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Design and Implementation of an Intelligent Spider-Inspired Quadruped Robot for Victim Detection in Collapsed Buildings Using Computer Vision Techniques

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victim detection, computer vision, search and rescue robotics, quadruped robot, embedded systems, Haar Cascade classifier

ABSTRACT

Urban disasters, including earthquakes, explosions, and the collapse of buildings, result in dangerous environments where the rescuers' ability to safely inspect damaged buildings and locate conscious or moving victims is highly restricted. Search and rescue (SAR) robotics have become a powerful technological tool to enhance the safety of rescue operations and speed up the response to disaster scenarios. This paper describes the design and implementation of a smart spider-inspired quadruped rescue robot designed for preliminary visual screening after building collapses. This robot uses an Arduino Uno microcontroller to control its movement and a Raspberry Pi 4 to perform process images. To capture real-time videos, a standard camera module is used, and Bluetooth communication provides manual remote control. The computer vision subsystem is built around the Open Source Computer Vision Library (OpenCV) and Haar Cascade classifiers for instant human face and motion detection. YOLO-like deep learning models provide highly accurate detections, but they are quite computationally expensive and usually run on high-end hardware only. Then again, our method can provide fairly accurate detection even on lightweight embedded systems with minimal resources. Experimental results demonstrate that the robot can efficiently move on rough terrain, send live video, and identify frontal faces and the motion of conscious individuals within the simulated collapse environment. The robot is proposed as an environmentally friendly, low-cost, and energy-efficient visual screening tool for consciously locating or moving individuals who are visibly accessible. Combining animal-like movement with advanced computer vision can significantly enhance rescue missions.

1. INTRODUCTION

Natural disasters and human-caused events, like earthquakes, bomb explosions, and structural failures, are primary reasons for buildings collapsing, leading to hazards for both victims and rescue teams [1]. It is common situation for rescuers to encounter unstable debris, confined spaces, high-risk environments, dust, and other dangerous conditions in the environment that make it impossible for rescuers to enter disaster areas [2]. As a result, robots have been playing a bigger and bigger role in disaster response teams these days because they can go to high-risk environments and, at the same time, they do not put human rescuers in danger [3].

Mobile rescue robots are mainly used for tasks such as reconnaissance, environmental monitoring, and victim detection [4]. Meanwhile, the conventional wheeled robots often struggle to get around rough terrains and rubble-strewn areas of collapsed buildings [5]. However, legged robotic systems biologically inspired by animals seem to convey a higher level of mobility, flexibility, and adjustment to different terrains [6]. Robots inspired by spiders, for example, present enhanced abilities for maintaining balance and crossing obstacles because of their multi-legged locomotion mechanisms [7].

Recently, there have been breakthroughs in artificial intelligence and computer vision technologies that have also aided the development of the rescue robots' functions [8]. Robots equipped with vision systems can find human victims, study the surroundings, and send the latest data to the rescue team at the same time [9]. Deep learning methods like YOLO and Faster Region-based Convolutional Neural Network (Faster R-CNN) have a great track record for accurate detection in object detection tasks [10]. However, these techniques need strong computer hardware and a high amount of energy, which makes them hardly compatible with lightweight embedded rescue systems [11].

Overcoming these limits, a few lightweight computer vision methods, mostly the Haar Cascade classifiers, are still the best solutions to be practically used in embedded robotics applications [12]. The Haar Cascade classifier is an algorithm that operates at high speed and in real-time for detecting objects with minimal computational complexity. Due to this property, they suit systems that are based on Raspberry Pi very well. The Open Source Computer Vision Library (OpenCV) is the ones that assist best in the efficient execution of image processing algorithms in affordable rescue robots [13].

This paper presents the conceptualization and actualization of a spider-inspired quadruped rescue robot integrated with a

computer vision system for detecting victims inside collapsed structures. The robot integrates a quadruped movement mechanism with OpenCV-based image processing using Haar Cascade classifiers. Motion control is based on an Arduino Uno, while computer vision is done using a Raspberry Pi 4. Communication over Bluetooth is implemented for controlling the robot remotely via smartphone [14]. The main contributions of the paper are the following:

(1) Design and construction of an affordable spider-like rescue robot capable of working even in dangerous areas.

