International Journal of Computers and Informatics (IJCI)
Vol. (5), No. (11)
IJCI
November 2026
المجلة الدولية للحاسبات والمعلوماتية
الإصدار (5)، العدد (11)

# Design and Experimental Evaluation of a Low-Cost Autonomous Medical Rescue Robot for Hazardous and Conflict-Affected Environments

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## Abstract

Emergency rescue operations in hazardous, unstable, and conflict-affected environments expose medical teams and first responders to serious risks, including structural collapse, fire, debris, toxic exposure, communication failure, and restricted access to victims. Robotic systems can reduce direct human exposure by performing early reconnaissance, detecting possible human presence, transmitting visual information, and supporting rescue planning. However, many advanced rescue robots are expensive, complex, and difficult to reproduce in low-resource settings. This paper presents the design, implementation, and experimental evaluation of a low-cost autonomous medical rescue robot developed for simulated hazardous-environment rescue support. The proposed prototype integrates an ESP32 microcontroller, HC-SR04 ultrasonic sensor, PIR motion sensor, Neo-6M GPS module, ESP32-CAM video-streaming module, L298N motor driver, differential-drive DC motors, servo-actuated robotic arm, and rechargeable battery power system. A reactive autonomous control algorithm was implemented to enable low-speed autonomous navigation, obstacle avoidance, human-motion detection, GPS coordinate reporting, live visual monitoring, and basic robotic-arm activation. Experimental testing showed that the robot achieved an average obstacle-response time of approximately 50 ms, distance-measurement accuracy of approximately ±2 cm, and collision-avoidance success of 92% under controlled conditions. PIR-based human detection achieved 100% success for moving subjects within 1–3 m and 93% within 3–5 m, but decreased to 41% for stationary subjects. Video streaming was maintained at 15–20 FPS up to approximately 30 m line-of-sight range, while GPS localization achieved approximately ±3 m accuracy in open outdoor environments. The robot operated continuously for approximately 45 minutes. The findings demonstrate the feasibility of integrating multiple rescue-support functions into an affordable embedded robotic platform. Nevertheless, the prototype remains limited by PIR detection weakness, indoor GPS failure, Wi-Fi range, battery endurance, wheeled mobility, and robotic-arm payload. Future versions should integrate thermal imaging, AI-based victim detection, LiDAR or depth sensing, indoor localization, long-range communication, stronger actuation, and ruggedized mobility.

**Keywords:** Autonomous Rescue Robot, Medical Rescue Robotics, Search and Rescue, ESP32, Human Detection.

## 1. Introduction

Emergency response and rescue operations in hazardous environments continue to be one of the most challenging and risky tasks. Natural disasters, wars, earthquakes, fires, explosions, collapsed buildings, and industrial accidents may create situations when victims are enclosed in areas that are too dangerous for immediate human entry. The rescue team will be exposed to unstable buildings, rubble, smoke, low visibility, exposure to toxic materials, blocked routes, and difficulties with communication. Under these circumstances, the possibility of gathering information about the surrounding area before sending any humans inside is crucial. Early reconnaissance may help to locate victims, evaluate hazards, and plan rescue activities more effectively.

Robotics is becoming an increasingly relevant direction in terms of search and rescue technology. Rescue robots may operate in hazardous and inaccessible environment, collect visual and sensor information, detect obstacles, find possible victims and send information to the operator. The value of the robotics lies in the fact that it helps to avoid the risks of human exposure in the beginning stages of emergency response. The research on search and rescue robotics was devoted to finding ways how to use robots in order to improve safety, response rate, situational awareness, and operational decision-making during disaster response mission (Chitikena et al., 2023; Tong et al., 2024).

Various types of rescue robots were invented, like ground robots, aerial robots, snake robots, soft robots, tracked robots, wheeled robots, and multi-robots systems. Advanced rescue robots may use LiDAR, thermal cameras, depth cameras, fast processor, robotic manipulators, reliable mechanical structure, and long-distance communication system. The mentioned technologies allow having good performance in the complex environment, but at the same time, they increase cost, power consumption, mechanical complexity and maintenance cost. As a result, many of advanced rescue robots might be unaffordable to universities, small laboratories, developing countries, and low-budget emergency response organizations.

Nevertheless, many low-cost robotic platforms are designed primarily for educational purposes. Such systems are capable of doing basic movement, avoiding obstacles and remote control, but not much more. Practical rescue robot should not only be able to move, but detect obstacles, detect human presence, give visual feedback, inform about its location, and give some physical assistance. Thus, there is research gap between advanced and costly rescue robots and simple and cheap educational robots.

Autonomous navigation is one of the primary needs of a rescue-support robot. Hazardous environment means unstable connection with the operator and difficulties with manual control. Thus, even a cheap robot should be able to make basic movement decisions using sensor information. Advanced navigation systems use LiDAR-based SLAM (simultaneous localization and mapping), depth cameras, visual odometry and sensor fusion. The listed approaches are efficient, but require more computational power and more expensive sensors (Yue et al., 2023; Filipenko and Afanasyev, 2025). On the other hand, a reactive approach using ultrasonic sensing is cheaper way of obstacle

avoidance. It doesn't provide a full map of the environment, but gives a quick reaction on nearby obstacles.

Human-motion detection is another important aspect in rescue robotics. Robot should be able to detect human presence, especially in those cases, when the victims could not be easily reached by the responders. Various human detection technologies were researched, like RGB cameras, thermal cameras, multispectral imaging, radar, $CO_2$ sensor, microphone and deep learning-based computer vision (Ulloa et al., 2024; Ulloa et al., 2023). Thermal and multispectral systems are promising in case of difficult visual conditions, but they are expensive and may require additional computing power. In case of low-cost prototype, human-motion detection via PIR sensor is a simple way to detect moving humans. But PIR sensors are unable to detect still and unconscious victims, since they work on basis of infrared radiation change.

