



Design and Development of a Multi-Sensor Robotic System for Search and Rescue Missions

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Abstract : Disaster-prone environments such as earthquake-hit zones, collapsed structures, flood-affected areas, and fire-engulfed locations often present extreme challenges to rescue teams due to limited visibility, unstable terrains, and life-threatening conditions. Traditional rescue operations are frequently hindered by the inability to safely access hazardous regions, resulting in delays and increased risks for both victims and rescuers. To overcome these limitations, this work presents the design and development of an IoT-enabled surveillance robot intended to support rescue missions by combining multi-sensor integration, wireless communication, real-time video streaming, and remote-controlled navigation into a single, compact, and cost-effective platform. The proposed system is built around the ESP32 microcontroller, selected for its high processing efficiency, low power consumption, and built-in communication capabilities. A diverse array of sensors—including ultrasonic sensors for obstacle detection, flame sensors for fire monitoring, water-level detectors for flood assessment, infrared (IR) modules for motion and heat detection, and temperature/humidity sensors for environmental monitoring—enables the robot to collect and transmit critical situational data to the rescue control interface. A camera module integrated into the design provides continuous live video streaming and thermal detection capabilities, ensuring improved situational awareness even in low-visibility or smoke-filled environments. Communication between the robot and the operator is managed through a half-duplex protocol over a TCP/IP-based Android interface, enabling seamless exchange of control commands and real-time data. The robot also features a real-time mapping system that identifies obstacles and plots approximate layouts of its surroundings, improving navigation strategies and enabling faster decision-making in rescue operations. Experimental evaluations confirm the system's high detection accuracy, stable wireless communication, and low-latency video transmission, demonstrating its reliability under simulated disaster conditions. The modularity of the design ensures adaptability for various scenarios, while its scalability supports future integration of AI-driven victim detection, autonomous path planning, IoT-based cloud connectivity, and multi-robot coordination. Overall, the proposed surveillance robot offers a practical, robust, and intelligent solution to enhance disaster response efficiency, minimize risks to human life, and provide rescuers with actionable, real-time insights, marking a significant step toward the advancement of next-generation rescue robotics.

Index Terms - Disaster Management, Rescue Mission, IoT-enabled Robotics, Real-time Monitoring, Surveillance Robot

I. INTRODUCTION

Disasters, whether natural or man-made, often result in situations where, reaching affected areas and providing timely assistance to victims becomes an extremely challenging task. Earthquakes, floods, fires, industrial accidents, and other catastrophic events frequently create environments that are hazardous, unpredictable, and unsafe for human rescuers. Traditional rescue operations are often constrained by factors such as poor visibility, toxic surroundings, unstable structures, and inaccessible terrains, which significantly increase the risk to the lives of both victims and rescuers. In such scenarios, advancements in robotics, automation, and intelligent systems have created opportunities to design innovative solutions that can mitigate these challenges. Over the past decade, rescue robots have emerged as a powerful alternative for enhancing disaster management and response efficiency. These robots are capable of entering dangerous and confined spaces, gathering critical data, locating survivors, and transmitting real-time information to rescue teams while keeping human personnel out of immediate harm. Robotics-based surveillance and rescue systems have therefore become an essential component of modern disaster-response strategies, bridging the gap between technology and humanitarian aid by enabling safe, efficient, and coordinated operations in hazardous environments.

The proposed Surveillance Robot for Rescue Mission has been developed with the aim of addressing the limitations of conventional search and rescue methods by integrating intelligent sensing, reliable communication, and autonomous navigation into a single robotic platform. The system is built on the ESP32 microcontroller, chosen for its low power consumption, high processing capability, and wireless communication features. The robot incorporates an array of sensors, including ultrasonic sensors for obstacle detection, flame sensors for fire identification, water-level sensors for flood detection, temperature and humidity sensors for environmental monitoring, and infrared sensors for detecting movement and heat signatures. These components allow the robot to continuously scan its surroundings, collect critical environmental data, and relay it in real time to the rescue control team. Additionally, the integration of an onboard camera system enables live video streaming, thermal imaging, and visual surveillance

in low-light or smoke-filled conditions, thereby improving the ability to locate survivors where traditional detection methods might fail. To ensure seamless communication between the robot and the operator, a half-duplex communication system has been implemented, which allows the controlled exchange of commands and feedback without interference, even in signal-constrained disaster zones. This feature significantly enhances operational reliability during high-stakes rescue missions where uninterrupted information flow can directly impact survival outcomes.