(2) Real-time frontal-face and motion detection through a lightweight OpenCV system combined with Haar Cascade classifiers.

(3) Combination of Arduino and Raspberry Pi for hybrid embedded control.

(4) Measurement of robot mobility and detection accuracy in disaster scenario simulations.

(5) Suggesting an energy-friendly option for deep learning-based rescue systems.

The rest of this article is divided into these parts: In Section 2, a review of the literature related to Search and rescue (SAR) robots, bio-inspired locomotion, and computer vision methods is provided. Section 3 explains the new system proposal, which includes the mechanical design, embedded hardware, communication methods, and the lightweight victim detection algorithm. Section 4 describes the experimental environment and measures the robot's mobility, detection rate, communication reliability, and energy use. Section 5 considers the performance of the system, its weaknesses, and also its comparison with other rescue systems. Finally, Section 6 summarizes the paper briefly and points out the possible areas of future work.

2. RELATED WORKS

SAR robotics has evolved, and this is because robots are the safest means to carry out such operations in high-risk situations. The literature review that has been most recent reveals that nowadays SAR missions frequently utilize autonomous or semi-autonomous systems for conducting the initial survey in areas where human first responders cannot get through [8, 9]. Still, the use of robots in areas of collapsed buildings is a real challenge that depends, as it does, on a favorable combination of technical aspects and the ability of the robots to adjust to various conditions without breaking down, the efficiency of their calculations, and the quality of their communication. As a result, the present literature review focuses on the newest developments in these three areas: unstructured locomotion, embedded detection of victims, and communication architectures.

2.1 Locomotion and communication architectures in Search and rescue robotics

Conventional wheeled robots operate effectively on flat surfaces but are severely hindered in mobility when they have to move around in highly irregular, debris-filled landscapes like those of collapsed buildings [15]. To address these physical constraints, bio-inspired, legged locomotion has become an attractive area of research. Liang and coworkers [6] revealed that multi-modal legged locomotion allows effective regulation of unilateral contact forces, a feature that not only brings a high level of stability on rough terrains but also outmatches wheeled robots here. Also, Nguyen and collaborators [5] developed adaptive gait control methods. To be exact, for quadrupedal walking platforms, thereby demonstrating the ability of these robots to dynamically navigate slopes and surface discontinuities of all kinds.

The idea of arthropod legs gave Nabende ideas for research [7]. Spider leg joint patterns and mechanics [16] have been shown in other studies as well, which led to multiple leg solutions for obstacle clearance and balance in very restricted areas. Although spiders biologically have eight legs, spider-like walking patterns and joint movements copied onto four legs have been proven to be sufficient as an alternative solution for terrain compliance. This type of platform offers a significant reduction in the mechanical complexity and the power requirement for the additional limbs [17].

Reliable communication has always been a top priority when it comes to effective teleoperation during disaster situations, but signal interference due to rubble and reinforced concrete still makes it a great challenge [18]. In standard search-and-rescue missions, control commands and payload transfer are physically separated. Directional low-bandwidth commanding through Bluetooth is popular, e.g., the HC-05 module, for its low power usage and integration with microcontroller platforms like the Arduino [19, 20].

The main issue is that real-time transfer of video streams and overlaying graphical detection exceeds the capability of Bluetooth in standard terms. That means nowadays lightweight rescue robots are using dual-channel communication systems. In this case, a low-bandwidth channel (Bluetooth) is used for controlling locomotion, and a high-bandwidth channel (Wi-Fi) is introduced through single-board computers like the Raspberry Pi that allow streaming videos at the same time [21]. This combination of different communication channels ensures the controller still gets the live view from the robot without affecting the responsiveness of its moving functions through a single loop; this solution proved to be efficient in the past in a group of low-cost surveillance and rescue robot projects [15].