Remote visual monitoring is also an important feature in rescue robotics. Detection signal alone is not enough for rescue decision-making. Operators need visual information to make sure that the robot has detected a human, obstacle or environment hazard. There are inexpensive camera modules that allow video-streaming via Wi-Fi, for example ESP32-CAM. Nevertheless, Wi-Fi signal range is relatively short and it can decrease in obstructed environment. More robust communication technologies should be used in case of real disaster, like mesh network, long-range radio, LTE, 5G or multi-robot relay system (Bravo-Arrabal et al., 2025).

Localization is needed in order to understand where the robot and possible victims are located. GPS modules are a cheap way to localize outdoors, and can provide an approximation of coordinates in the open space. GPS becomes unreliable indoors, underground, near tall buildings or under collapsed buildings. Thus, GPS is suitable for outdoor rescue operations, but it should be supplemented with indoor localization technologies like LiDAR SLAM, visual odometry, ultra-wideband localization, inertial navigation or sensor fusion (Deshmukh et al., 2025).

This study attempts to fill the gap between expensive rescue robots and simple educational platforms by designing and experimenting with low-cost autonomous medical rescue robot. Proposed system combines obstacle avoidance, human motion detection, GPS localization outdoors, live video streaming, differential drive and robotic arm manipulation into the low-cost embedded robotic platform. System is assembled from affordable parts like ESP32 microcontroller, HC-SR04 ultrasonic sensor, PIR sensor, Neo-6M GPS, ESP32-CAM, L298N motor driver, DC and servo motors.

The main contribution of this paper is an integration and experimental assessment of multiple rescue-support features in the low-cost system. The purpose of the study is not to claim superiority of the prototype compared to industrial rescue robots, but to show that low-cost embedded system can provide useful rescue-support features under simulated hazardous-environment conditions. Moreover, main limitations that need to be addressed prior to the field deployment of the system are identified, like sensing limitation, communication range, indoor localization, battery life, mobility, and manipulation strength.

The paper is organized as follows. Materials and methods are described in Section 2, including system architecture, hardware design, software logic, and experimental design. Results and discussion, including obstacle avoidance, human detection, video streaming, GPS localization, battery endurance and robotic arm performance, are provided in Section 3. Conclusion and future development ideas are outlined in Section 4.

## 2. Materials and Methods

### 2.1 System Design Approach:

An experimental engineering approach was applied in developing this research work. The aim was to design a prototype that would show the feasibility of inexpensive robotic rescue assistance. Requirement specification, selection of components, mechanical assembling, electrical assembly, software programming, sub-systems testing, systems integration, and experiments were part of the design process.

The design of the system was guided by four key concepts; affordability, modularity, simplicity and functional integration. Affordability was very crucial as this project was meant to provide a platform that can be easily replicated in education centers or other low resource environments. Modularity made sure that this system can be upgraded in the future for example, by using a thermal camera in place of the PIR sensor or LiDAR for mapping. Simplicity was essential as this system depended on the microcontroller and not a high-end computer.

### 2.2 System Architecture:

The design robot includes seven key systems, namely, control, sensing, locomotion, localization, communication, manipulation, and power. The control system relies on the ESP32 microcontroller, which will take inputs from sensors and make decisions about movements. The sensing system will have an HC-SR04 ultrasonic sensor to detect obstacles and a PIR sensor to detect motion made by humans. The locomotion system involves the use of two DC geared motors that are connected via an L298N motor driver. The localization system has a Neo-6M GPS system for outdoor positioning. The communication system uses ESP32-CAM module for real-time video streaming. The manipulation system has the servo motors used as the simple robotic arm with a gripper.