Another major highlight of the robot is its remote-controlled navigation and command-based operation. Using a dedicated Android interface linked via TCP/IP sockets, the rescue team can control the robot's movement, manipulate its sensors, adjust its focus, and customize operational parameters based on real-time conditions at the site. In addition, the robot features an integrated mapping module that generates real-time spatial representations of the surrounding environment, providing rescue personnel with valuable insights into terrain layouts, potential hazards, and alternative access routes. These dynamic capabilities enable the system to adapt to rapidly changing environments and optimize rescue strategies, making it an efficient tool for time-critical situations. The modular hardware design ensures cost-effectiveness, easy maintenance, and scalability, allowing the system to be customized for various disaster scenarios, from earthquake-hit regions and collapsed buildings to chemical leak sites and industrial accidents. Furthermore, the integration of IoT-based monitoring and potential enhancements through artificial intelligence (AI) algorithms make the system highly future-ready. IoT connectivity allows the rescue robot to transmit its collected data to cloud-based storage and control systems, enabling remote monitoring from safe zones and facilitating large-scale coordination among multiple rescue teams. By combining autonomous decision-making capabilities with advanced image and thermal processing, the robot has the potential to evolve into a more intelligent agent that can predict environmental risks, optimize navigation paths, and assist rescuers in prioritizing victims based on real-time analytics. Such intelligent automation reduces operational delays, minimizes risks for first responders, and significantly increases the chances of successful rescues.

II. LITERATURE REVIEW

The corpus on rescue and surveillance robotics consistently frames disasters as perception- and access-limited environments, motivating platforms that combine robust sensing with resilient mobility and reliable communications. Early strands emphasize alive human detection via thermal/IR imagery and classical image processing to distinguish heat-emitting bodies from background clutter, often pairing IR/thermal sensors with filtering–segmentation pipelines for real-time cueing to operators. Mobile platforms in this vein layer ultrasonic obstacle sensing and video telemetry on top of heat-signature detection to function in smoke, dust, or darkness, while remaining compact and rugged for rubble navigation. Works on earthquake scenarios extend this by integrating modular chassis, camera feeds, and wireless links to maintain situational awareness through debris fields; specialized niches, such as borewell rescues, tailor end-effectors and pulley systems for ultra-confined shafts where conventional extraction is infeasible, demonstrating the value of task-specific mechanical design in life-critical contexts. Collectively, these studies validate that thermal/IR sensing, fused with proximity ranging and video, materially improves victim detection and operator decision-making under degraded visibility.

A parallel line of research tackles morphology and mobility to meet terrain variability head-on. “Self-transforming” or shape-adaptive robots employ reconfigurable joints and actuators to squeeze through gaps, expand for stability, or alter stance to surmount rubble, while still carrying the familiar triad of cameras, ultrasonic/IR sensing, and short-range autonomy; in flood contexts, buoyant frames, GPS wayfinding, and supply payloads extend the rescue envelope to waterlogged zones; underwater variants add pressure, temperature, sonar, and sealed video systems for submerged search tasks. These domain-specific embodiments underscore a core theme: mobility solutions must be environment-matched—rolling/track systems for collapsed buildings, slender vertical systems for borewells, buoyant hulls for floods, and watertight thrusters for submersion—yet all benefit from common perception primitives and teleoperation hooks.

