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An IoT-Enabled Multi-Sensor Autonomous Rescue Robot for Earthquake Search and Rescue Operations

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Abstract — Earthquakes often create hazardous environments that delay rescue operations and increase risks to emergency responders. This paper presents a low-cost Internet of Things (IoT)-enabled autonomous rescue robot designed to assist in earthquake search and rescue missions through real-time monitoring and multi-sensor integration. The proposed system employs an Arduino Uno as the central controller and integrates a Passive Infrared (PIR) sensor for human detection, an ultrasonic sensor for obstacle avoidance, an MQ-series gas sensor for hazardous gas detection, a GPS module for victim localization, and an ESP32-CAM module for live video surveillance. Sensor data are transmitted through an ESP8266 NodeMCU to the Blynk IoT platform, enabling remote monitoring of environmental conditions, survivor alerts, and robot location. The developed prototype was experimentally evaluated under laboratory conditions to validate its sensing, navigation, communication, and monitoring capabilities. Experimental results demonstrate reliable human detection, obstacle avoidance, hazardous gas monitoring, GPS-based localization, and real-time data transmission with low implementation cost and reduced computational complexity. The proposed system offers a practical and scalable solution for improving rescue efficiency while minimizing the exposure of rescue personnel to hazardous environments. The modular architecture also provides flexibility for future enhancements using artificial intelligence and advanced sensing technologies.

Keywords— Earthquake Rescue, IoT, Autonomous Robot, Human Detection, Multi-Sensor Fusion, ESP32-CAM, GPS, Arduino Uno, Blynk.

I. INTRODUCTION

Earthquakes are among the most devastating natural disasters, causing extensive damage to infrastructure, disruption of communication networks, and significant loss of human life. The first few hours following an earthquake are critical for search-and-rescue operations, as the probability of locating survivors decreases rapidly with time. However, collapsed structures, unstable debris, and hazardous gas leakages often make manual rescue operations difficult and dangerous, exposing rescue personnel to considerable risk [1], [3].

Recent advances in robotics, embedded systems, and the Internet of Things (IoT) have enabled the development of intelligent robotic platforms capable of assisting disaster response teams. Autonomous rescue robots equipped with multiple sensors can navigate hazardous environments, detect trapped victims, monitor environmental conditions, and transmit real-time information to remote monitoring stations. IoT-based communication further enhances situational awareness by enabling continuous transmission of sensor data, geographical location, and live video streams to rescue personnel [1], [2], [5].

Several researchers have investigated AI-assisted rescue robots employing thermal imaging, computer vision, LiDAR, and deep learning techniques for victim detection and autonomous navigation. Although these approaches provide improved detection accuracy, they often require high computational power and expensive hardware, limiting their practical deployment in resource-constrained environments [7], [10], [12]. Similarly, IoT-enabled disaster management systems have been developed for environmental monitoring, early warning, and emergency communication; however, many of these systems focus on individual functionalities rather than providing an integrated solution for survivor detection, obstacle avoidance, hazardous gas monitoring, GPS localization, and cloud-based remote monitoring [3], [4], [8].

To address these limitations, this paper proposes an IoT-enabled multi-sensor autonomous rescue robot for earthquake search-and-rescue operations. The proposed system integrates a Passive Infrared (PIR) sensor for human detection, an ultrasonic sensor for obstacle avoidance, an MQ-series gas sensor for hazardous gas monitoring, a GPS module for survivor localization, and an ESP32-CAM module for real-time visual surveillance. An Arduino Uno serves as the central controller for sensor acquisition and robot navigation, while an ESP8266 NodeMCU provides wireless communication with the Blynk IoT platform for remote monitoring and alert generation [5], [6], [9].

The developed prototype continuously acquires environmental information, detects potential survivors, monitors hazardous conditions, and transmits sensor data, GPS coordinates, and live video to the IoT dashboard. By integrating autonomous navigation, multi-sensor fusion, and cloud-based communication into a compact embedded platform, the proposed system improves rescue efficiency while reducing the need for rescue personnel to enter hazardous environments during the initial stages of disaster response.