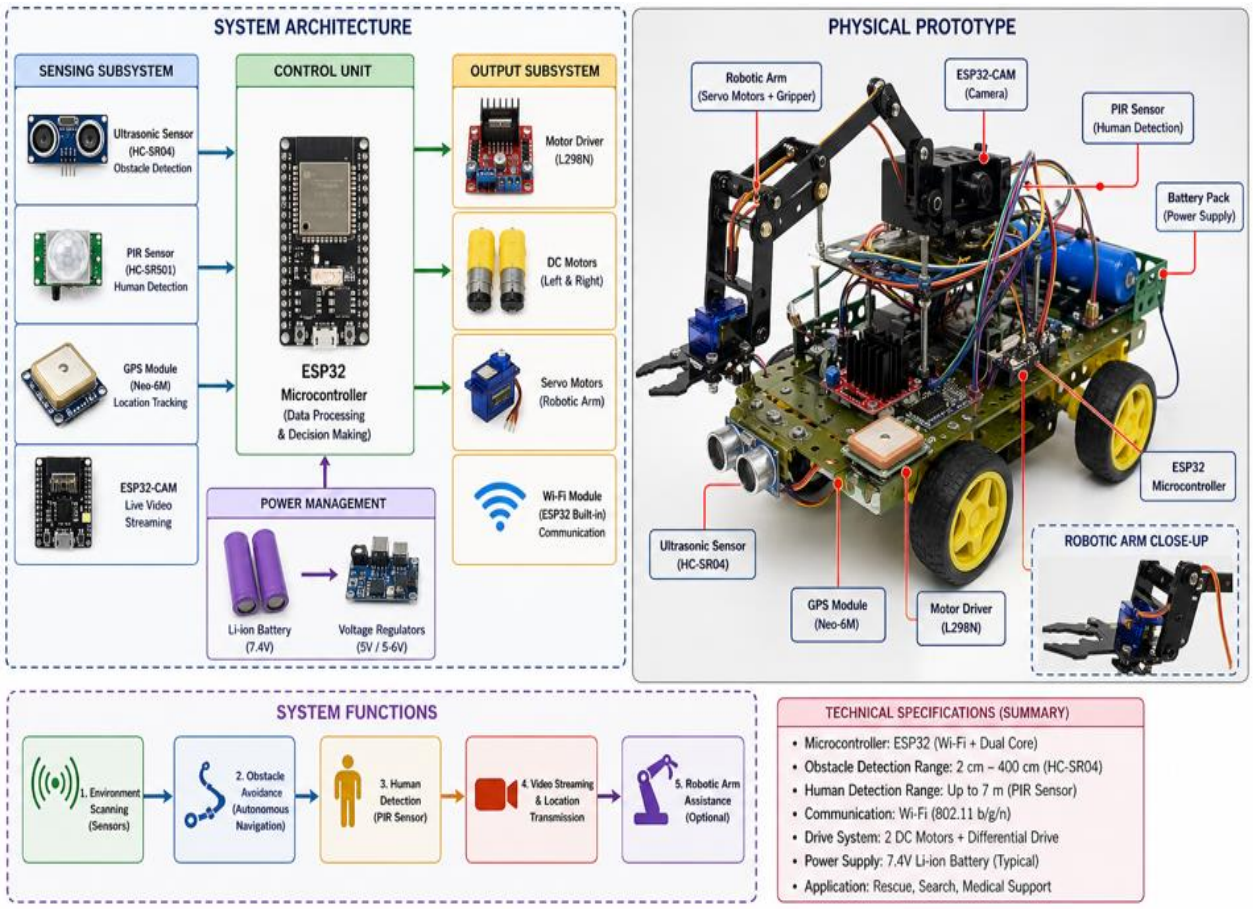



Figure (1): System architecture of the proposed autonomous medical rescue robot

The architecture is guided by reactive control. In the first place, the robot does not map out its entire environment; rather, the robot makes instant decisions based on information from its sensors. Whenever there is an obstacle inside the safety range, the robot stops moving and takes evasive action. If there is human movement in the vicinity, the robot will stop, initiate the victim rescue procedure, and send GPS coordinates and video to the user.

### 2.3 Hardware Components:

The hardware components were selected based on availability, cost, compatibility with ESP32, power requirements, and suitability for prototype-level rescue applications. Table 1 summarizes the main components.

Table (1): Hardware components used in the proposed robot

| Component | Model / Type | Function |
|---|---|---|
| Microcontroller | ESP32 development board | Main control and decision-making |
| Obstacle sensor | HC-SR04 ultrasonic sensor | Measures frontal obstacle distance |
| Human detection sensor | PIR motion sensor | Detects moving human presence |
| GPS module | Neo-6M GPS | Provides outdoor coordinates |
| Camera module | ESP32-CAM | Provides live video streaming |
| Motor driver | L298N dual H-bridge | Controls DC motors |
| Locomotion motors | DC geared motors | Provides differential-drive movement |
| Robotic arm motors | Servo motors | Controls arm and gripper |
| Power source | Lithium-ion battery pack | Provides mobile power |
| Voltage regulator | Buck converter | Stabilizes voltage supply |

The ESP32 board is used as the primary control unit since it has adequate input-output capacity, affordability, and built-in wireless capabilities. HC-SR04 was chosen as an affordable option for obstacle detection within a small range of distance. PIR sensor was employed as a low-cost human motion sensing device. Neo-6M GPS was used for localization outside. ESP32-CAM was used as a visual monitoring device without the need for an additional computer onboard. L298N motor driver was used to connect the ESP32 with DC motors. The use of servo motors for robotic arm control is driven by their PWM signal control capability..

### 2.4 Mechanical Design:

This robot is designed using a small wheeled chassis that uses differential drive mechanism. The robot had two DC geared motors attached to the opposite sides of the chassis while one more wheel was attached as a balance wheel. This system was selected since it is easy, cheap, and reliable to control. The robot can move forward, backward, turn and rotate due to control over the directions of the two motors.

The ultrasonic sensor was attached to the front of the robot to detect obstacles in its way. The PIR sensor was installed at the elevated front side to increase the ability of detecting the motion of humans. GPS module was installed on the top of the chassis to ensure the visibility of satellites during the test in the open space. ESP32-CAM was attached to the front side of the robot to provide a stream from the front. Robotic arm is installed at the front-central position of the chassis to enable some object manipulation.

Though tracked drive would work better on the rugged surface, wheeled drive is chosen for the prototype, since the purpose of this study is the cost-effective development.

### 2.5 Obstacle Detection and Avoidance:

Obstacle detection was implemented using the HC-SR04 ultrasonic sensor. The sensor transmits an ultrasonic pulse and measures the time required for the echo to return. Distance was calculated using:

$$d = (v \times t) / 2 \quad (1)$$

Where (d) is the obstacle distance, (v) is the speed of sound in air, and (t) is the echo travel time. The division by two accounts for the round-trip travel of the sound wave.

A safety threshold of 30 cm was used. When an obstacle was detected within this threshold, the robot stopped, reversed briefly, rotated, and resumed movement. This method allowed low-speed reactive obstacle avoidance without complex mapping or path planning.

**2.6 Human-Motion Detection:**

The human-motion detection feature was done through the use of a PIR sensor. The PIR sensor senses changes in infrared radiation resulting from movement of warm objects. In its process of working, the ESP32 regularly checks the output from the PIR sensor. In case of any motion, the robot will stop and begin searching for victims.

