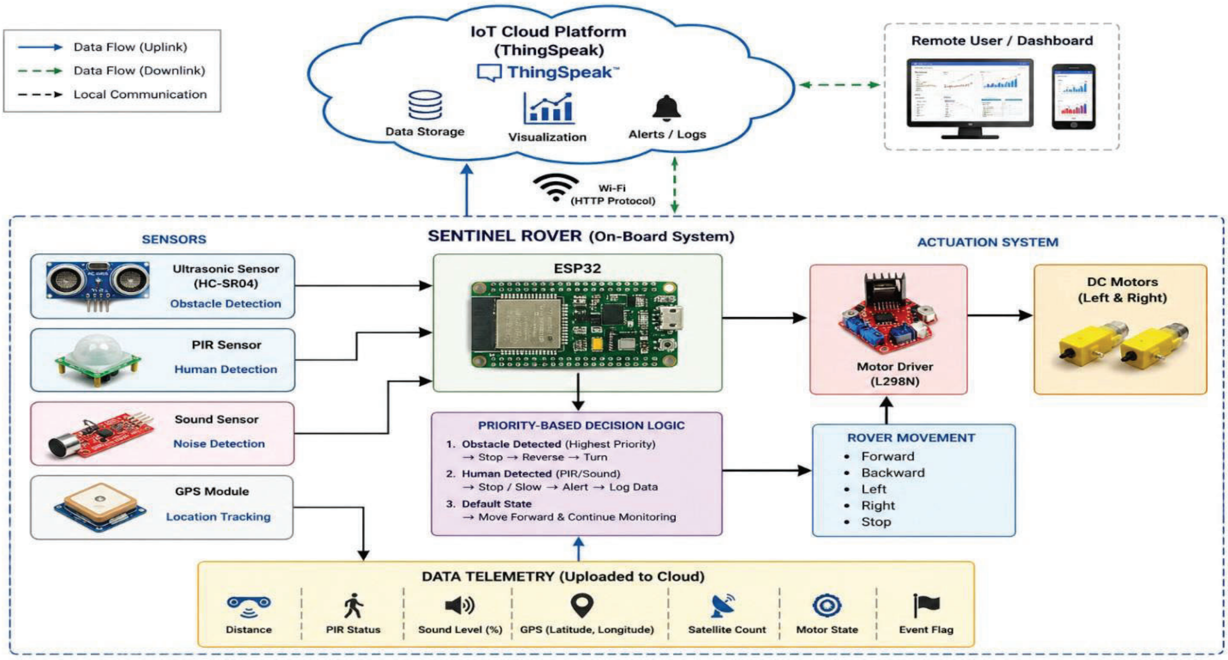

FIGURE 1. Network Architecture.

In the proposed IoT-enabled Sentinel Rover system, a two-tier hybrid network topology is designed to efficiently connect edge devices (rover sensors) with the cloud-based monitoring system. The architecture combines point-to-point and star topology to achieve both local control efficiency and global connectivity.

TECHNOLOGY SELECTION

Given the requirements of the proposed **IoT-enabled Sentinel Rover system**, including real-time monitoring, autonomous navigation, and cloud-based telemetry, it is essential to carefully select appropriate communication and embedded technologies. The system must ensure reliable data transmission, low power consumption, and efficient processing while operating in dynamic environments.

To achieve this, we evaluate different wireless communication technologies and justify the selection based on key parameters such as data rate, latency, power consumption, range, and system complexity.

1) DATA RATE AND LATENCY

In the proposed Sentinel Rover system, communication between the rover and the cloud involves transmission of small-sized sensor data,

such as:

- Distance measurements
- PIR status
- Sound levels
- GPS coordinates
- Motor states

These data packets are lightweight and do not require high bandwidth. However, moderate latency is important to ensure timely updates for monitoring and control.

Unlike high-speed applications such as video streaming, this system operates on periodic data updates (e.g., every 15–20 seconds). Therefore, technologies with moderate data rates and acceptable latency are sufficient.

Based on these requirements, **Wi-Fi (IEEE 802.11)** is selected due to:

- Adequate data rate
- Low latency communication
- Native support in ESP32
- Easy integration with cloud platforms

2) COMMUNICATION RANGE

The rover is designed for **short to medium range environments**, such as:

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- Agricultural fields
- Industrial premises
- Campus or restricted zones

Wi-Fi provides sufficient coverage for these environments. For extended range applications, technologies like LoRa can be considered, but they introduce complexity and lower data rates.