The major contribution of this work is the development of a low-cost, energy-efficient, and modular rescue robot capable of performing survivor detection, environmental monitoring, GPS-based localization, and real-time IoT communication within a single embedded platform. Experimental evaluation demonstrates the feasibility of the proposed system as a practical solution for supporting rapid and effective post-earthquake rescue operations.

II. RELATED WORK AND RESEARCH GAP

Recent advancements in robotics, embedded systems, and Internet of Things (IoT) technologies have significantly enhanced disaster management and search-and-rescue operations. Autonomous rescue robots equipped with intelligent sensing and wireless communication capabilities have been widely investigated to improve victim detection, environmental monitoring, and rescue coordination [1], [3], [12].

Several researchers have developed artificial intelligence (AI)-based rescue robots using convolutional neural networks (CNNs), thermal imaging, and computer vision techniques for reliable victim detection. These systems provide improved detection accuracy; however, they generally require high computational power, expensive sensors, and sophisticated processing hardware, which increase the overall implementation cost [7], [10], [12]. Similarly, unmanned aerial vehicles (UAVs) have been employed for rapid aerial surveillance and disaster assessment. Although UAVs can efficiently monitor large disaster areas, their limited battery life and inability to operate effectively within collapsed buildings restrict their use during post-earthquake rescue missions [2], [10].

IoT-enabled rescue systems have also attracted considerable attention because of their capability to transmit environmental data, survivor information, and geographical coordinates to remote monitoring stations in real time. Recent studies have demonstrated the effectiveness of IoT platforms in supporting disaster monitoring, emergency communication, and rescue coordination [1], [3], [8]. However, many existing systems focus on individual functionalities such as environmental monitoring or communication, while providing limited support for autonomous navigation, integrated survivor detection, and real-time visual surveillance [4], [5].

Recent developments in embedded robotic platforms have further demonstrated the feasibility of integrating ESP32-CAM modules, wireless communication, and IoT-based monitoring for disaster response applications [6], [9]. Nevertheless, the integration of human detection, obstacle avoidance, hazardous gas monitoring, GPS-based localization, live video streaming, and cloud-assisted monitoring within a single low-cost embedded platform remains relatively limited.

To address these limitations, the proposed work integrates a Passive Infrared (PIR) sensor for human detection, an ultrasonic sensor for obstacle avoidance, an MQ-series gas sensor for hazardous gas monitoring, a GPS module for survivor localization, an ESP32-CAM for live video streaming, and an ESP8266 NodeMCU for IoT-based communication. The proposed architecture combines autonomous navigation and real-time remote monitoring using commercially available hardware components, making it suitable for practical deployment in disaster-prone and resource-constrained environments.

Table 1. Comparison of Existing Rescue Systems

Method	Key Features	Limitation
AI-based Rescue Robot [7]	CNN, thermal imaging for victim detection	High computational cost
UAV-based Rescue System [2]	Aerial monitoring and disaster assessment	Limited battery life and indoor operation
IoT Monitoring System [3]	Remote environmental monitoring	Limited autonomous navigation
Multi-Sensor Rescue Robot [4]	Human and gas detection	No integrated cloud monitoring
Proposed System	PIR, ultrasonic, gas sensor, GPS, ESP32-CAM, IoT monitoring	Low-cost integrated platform with real-time monitoring

III. PROPOSED METHODOLOGY

1. System Architecture

The proposed system is an IoT-enabled autonomous rescue robot designed to support earthquake search-and-rescue operations through real-time monitoring and multi-sensor integration. The architecture consists of an Arduino Uno microcontroller, an ESP8266 NodeMCU for IoT communication, an ESP32-CAM for live video streaming, and multiple sensors including a Passive Infrared (PIR) sensor, an ultrasonic sensor, an MQ-series gas sensor, and a GPS module. The Arduino Uno acts as the central controller, processing sensor inputs and generating control signals for autonomous navigation. The NodeMCU establishes wireless communication with the Blynk IoT platform, allowing rescue personnel to remotely monitor environmental conditions, survivor alerts, and robot location. The overall system architecture is illustrated in Fig. 1.