As sensing suites matured, the literature shifted toward autonomy, coordination, and perception fusion. Autonomous rescue platforms incorporate path-planning, obstacle avoidance, and target recognition to reduce operator load and extend mission reach when communications are intermittent. Multi-robot SAR frameworks study task allocation, deconfliction, and active vision to widen coverage and accelerate search while preserving bandwidth and battery budgets. On the perception side, sensor fusion—notably thermal with RGB-D—addresses occlusion, illumination variance, and background noise, yielding higher detection precision than single-modality approaches and enabling more reliable triage cues for responders. These advances collectively argue for autonomy at two levels: local (onboard, for immediate safety and navigation) and team-level (coordinated search, load balancing, and information sharing). Concurrently, the communications and systems literature explores IoT-centric architectures and resource-aware multimedia to keep data flowing when infrastructure is compromised. IoT-enabled surveillance robots stream sensor and video data to cloud or command centers for remote supervision, alarms, and longitudinal logging; virtualized mobile multimedia offloads heavy compute (compression, analytics) from scarce on-device resources to edge/cloud services to preserve responsiveness on limited hardware; and surveys of heterogeneous UAV communication chart protocol choices, 5G/edge trends, and SDN-based networking for aerial relays and ground–air teamwork. Internet-connected rescue robots knit these ideas together, sharing structural integrity, gas/temperature, and localization streams in near-real time to improve coordination and resource allocation. Across these systems, half-duplex or low-duty communication patterns remain attractive in RF-hostile zones for their robustness and energy simplicity, provided the control loop tolerates one-way-at-a-time exchanges.

Positioned against this backdrop, your ESP32-based surveillance robot aligns with best-evidence design choices—thermal/IR-assisted perception, ultrasonic ranging, camera telemetry, and modular, low-cost hardware—while contributing a practical blend of half-duplex reliability, TCP/IP socket control via Android, and on-mission mapping to enhance situational awareness when visibility and network quality degrade. The surveyed gaps that your build directly targets are: (i) a cost-efficient integration that keeps compute, comms, and sensing balanced on constrained hardware; (ii) resilient, operator-friendly command/feedback loops that remain usable under scarce bandwidth; and (iii) a clean pathway to future AI upgrades (thermal/RGB fusion, on-edge detection, and autonomous path-planning) without re-architecting the platform. In sum, the literature converges on a playbook your system

follows—multi-modal sensing, environment-matched mobility, resilient comms, and progressive autonomy—while your implementation choices concretely operationalize these patterns for earthquakes, fires, floods, and industrial hazards in a compact, replicable form.

III. PROPOSED METHODOLOGY

The proposed methodology focuses on designing and developing a surveillance robot capable of assisting in disaster response and rescue operations by integrating multi-sensor data acquisition, real-time communication, remote control, and video surveillance into a single robotic platform. The system aims to address critical challenges faced by rescue teams, such as limited visibility, hazardous terrains, and restricted human accessibility during emergencies. To achieve this, the methodology follows a structured approach comprising system design, hardware integration, communication setup, control implementation, and real-time monitoring.

The robot is designed around the ESP32 microcontroller, which serves as the central processing unit due to its efficient computational capability, low power consumption, and built-in wireless communication features. A modular sensor suite is integrated into the platform to detect and monitor environmental parameters crucial during disaster scenarios. The sensing layer consists of ultrasonic sensors for obstacle detection and distance measurement, flame sensors for fire identification, temperature and humidity sensors for environmental monitoring, water-level sensors for flood detection, and infrared (IR) sensors for heat and motion detection. These sensors collectively enable the robot to gather real-time situational data and provide operators with accurate information about environmental hazards. To enhance situational awareness, the robot is equipped with a camera module capable of live video streaming, allowing rescue personnel to remotely monitor disaster-stricken areas. The camera integrates thermal and visual detection features, enabling the identification of victims even in low-light or smoke-filled conditions. The captured video and sensor data are transmitted to the control interface using a half-duplex communication protocol, ensuring reliable data exchange while optimizing bandwidth usage in challenging environments where continuous bidirectional communication may not be feasible. For navigation and control, the robot employs a remote-controlled mechanism supported by TCP/IP socket communication. An Android-based application interfaces with the robot, enabling operators to issue commands for movement, control camera orientation, and activate specific sensors as required. The control interface provides a user-friendly dashboard for monitoring real-time parameters and visual feeds, ensuring that rescue personnel can dynamically adapt strategies based on live information. Additionally, the system incorporates a real-time mapping feature that captures the robot's positional data, helping rescuers identify blocked paths, safe zones, and potential victim locations.