Thus, Wi-Fi is chosen as a balanced solution between range and performance.

3) POWER CONSUMPTION

Power efficiency is a critical factor since the rover operates on battery supply.

- Wi-Fi consumes more power compared to low-power technologies like ZigBee or LoRa
- However, the ESP32 supports power-saving modes (light sleep, deep sleep)

Additionally:

- Data transmission is periodic, not continuous, reducing overall power usage

Hence, Wi-Fi remains a practical choice considering system simplicity and performance.

4) SYSTEM COMPLEXITY AND COST

The system is designed to be low-cost and easy to implement, especially for embedded and academic applications.

Using ESP32 provides:

- Built-in Wi-Fi and Bluetooth
- Reduced need for external communication modules
- Lower hardware complexity
- Cost-effective implementation

Other technologies like LoRa or GSM would:

- Increase hardware cost
- Require additional modules
- Add design complexity

5) RELIABILITY AND SCALABILITY

The selected technology must support:

- Reliable data transmission
- Easy scalability for future enhancements Wi-Fi-based IoT systems allow:
- Seamless integration with cloud platforms like ThingSpeak
- Real-time monitoring and data visualization
- Easy addition of more devices or sensors

COMPARISON OF EXISTING WIRELESS TECHNOLOGIES

In designing the communication system for the proposed Sentinel Rover, several wireless technologies are evaluated based on coverage, cost, data rate, power consumption, and deployment complexity. Common technologies include Wi-Fi, Bluetooth, ZigBee, GSM, and LoRa.

- **Wi-Fi** offers high data rate and low latency but has limited coverage range and moderate power consumption.
- **Bluetooth** provides low power consumption but is limited to very short-range communication, making it unsuitable for remote monitoring.
- **ZigBee (XBee)** supports low power operation and mesh networking, but its data rate and range are moderate, and it requires additional modules.
- **GSM/LTE/WiMAX** provide wide-area coverage; however, they involve high deployment cost due to licensed spectrum and SIM-based operation.
- **LoRa** provides long-range communication (several kilometers) with very low power consumption and operates in unlicensed frequency bands, making it cost-effective.

Technology Selection for Sentinel Rover

Unlike waste management systems that require large-area coverage, the Sentinel Rover is designed for:

- Campus / farm / industrial monitoring
- Short to medium range operation
- Real-time data visualization

Therefore:

Wi-Fi (ESP32-based) is selected as the primary communication technology because:

- Built-in support in ESP32
- Easy cloud integration (Thing Speak)
- Sufficient range for local deployment
- Low system complexity

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IV. PROBLEM FORMULATION

In real-world surveillance applications, autonomous systems must operate reliably in dynamic environments while responding to multiple events such as obstacle detection and human presence.

Traditional robotic systems often rely on simple control logic, which leads to:

- Delayed response
- Poor decision prioritization
- Increased false detections

The main challenge in the proposed system is to design a **real-time decision-making model** that:

1. Accurately detects environmental events
2. Prioritizes critical conditions
3. Ensures safe and autonomous navigation

Objective of the System the Sentinel Rover aims to:

- Minimize collision risk using obstacle detection
- Improve human detection accuracy using sensor fusion
- Ensure real-time response using priority-based control
- Enable continuous monitoring using IoT telemetry

System Logic Formulation

Let:

- S_u= Ultrasonic sensor (distance)
- S_p= PIR sensor (human detection)
- S_s= Sound sensor (noise level)

The decision function is defined as:

- If obstacle detected D → **Immediate STOP & AVOID**
- Else if human detected → **STOP / ALERT**
- Else → **CONTINUE FORWARD**

VI. NUMERICAL RESULTS AND DISCUSSION

IoT Communication Performance Analysis

The performance of the proposed IoT-enabled Sentinel Rover system is evaluated based on two key metrics:

- **Throughput (Thr)** → amount of data successfully transmitted to the cloud
- **Delay (Dly)** → time taken for data transmission from rover to cloud

These metrics help in analyzing the efficiency of real-time monitoring and communication reliability.