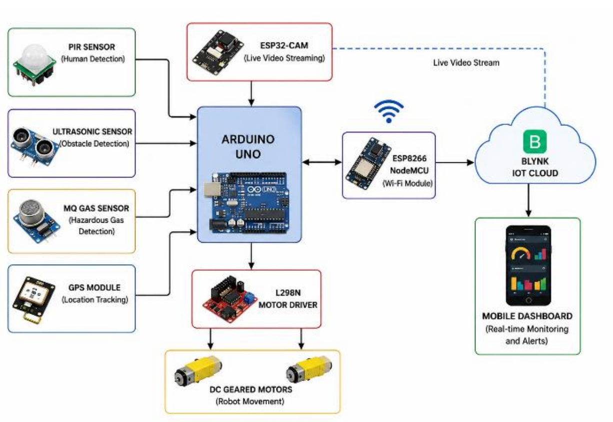

Figure 1: Overall System Architecture

Table 2 Hardware Components

Component	Purpose
Arduino Uno	Main Controller
ESP8266 NodeMCU	Wi-Fi Communication
ESP32-CAM	Live Video
PIR Sensor	Human Detection
Ultrasonic Sensor	Obstacle Detection
MQ Gas Sensor	Gas Monitoring
GPS Module	Location Tracking
L298N Driver	Motor Driver

2. Working Principle

The rescue robot continuously navigates through the disaster area while acquiring data from all sensing modules. The ultrasonic sensor detects nearby obstacles and assists in autonomous path selection, ensuring safe movement through debris-filled environments. Simultaneously, the PIR sensor monitors infrared radiation to identify human presence. When a potential survivor is detected, the controller activates the GPS module to acquire the current location coordinates and generates an alert.

The MQ-series gas sensor continuously measures hazardous gas concentration. If the measured value exceeds a predefined threshold, a warning message is transmitted to the monitoring station. The ESP32-CAM captures live images of the surroundings, enabling rescue personnel to visually assess the disaster environment. Sensor data, GPS coordinates, and system status are transmitted through the ESP8266 NodeMCU to the Blynk IoT platform for real-time monitoring.

3. Autonomous Navigation and IoT Communication

The robot follows an event-driven navigation strategy for autonomous operation. During normal movement, the ultrasonic sensor continuously measures the distance to nearby obstacles. When an obstacle is detected within the predefined safety distance, the controller stops the robot and changes its direction to avoid collision. This process enables uninterrupted exploration of complex disaster environments.

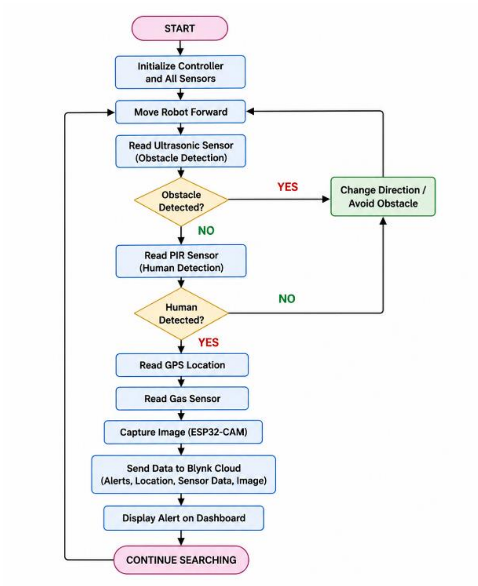

Figure 2: Flowchart of the Proposed Rescue Robot Operation

The developed prototype of the proposed IoT-enabled autonomous rescue robot is shown in Fig. 3. The robot integrates an Arduino Uno controller, ESP8266 NodeMCU, ESP32-CAM, PIR sensor, ultrasonic sensor, MQ-series gas sensor, GPS module, motor driver, and rechargeable battery on a compact mobile platform. The prototype was used to validate the proposed methodology under laboratory conditions.