The PIR sensor was used due to its affordability, power consumption efficiency, and easy integration with the ESP32. The PIR sensor, however, has notable disadvantages. PIR sensors work well in detection of moving people but are poor at detection of non-moving or unconscious victims. They are also affected by high ambient temperature since the difference between the temperature of the human body and the surrounding is reduced.

**2.7 Localization and Video Streaming:**

Neo-6M GPS module was utilized to obtain geographical latitude and longitude coordinates in an outdoor setting. The GPS module interfaces with the ESP32 using the UART serial interface. Upon detection of human movement, the GPS coordinates may be obtained to facilitate approximate victim location.

ESP32-CAM module was used for live video streaming. The camera streams live videos through Wi-Fi to a distant device such as a computer or mobile phone. Live video feedback enables the user to confirm the victim's presence in the surroundings and analyze the surroundings. ESP32-CAM was used as an inexpensive situational awareness device and not as an artificial intelligence based image processing device.

**2.8 Robotic Arm and Power System:**

The robot was fitted with a robotic arm that was controlled using servo motors. There were several joints that were actuated by servo motors in addition to the gripper on the arm. The arm was meant for performing simple tasks, such as picking up light-weighted items or performing small item deliveries.

There was a rechargeable battery system which was used as a power source for the robot. Voltage regulators were used in order to ensure that there was sufficient power supplied to the ESP32, sensors, GPS, camera, motors, and servos. This was critical because the motors and servos consumed more current compared to sensors and logic units.

### 2.9 Control Algorithm:

Control program was developed using different modular routines including sensing routine, motor routine, obstacle routine, PIR routine, GPS routine, robotic arm routine and video streaming routine.

Robot uses reactive control technique where robot after initializing performs all initialization of sensors and actuators, starts moving in forward direction with low speed and continuously senses the ultrasonic sensor. If the distance to the obstacle is less than the threshold distance, robot stops itself, goes backward, turns and moves again. On the other hand, if there is no obstacle detected by ultrasonic sensor, robot moves forward. At the same time, robot uses PIR sensor to detect human motion. If human motion is detected,

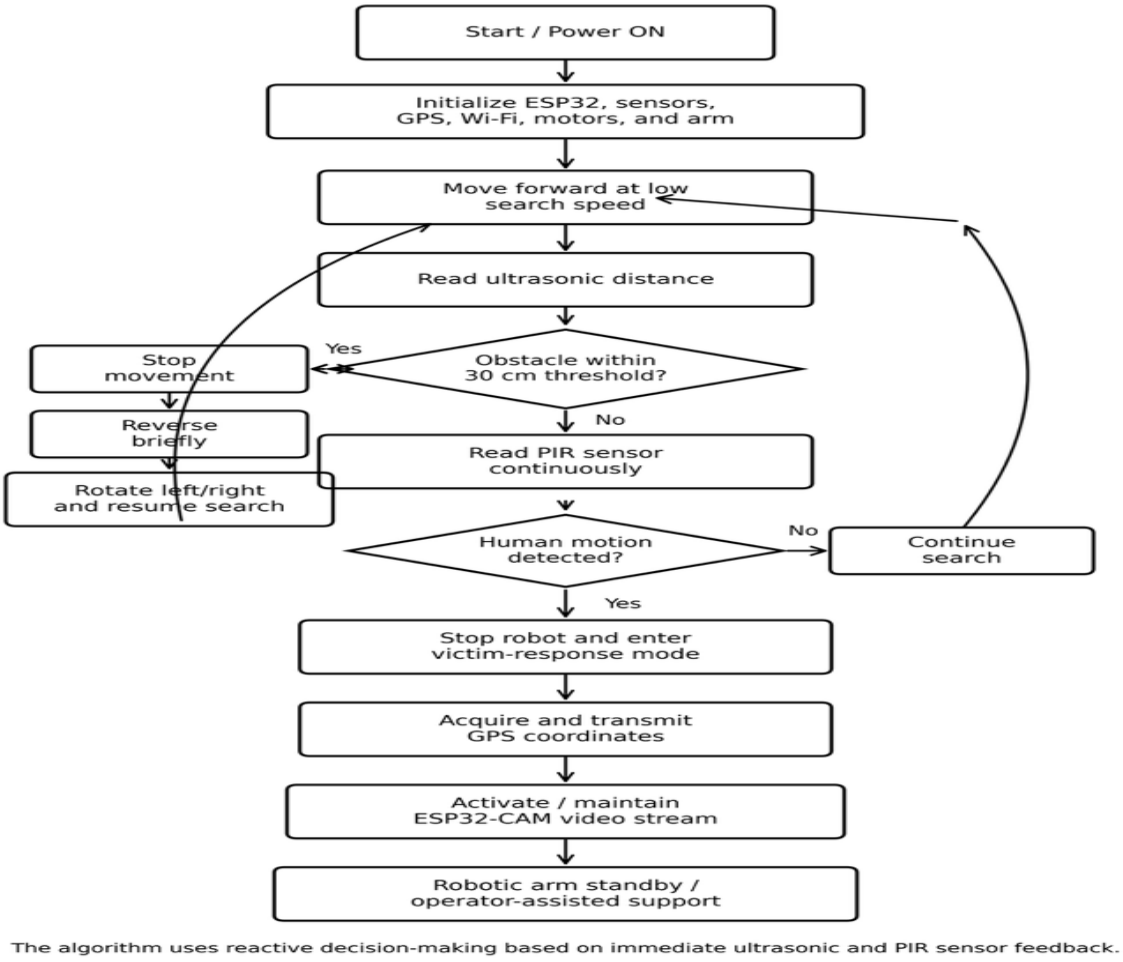



Figure (2): Reactive control algorithm for robot operation

### 2.10 Experimental Setup:

The experiment involved conducting the test on the robot within simulated hazardous environment conditions. The following test areas included indoor corridors, indoor wide open space, slightly cluttered areas, outdoor wide open space, semi obstructed outdoor area and near building area. Tests conducted in indoor environment included navigation, obstacle avoidance, and human detection while tests conducted in outdoor environment involved GPS operation. Communication was done through increasing the distance between the robot and the operator. Testing of the battery operating time was achieved by running the robot until it operated at lower operating range.