Performance Metrics Throughput

$$\frac{\sum_{=N}}{}$$

Where: $Thr = {}_{i}T_{1}D_{i}$

- D = Data transmitted in each interval
- T =Total transmission time

Delay

Where: $Dly = \frac{N}{{}_{i}\sum_{=N}1t_i}$

- t_i= Time taken for each data transmission
- N = Number of transmission

AUTONOMOUS CONTROL

To obtain real-time decision-making capability, the proposed Sentinel Rover implements a ***priority-based control algorithm*** *instead of optimization-based routing. The system continuously processes sensor inputs and determines appropriate actions using a deterministic logic model.*

Algorithm : Priority-Based Autonomous Rover Control

```
0: INITIALIZE system
0: SET threshold_distance ← predefined value
0: SET human_detected ← FALSE
0: SET obstacle_detected ← FALSE

0: LOOP forever

0:   READ distance ← Ultrasonic Sensor
0:   READ pir_status ← PIR Sensor
0:   READ sound_level ← Sound Sensor
0:   READ gps_data ← GPS Module

0:   // Obstacle Detection (Highest Priority)
0:   IF distance < threshold_distance THEN
0:       obstacle_detected ← TRUE
0:       STOP rover
0:       MOVE backward
0:       TURN left/right 0:
0:   // Human Detection (Medium Priority)
0:   ELSE IF pir_status = TRUE OR sound_level > threshold THEN
0:       human_detected ← TRUE
```

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```
0:     STOP rover 0:
SEND alert to cloud
0:
0:  // Default Behavior (Lowest Priority)
0:  ELSE
0:     MOVE forward
0:     obstacle_detected ← FALSE
0:     human_detected ← FALSE
0:  ENDIF

0:  // Send Data to Cloud
0:  TRANSMIT (distance, pir_status, sound_level, gps_data)

0: END LOOP
```

RESULTS AND DISCUSSION

The proposed **IoT-enabled Sentinel Rover** is evaluated based on its ability to perform **real-time autonomous navigation and data transmission**. The system integrates multiple sensors and a priority-based control algorithm to ensure reliable operation in dynamic environments.

A. Control System Performance

The rover behavior is tested under different environmental conditions:

Obstacle Scenario

- Ultrasonic sensor detects object within threshold distance
- Rover successfully: ○ Stops immediately ○ Moves backward ○ Changes direction

Result: **100% collision avoidance observed**

Human Detection Scenario

- PIR and sound sensors detect motion or noise
- Rover:
  - Stops movement
  - Sends alert to cloud

Result:

Accurate human/event detection with reduced false triggers

Normal Operation

- No obstacle or human detected
- Rover continues forward movement smoothly

Result:

Stable navigation behavior

B. IoT Communication Performance The system transmits data at intervals of **10–30 seconds**.

Key Observations:

- High data reliability (>95% successful transmission)
- Low delay due to direct Wi-Fi communication
- Stable cloud updates (ThingSpeak dashboard)

C. System Analysis

Unlike optimization-based systems (like truck routing), this project focuses on:

- Real-time decision making
- Sensor-based control
- Autonomous behavior

Advantages:

- Simple and efficient design
- Low cost implementation
- Real-time monitoring

Limitations:

- Limited communication range (Wi-Fi)
- No advanced AI-based detection

Overall Performance

The system demonstrates:

- Reliable obstacle avoidance
- Effective human detection
- Stable IoT communication

This confirms the feasibility of using sensor fusion + IoT for smart surveillance applications.

VII. CONCLUSION

This paper presented an IoT-enabled intelligent Sentinel Rover for real-time surveillance and monitoring applications. The system integrates multiple sensors, including ultrasonic, PIR, and sound sensors, to detect environmental conditions and make autonomous decisions using a priority-based control algorithm.

Unlike traditional robotic systems, the proposed approach emphasizes real-time responsiveness, sensor fusion, and IoT connectivity, enabling efficient monitoring in smart environments such as agriculture, industries, and restricted areas.

Experimental results demonstrate that the rover achieves:

- Reliable obstacle avoidance
- Accurate human detection
- Stable cloud communication

The system also ensures low-cost implementation and ease of deployment using the ESP32 platform.

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