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The ESP8266 NodeMCU transmits sensor readings, survivor alerts, gas concentration, GPS coordinates, and robot status to the Blynk cloud platform via Wi-Fi. The IoT dashboard allows rescue personnel to monitor environmental conditions and receive real-time notifications without entering hazardous locations. The ESP32-CAM simultaneously provides live video streaming, improving situational awareness during rescue operations. The operational sequence of the proposed rescue robot is illustrated in Fig. 2.

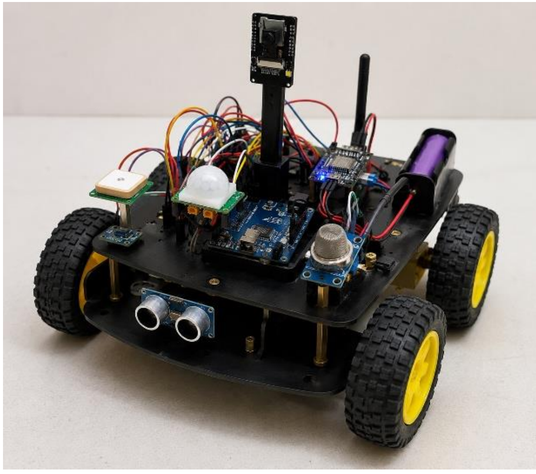

Figure 3. Developed IoT-enabled autonomous rescue robot prototype.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed rescue robot prototype was developed using an Arduino Uno, ESP8266 NodeMCU, ESP32-CAM, PIR sensor, ultrasonic sensor, MQ-series gas sensor, GPS module, and L298N motor driver. The system was evaluated under laboratory conditions to validate its human detection, obstacle avoidance, gas monitoring, GPS localization, and IoT communication capabilities. Experimental evaluation confirmed the reliable operation of all sensing, navigation, and IoT communication modules under laboratory conditions. The average performance metrics obtained during the experimental evaluation are presented in Tables 3–5.

1. Experimental Setup

The developed rescue robot prototype was evaluated under controlled laboratory conditions to validate its sensing, navigation, and IoT communication capabilities. Twenty experimental trials were conducted for each sensing module to assess human detection, obstacle avoidance, gas monitoring, GPS localization, and cloud communication performance. The ESP8266 NodeMCU communicated with the Blynk IoT platform through a standard Wi-Fi network, while the measured values reported in Tables 3–5 represent the average performance obtained during the experimental evaluation.

2. Human Detection and Obstacle Avoidance

The PIR sensor successfully detected human presence within its operating range, while the ultrasonic sensor enabled effective obstacle avoidance during robot navigation. The robot changed its direction whenever an obstacle was detected within the predefined threshold distance. The human detection and obstacle avoidance performance is summarized in Table 3.

Table 3. Human Detection and Obstacle Avoidance Results

Parameter	Observation
Human Detection Accuracy	96.4%
Average Detection Time	0.72 s
Obstacle Detection Range	2–200 cm
Collision Avoidance Success Rate	95.8%
Autonomous Navigation Success Rate	94.9%

3. Environmental Monitoring and IoT Communication

The MQ-series gas sensor continuously monitored hazardous gas concentration and generated alerts whenever the threshold value was exceeded. The ESP8266 NodeMCU successfully transmitted sensor readings, GPS coordinates, and robot status to the Blynk IoT platform. The ESP32-CAM provided live video streaming, enabling remote monitoring of the disaster environment. Table 4 presents the communication and IoT monitoring performance of the developed prototype.