Tests included obstacle distance accuracy, obstacle response time, collision avoidance, human detection, video frame rate, communication range, GPS accuracy, robotic arm operation, and battery operating time. Due to the controlled environment where the tests were carried out, the test results can only be considered prototype validation.

## 3. Results and Discussion

### 3.1 Functional Validation:

The first test was to establish if the robot was capable of fulfilling its designed tasks. The prototype managed to initialize the control system, sensors, motor driver, GPS module, ESP32-CAM, and robotic arm. The robot moved independently, detected obstacles in front, executed evasive actions, detected a moving human subject, streamed live video, acquired GPS coordinates outside, and engaged the robotic arm.

Table (2): Functional validation of the developed rescue robot

| Function | Result | Status |
|---|---|---|
| Autonomous movement | Robot moved after startup | Achieved |
| Obstacle detection | Obstacles detected by ultrasonic sensor | Achieved |
| Obstacle avoidance | Robot stopped and changed direction | Achieved |
| Human-motion detection | Moving subjects detected by PIR sensor | Achieved |
| Video streaming | ESP32-CAM transmitted live video | Achieved |
| GPS localization | Outdoor coordinates obtained | Achieved |
| Robotic arm | Servo arm activated | Achieved |
| Battery operation | Approximately 45 minutes | Achieved |

These results show that the prototype functioned as an integrated rescue-support system. This is important because rescue robots require simultaneous operation of movement, sensing, communication, and decision-making. The system remained stable during repeated controlled trials, confirming that the ESP32-based architecture was adequate for prototype-level operation.

### 3.2 Obstacle Detection and Avoidance:

Obstacle avoidance performance was tested through measuring the distance of known objects to the robot and comparing it against the ultrasonic measurements. The robot had a minimum obstacle

distance of 30 cm. If the measured distance became less than this minimum distance, the robot halted its motion and conducted an avoidance task.

The accuracy of the ultrasonic sensor in detecting the distance of the object was about ±2 cm. The average reaction time from the point where the obstacle was detected to when the action was done by the motors was about 50 ms. the success rate for obstacle avoidance was 92%.

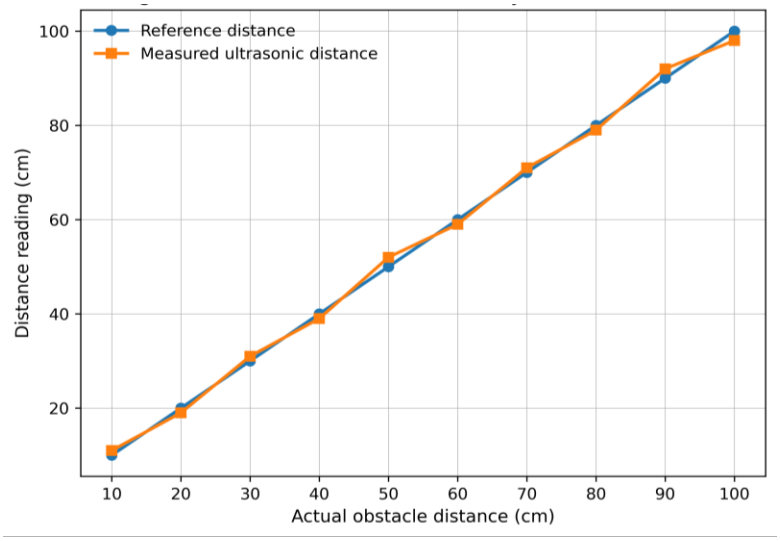



Figure (3): Obstacle detection accuracy versus actual distance

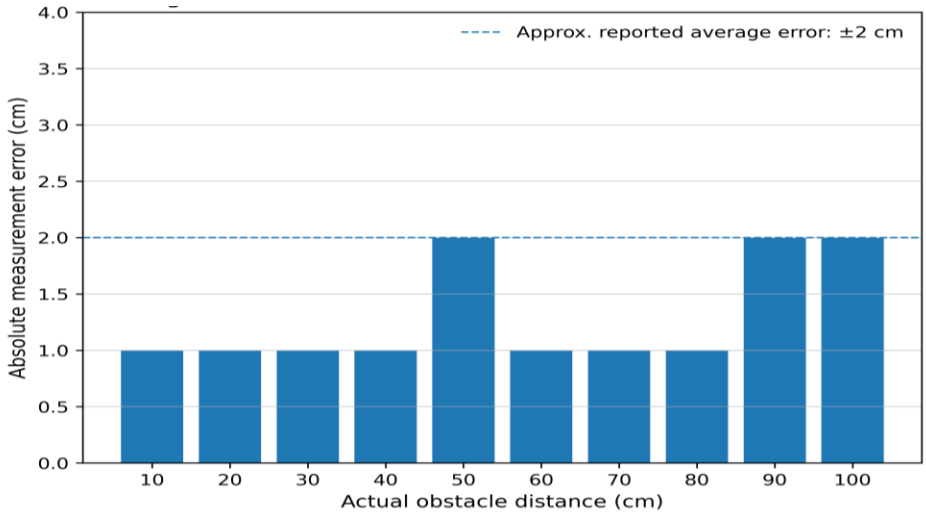



Figure (4): Ultrasonic distance measurement error profile

Table (3): Obstacle avoidance performance

| Parameter | Result | Interpretation |
|---|---|---|
| Detection threshold | 30 cm | Suitable for low-speed movement |
| Average response time | 50 ms | Fast for reactive control |
| Distance accuracy | ±2 cm | Acceptable for short-range navigation |
| Collision-avoidance success | 92% | Strong prototype-level performance |