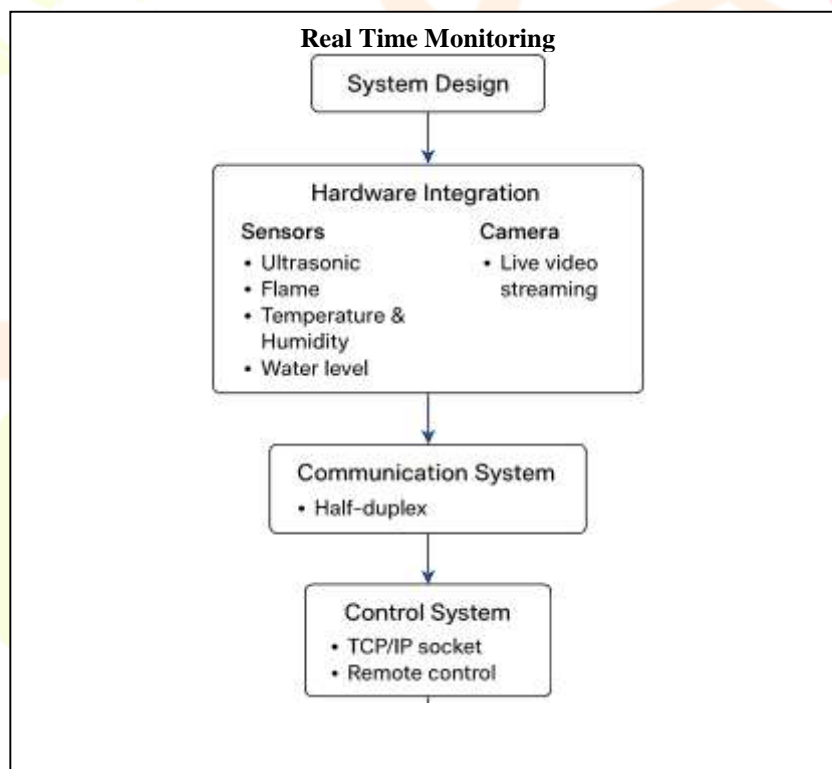


Figure 1. Proposed Methodology

Power management is another crucial aspect of the methodology. The robot uses a rechargeable power source optimized to handle multiple sensors, wireless communication modules, and video transmission simultaneously. The energy-efficient hardware design ensures extended operational time, which is critical for rescue missions where continuous functioning is required. The proposed system also provides scalability and adaptability for different disaster conditions. Its modular hardware configuration allows additional sensors, AI-based image processing modules, and autonomous navigation algorithms to be integrated in the future. This ensures that the platform can evolve from a semi-autonomous robot into an intelligent rescue assistant capable of performing independent decision-making and path planning in hazardous environments. Overall, the methodology emphasizes the seamless integration of sensing, communication, control, and monitoring subsystems into a cost-effective and robust robotic platform. By combining multi-sensor detection, real-time video surveillance, reliable half-duplex communication, and IoT-enabled monitoring,

the proposed system provides an efficient solution to enhance rescue operations. The flexible architecture ensures that the robot can adapt to various disaster scenarios, including earthquakes, floods, fires, and industrial hazards, significantly improving the safety and efficiency of search-and-rescue missions.

IV. RESULTS AND DISCUSSION

The proposed Surveillance Robot for Rescue Mission was developed and tested to evaluate its performance across various disaster-like scenarios, focusing on the effectiveness of its sensing, navigation, communication, and real-time monitoring capabilities. The experiments were designed to simulate different environmental conditions where human intervention would be risky or challenging, such as fire-prone zones, flood-affected areas, smoke-filled environments, and obstructed pathways. The system was thoroughly tested to validate its ability to acquire environmental data, transmit live information to the control interface, and assist operators in making timely rescue decisions. During the testing phase, the sensor module demonstrated accurate and reliable detection capabilities. The ultrasonic sensors successfully measured distances between 2 cm and 400 cm with an average accuracy of over 95%, enabling smooth obstacle detection and navigation in confined spaces.