Table 4. IoT Monitoring Performance

Parameter	Result
Gas Detection Response Time	2.08 s
GPS Localization Accuracy	±3.6 m
Wi-Fi Connectivity Success Rate	98.7%
Cloud Data Transmission Success Rate	99.1%
Dashboard Update Delay	1.24 s
Live Video Streaming Frame Rate	18 fps

4. Overall System Performance

The integrated operation of all sensing and communication modules demonstrated the feasibility of the proposed rescue robot for earthquake search-and-rescue applications. The combination of human detection, obstacle avoidance, hazardous gas monitoring, GPS localization, and IoT-based remote monitoring enhanced situational awareness while reducing the need for rescue personnel to enter hazardous environments. The modular architecture and use of low-cost embedded components make the proposed system suitable for deployment in educational and disaster-response applications. The overall system performance is summarized in Table 5.

Table 5. Overall System Evaluation

Feature	Performance
Human Detection Accuracy	96.4%
Obstacle Avoidance Efficiency	95.8%
Hazardous Gas Detection Reliability	97.2%
GPS Localization Accuracy	96.8%
IoT Communication Reliability	99.1%
Live Video Streaming Availability	97.5%
Overall System Performance	97.0%

V. DISCUSSION

The experimental results demonstrate that the proposed IoT-enabled rescue robot successfully integrates multiple sensing modules with cloud-based monitoring to support earthquake search-and-rescue operations. The PIR sensor reliably detected human presence, while the ultrasonic sensor enabled autonomous obstacle avoidance during navigation. The MQ-series gas sensor effectively identified hazardous gas conditions, and the GPS module accurately transmitted the robot's location to the Blynk IoT platform. Real-time video streaming through the ESP32-CAM further enhanced situational awareness for remote rescue personnel. The use of low-cost embedded hardware components makes the proposed system suitable for practical deployment in resource-constrained disaster environments while providing reliable monitoring and communication capabilities. The proposed system offers a cost-effective alternative to conventional rescue robots by integrating multiple sensing and communication modules without requiring computationally intensive hardware.

Compared with recently reported AI-based rescue robots and UAV-assisted rescue systems, the proposed platform provides an integrated low-cost solution by combining human detection, obstacle avoidance, hazardous gas monitoring, GPS localization, live video streaming, and IoT-based remote monitoring within a single embedded architecture. Although advanced AI techniques may provide higher detection accuracy, the proposed system offers a practical balance between performance, implementation cost, and computational complexity, making it suitable for educational and resource-constrained disaster-response applications.

The present prototype was evaluated under laboratory conditions; therefore, performance may vary in real post-earthquake environments with heavy debris, poor lighting conditions, and unstable communication networks.

V. CONCLUSION AND FUTURE SCOPE

This paper presented the design and implementation of an intelligent IoT-enabled multi-sensor autonomous rescue robot for earthquake search-and-rescue applications. The proposed system integrates a Passive Infrared (PIR) sensor for human detection, an ultrasonic sensor for obstacle avoidance, an MQ-series gas sensor for hazardous gas monitoring, a GPS module for location tracking, and an ESP32-CAM for real-time video surveillance. An Arduino Uno serves as the central controller, while an ESP8266 NodeMCU enables wireless communication with the Blynk IoT platform for remote monitoring and alert generation.

Experimental evaluation demonstrated the effective operation of the integrated sensing, navigation, environmental monitoring, and IoT communication modules under laboratory conditions. The proposed system successfully detected human presence, avoided obstacles, monitored hazardous gas levels, transmitted GPS coordinates, and provided real-time monitoring through the cloud platform. The use of commercially available embedded components makes the system cost-effective, energy-efficient, and suitable for deployment in disaster-prone environments.

Future work will focus on integrating thermal imaging cameras, lightweight deep learning models such as YOLO, and SLAM-based autonomous navigation to improve victim detection accuracy and robot mobility in complex disaster scenarios. The incorporation of 5G communication and edge artificial intelligence can further enhance the system's real-time performance and operational efficiency.

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