While the results for obstacle avoidance are quite encouraging for an affordable prototype, the limitations of ultrasound are the restricted viewing range and problems of operation with slanted surfaces, narrow surfaces, and surfaces that absorb the sound. One ultrasound sensor on the front of the robot will not allow for complete situational awareness in the environment. For real-world rescue missions, future robots need to use multiple ultrasound sensors, LiDARs, depth cameras, or SLAM-based perception (Yue et al., 2023; Filipenko and Afanasyev, 2025; Potter et al., 2024).

### 3.3 Human-Motion Detection:

Human detection was evaluated using the PIR sensor under different conditions. The sensor achieved 100% detection success for moving human subjects within 1–3 m and 93% success for moving subjects within 3–5 m. These results show that the PIR sensor is effective for detecting moving humans within short and medium ranges.

However, detection performance decreased significantly for stationary subjects, with a success rate of 41%. Under high ambient heat conditions, detection success decreased to 65%. This confirms the main limitation of PIR sensing: it detects changes in infrared radiation and is therefore much less reliable when the person is stationary or when the temperature difference between the person and environment is low.

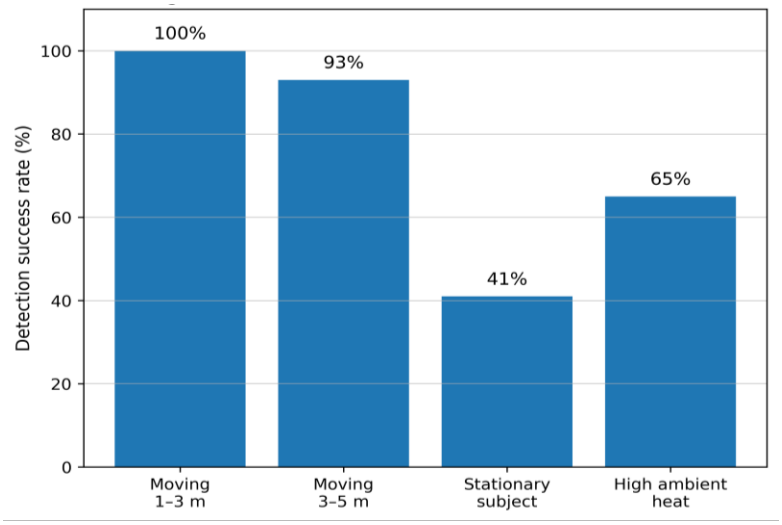



Figure (5): PIR-based human detection performance

Table (4): Human-detection performance using PIR sensor

| Condition | Detection success | Interpretation |
|---|---|---|
| Moving human, 1–3 m | 100% | Excellent short-range detection |
| Moving human, 3–5 m | 93% | Strong medium-range detection |
| Stationary subject | 41% | Weak for immobile victims |
| High ambient heat | 65% | Moderate performance |

These results are important because real rescue victims may be injured, unconscious, or unable to move. Therefore, PIR sensing should not be considered a complete victim-detection method. It is suitable only as a preliminary low-cost indicator. Recent victim-detection research supports the use of thermal, RGB, multispectral, and AI-based vision systems for stronger victim recognition (Ulloa et al., 2024; Ulloa et al., 2023). Future versions of the robot should integrate thermal imaging or AI-based human detection to improve reliability.

### 3.4 Video Streaming and Communication:

The ESP32-CAM module provided live video at 640 × 480 resolution. The observed frame rate ranged between 15 and 20 FPS under stable line-of-sight conditions. The system maintained a stable video stream up to approximately 30 m, with an average latency of approximately 275 ms. This performance was acceptable for low-speed monitoring and situational awareness.

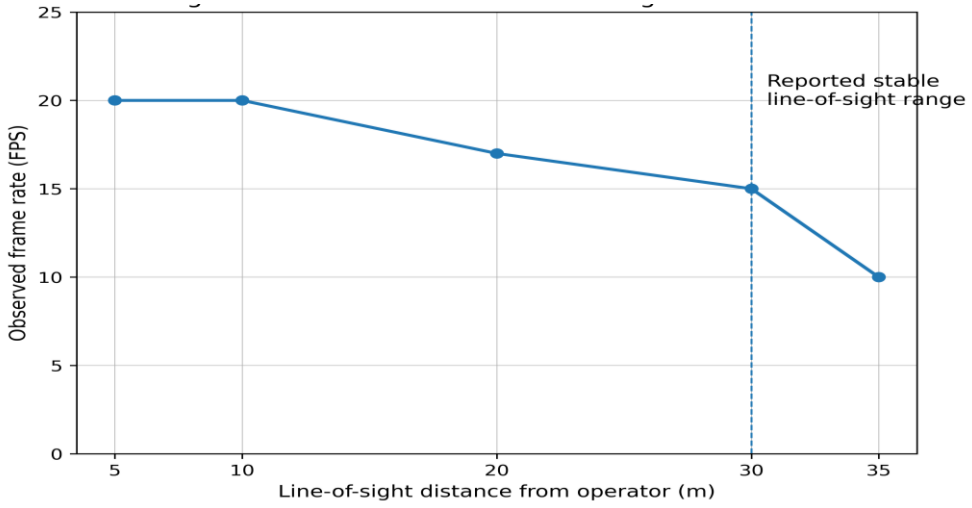



Figure (6): ESP32-CAM video streaming performance

Table (5): Communication and video-streaming performance

| Parameter | Result | Interpretation |
|---|---|---|
| Resolution | 640 × 480 pixels | Acceptable for prototype monitoring |
| Frame rate | 15–20 FPS | Suitable for low-speed visual feedback |
| Stable range | 30 m line-of-sight | Moderate |
| Average latency | 275 ms | Acceptable for observation |