2.2 Computer vision for victim detection in embedded systems

Victim localization no longer solely depends on thermal and ultrasonic sensors but integrates camera-based computer vision that uses advanced algorithms [1, 9]. Recently, the most popular deep learning architectures have been YOLO variants and Faster R-CNN, which have reached a new level of capability in human detection tasks. For example, a paper by Azizi et al. [12] introduced a two-level deep learning method (DeepSafe) to detect victims trapped beneath rubble after disasters, and Zhang et al. [11] showed how harmonious composite images can be used to train YOLO for a UAV victim search task.

Although their accuracy is great, computationally these types of models are too much for embedded systems, which are usually lightweight. Lazarevich et al. [10] did a performance study of efficient object detectors running on embedded systems, and they found that only with major hardware acceleration (GPUs/Edge AI) is it possible to run YOLO models in real-time. At the same time, Oleiwi and Kadhim [22] pointed out the difficulties and practical limitations of deploying real-time deep learning in an environment with standard microcontrollers.

To overcome these limitations, lightweight computer vision

techniques continue to play a big role in the development of embedded rescue robots. The Viola-Jones structure [23], through the use of Haar Cascade classifiers, has given a reliable method of detecting faces and movements in real-time at a minimal computational cost. New works [24, 25] have managed to combine Haar Cascade classifiers running under OpenCV [26] on embedded systems, which shows that such lightweight detection systems can deliver acceptable detection quality at good frame rates without requiring any GPU-powered accelerator hardware, thereby making them well-suited for low-power-consuming four-legged platforms [13].

3. PROPOSED SYSTEM DESIGN

3.1 System overview and hardware architecture

The proposed quadruped robot serves as a vital tool for civil defense teams during SAR operations after buildings have collapsed. This type of robot combines mechanical movement, embedded control systems, radio communication, and computer vision to carry out instant surveillance and identification of victims. The design is based on the distribution of processing that consists of two isolated but linked subsystems: the mobility and locomotion subsystem and the vision and victim detection subsystem.

All steps of the proposed system's procedure are performed in this way:

(1) A smartphone app is used by the operator to send motion commands.

(2) Commands are sent from the app to the Arduino Uno through Bluetooth.

(3) Upon receiving the commands, the Arduino Uno interprets them and runs the servo motors to animate the spider legs.

(4) At the same time, the onboard camera is used for video capture of the environment.

(5) With the help of OpenCV, the video stream gets to be processed by the Raspberry Pi 4.

(6) Human faces and motion are detected by Haar cascade algorithms.

(7) The operator gets live video and detection results back through the interface. The integration of the entire system and the way the mobility and vision subsystems work together are shown in Figure 1.

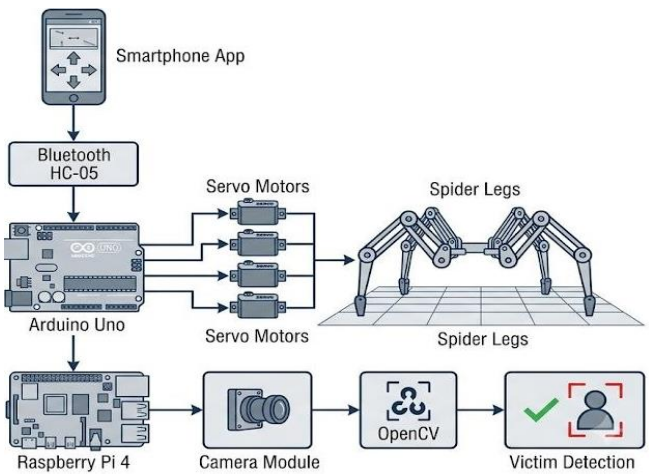


Figure 1. Overall architecture of the proposed spider-inspired quadruped rescue robot

The hardware architecture is constructed on a dual-controller structure to make sure the processing loads are efficiently balanced. Arduino Uno is used for handling the basic real-time movement operations, and the Raspberry Pi 4 is used for the computationally intensive image processing tasks. Such a distributed design leads to the improvement of the whole system's stability and the prevention of processing overload. Table 1 shows the common features of the hardware components and their functions.