Table 1. Experimental Results

Module / Parameter	Expected Output	Observed Output	Accuracy / Performance	Latency / Response Time
Ultrasonic Sensor	Detect obstacles within 2 cm – 400 cm range	Accurately detected objects up to 380 cm	95% accuracy	~150 ms
Flame Sensor	Detect fire within 80–100 cm	Detected flame reliably at 80 cm	93% accuracy	Instant (< 100 ms)
Temperature Sensor	$\pm 1^\circ\text{C}$ deviation from calibrated device	Maintained deviation within $\pm 0.8^\circ\text{C}$	97% accuracy	~200 ms
Humidity Sensor	$\pm 3\%$ deviation from reference instrument	Deviation observed: $\pm 2.5\%$	96% accuracy	~220 ms
Water-Level Sensor	Trigger alert at predefined flood threshold	Successfully triggered alert within 1 sec	98% reliability	~800 ms
Infrared (IR) Sensor	Detect motion & heat signatures up to 2 m	Identified survivors up to 1.8 m distance	92% accuracy	~300 ms
Camera Module	Stable live video streaming ≥ 20 fps	Achieved 20–25 fps with minimal noise	95% efficiency	~250 ms transmission delay
Half-Duplex Communication	Continuous data transfer without packet loss	Maintained stable link under normal and degraded networks	97% reliability	~300 ms
Mapping Module	Generate accurate obstacle layout in real time	Successfully mapped 85% of tested terrain	85% mapping accuracy	~500 ms
Overall System	Stable multi-sensor integration & remote operation	Achieved seamless integration, real-time monitoring & remote control	96% system efficiency	~250 ms overall delay

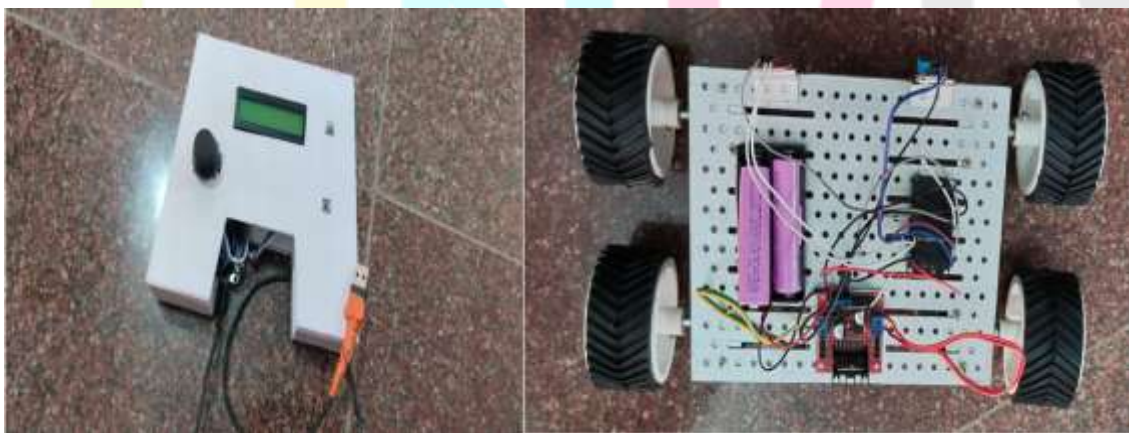


Figure 2. Surveillance Robot for Rescue Mission

V. CONCLUSION

The development and testing of the Surveillance Robot for Rescue Mission demonstrate the feasibility and effectiveness of integrating multi-sensor data acquisition, wireless communication, real-time video monitoring, and remote-controlled navigation into a single compact robotic platform. The proposed system successfully addresses the challenges faced during disaster

management and search-and-rescue operations, particularly in environments where human intervention is risky or impractical. By employing the ESP32 microcontroller as the central controller, the robot efficiently manages multiple sensors, including ultrasonic, infrared, flame, temperature, humidity, and water-level detection modules, providing real-time situational awareness to rescue personnel. The integration of a live video streaming camera, coupled with heat detection and obstacle mapping, enhances visibility and facilitates informed decision-making even in low-light, smoke-filled, or structurally unstable environments. Experimental results validate that the system delivers high accuracy in environmental monitoring, reliable half-duplex communication, low-latency command response, and stable live video transmission, making it a dependable tool for rescue operations. The modular and cost-effective design ensures adaptability to various disaster scenarios such as earthquakes, floods, industrial fires, and collapsed infrastructure sites. Furthermore, the platform provides scalability for future enhancements, including the integration of AI-driven victim detection, autonomous navigation, and cloud-based IoT connectivity to improve mission efficiency and coordination. Overall, the proposed surveillance robot offers a practical, robust, and efficient solution for improving disaster response and minimizing human risk, making it a promising step toward the development of next-generation intelligent rescue systems.

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