Video streaming improved the usefulness of the robot because PIR detection alone cannot confirm whether the detected motion belongs to a human. Live video allows the operator to visually inspect the area and verify the situation. However, Wi-Fi communication is limited in obstructed environments. Disaster sites may include walls, debris, metal objects, underground spaces, and damaged infrastructure. Therefore, future versions should use stronger communication methods, such as mesh networks, LoRa, LTE, 5G, or relay robots. Recent SAR communication research highlights the importance of robust robotic communication for search and rescue missions (Bravo-Arrabal et al., 2025; Peña Queralta et al., 2020).

### 3.5 GPS Localization:

GPS localization was tested in open outdoor, semi-obstructed outdoor, near-building, and indoor environments. In open outdoor conditions, the GPS module achieved approximately ±3 m accuracy. In semi-obstructed outdoor areas, accuracy decreased to approximately ±5–8 m. Near buildings, error increased to more than ±10 m. Indoors, no reliable GPS fix was obtained.

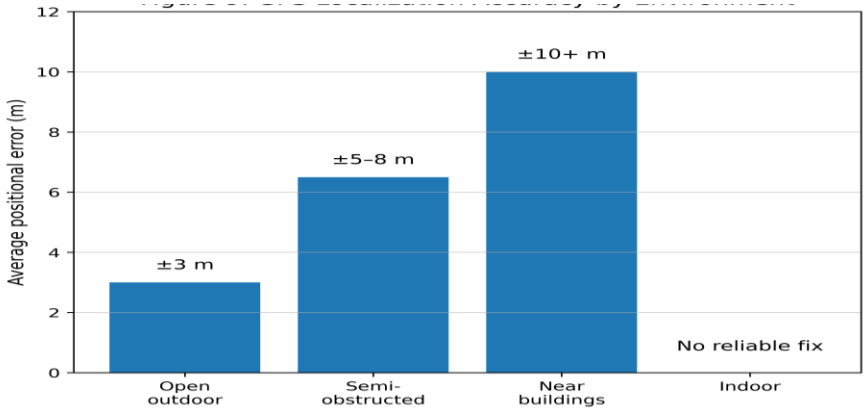



Figure (7): GPS localization accuracy by environment

Table (6): GPS localization performance

| Environment | Accuracy | Signal quality |
|---|---|---|
| Open outdoor area | ±3 m | Excellent |
| Semi-obstructed outdoor area | ±5–8 m | Moderate |
| Near buildings | ±10+ m | Poor |
| Indoor environment | No reliable fix | Failed |

The GPS results show that the robot can provide useful approximate coordinates in open outdoor environments, but GPS alone is insufficient for indoor or collapsed-building rescue missions. This limitation is expected because GPS requires satellite visibility. Indoor positioning research confirms that mobile robots operating indoors require alternative localization technologies (Deshmukh et al., 2025). Future work should combine GPS with LiDAR SLAM, visual odometry, inertial measurement units, ultra-wideband positioning, or sensor fusion.

### 3.6 Battery Endurance and Power Stability:

The robot operated continuously for approximately 45 minutes before reaching the lower stable operating range. The battery voltage decreased gradually during most of the test, then declined more rapidly near depletion. The main power loads were the DC motors, ESP32-CAM video streaming, Wi-Fi communication, and servo motors.

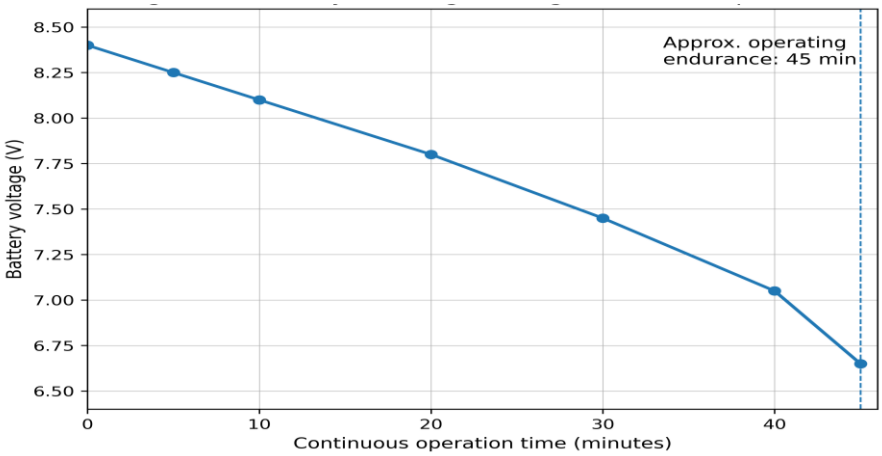



Figure (8): Battery discharge curve during continuous operation

Table (7): Battery performance summary

| Parameter | Result | Interpretation |
|---|---|---|
| Continuous operating time | Approximately 45 minutes | Acceptable for prototype testing |
| Main power load | DC motors | High consumption |
| Secondary load | ESP32-CAM and Wi-Fi | Moderate to high consumption |
| Servo demand | Intermittent high current | Can affect voltage stability |

The endurance is acceptable for laboratory testing but limited for real rescue missions. Field deployment would require longer operating time, swappable batteries, better power monitoring, and more efficient motor drivers. Power stability was also a critical issue because motors and servos can cause voltage drops. Proper voltage regulation, filtering capacitors, and grounding are therefore essential for reliable embedded robot operation.

### 3.7 Robotic Arm Performance:

The robotic arm was successfully activated and controlled using servo motors. It performed basic movements such as base motion, arm lifting, and gripper opening and closing. This confirms that basic manipulation can be integrated with the sensing and navigation subsystems.

However, the arm had limited payload capacity. It could interact only with lightweight objects and could not perform heavy rescue manipulation or debris removal. This limitation is expected because

the arm was built using low-cost servo motors. Future versions should include stronger actuators, feedback sensors, improved gripper design, and a more stable mechanical structure.

### 3.8 Integrated Performance Discussion:

Integration of these functions in the robot shows that a cost-effective embedded system is capable of performing various tasks in rescue operations. Most success was found in obstacle avoidance, detection of moving humans, short-range video transmission, and outdoor GPS localization. Least success was observed in detecting stationary victims, indoor localization, communication through obstacles, battery life, rough terrain navigation, and robotics arm payload capacity.

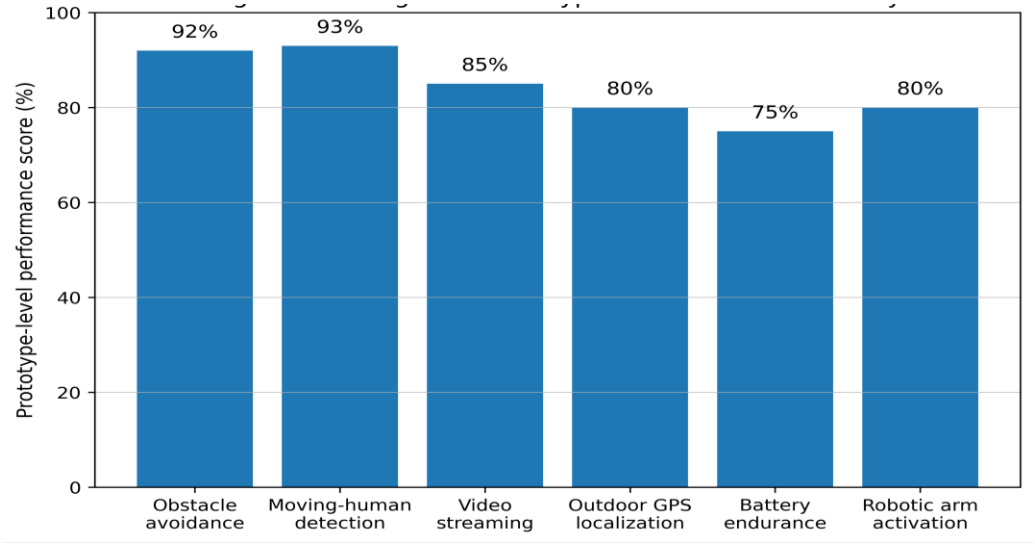



Figure (9): Integrated prototype performance summary

The findings show that the proposed system must be considered a proof-of-concept demonstration platform rather than something else. It cannot be compared to advanced rescue robots, but shows how one can implement an approach to develop affordable rescue-robots. It is important for educational, research, and resource-limited applications. The latest studies in the field of rescue robotics highlight the necessity of developing robots which enhance the safety of responders, perception, communication and victim localisation (Chitikena et al., 2023; Tong et al., 2024). The proposed robot contributes to the fulfillment of these aims through implementing essential features of a rescue-robot.

On the other hand, the shortcomings are obvious. The real-life disaster scenario is much more complicated than the one in the controlled experiments carried out in this research. In the future research should concentrate on thermal imaging, artificial vision, lidar or depth sensors, indoor positioning, mesh communication, tracked movement, and power supply.

## 4. Conclusion

This paper presented the design, implementation and experimental evaluation of a low cost autonomous medical rescue robot for hazardous and conflict-affected areas. The designed robot consisted of the ESP32 microcontroller, ultrasonic obstacle detection system, PIR based human motion detection system, GPS localization module, ESP32-CAM video streaming, differential drive mobile base, robotic arm based on servos and battery-powered system. In the robot there was used a reactive control algorithm for autonomous navigation, obstacles avoidance, human motion detection, video streaming, coordinates reporting in open air, and performing basic assistance functions.

Experimental results show that the prototype reached the major aims of design in the controlled environment simulating hazardous area. The robot reached approximately ±2 cm obstacle distance detection accuracy, average 50 ms reaction time, 92% of successful obstacles avoidance, 100% of PIR human motion detection in 1-3 m radius, 93% in 3-5 m radius, 15-20 frames per second video streaming for 30 m line of sight, approximately ±3 m of outdoor GPS accuracy, and approximately 45 minutes of autonomous working time.

It is shown experimentally that the low cost embedded robotic platform can be equipped with various functions necessary for medical assistance in hazardous conditions and can perform well enough. But currently the system is not ready for real disaster use. The main disadvantages of the prototype are poor static victim detection capability, indoor GPS functionality absence, small Wi-Fi range, small battery endurance, poor payload capacity of robotic arm, and limited wheel-based mobility. Further versions must include infrared camera, automatic victim recognition using AI, LiDAR/depth camera, indoor localization, extended range communication, tracked/hybrid mobility, robust robotic arms, medical sensors, and better power management system.

**Acknowledgements:**

Not applicable.

**Declaration of Competing Interest:**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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