Table 1. Embedded hardware architecture components

Hardware Component	Description/Function
Arduino Uno	Controls locomotion and coordinates servo motors
Raspberry Pi 4	Executes image processing and victim detection algorithms
Standard USB Camera	Live video acquisition
HC-05 Bluetooth Module	Wireless communication for remote control
Servo Motors	Actuation of the four spider legs
Battery Pack	Power supply for the entire system
Smartphone Interface	Manual navigation control and monitoring

3.2 Mechanical design and communication architecture

Taking inspiration from the way spiders move, the robot has been built with four legs to provide it with better mobility in highly irregular and tight areas like those of collapsed buildings. Unlike regular wheeled robots, the multi-legged system enables the robot to walk on uneven surfaces, climb over debris, and pass through confined spaces. Each leg consists of several joints controlled by servo motors, which allow the legs to move in multiple directions, rotate, maintain balance, and overcome obstacles. The main body is used for safely storing the Arduino Uno, Raspberry Pi 4, and battery pack, whereas the camera module is located in front to provide a clear field of view. Figure 2 illustrates the physical arrangement of the electronic components on the robot's chassis as well as the detailed joint structure of a single leg operated by three servo motors.

Communication is split into external remote control and internal coordination. As for external control, the HC-05 Bluetooth module establishes a wireless serial connection between the smartphone app and the Arduino controller. The communication protocol consists of direction commands, stop signals, and status monitoring. Bluetooth was selected because it is the simplest and most efficient means of communication in terms of power consumption within a short range of operation. One should mention that although the HC-05 Bluetooth module is used by the Arduino for low-bandwidth directional commands, the live video stream and detection graphic images of the object are simultaneously sent from the Raspberry Pi 4 to the operator's smartphone by the Raspberry Pi itself through an inbuilt Wi-Fi module, which creates a separate local network for transporting high-bandwidth data. Inside, the Raspberry Pi 4 and Arduino Uno are connected via a USB serial cable (UART protocol). This internal wired connection gives the Raspberry Pi the capability of sending the high-level navigation commands that it receives from the operator's smartphone to the Arduino, whereas the Arduino sends the locomotion status and motor feedback in real time back to the Raspberry Pi. This two-way serial communication

not only guarantees the accurate coordination of the vision processing unit and the mobility controller, but also does not cause any processing delay or hinder the video analysis.

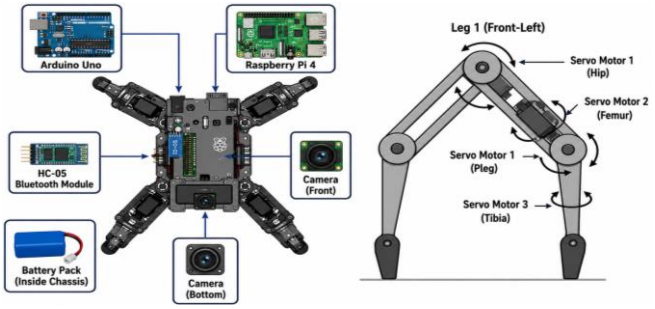


Figure 2. Mechanical structure of the spider-inspired quadruped rescue robot

3.3 Software implementation and victim detection algorithm

The software architecture is based on two main layers running in parallel:

(1) Motion Control Layer: Arduino Uno is coded with Arduino IDE using C/C++. It changes servo motor angles per Bluetooth movement commands, which allows different modes like forward/backward, turning left/right, and stopping.

(2) Computer Vision Layer: The Raspberry Pi deals with image processing using Python and OpenCVs. A victim detection algorithm is designed as a lightweight pipeline to suit embedded systems:

•System initialization and video frame acquisition.

•Grayscale conversion of the captured image is done to lessen computational complexity.

•Usage of noise reduction filters to improve image stability.

•Getting Haar-like features and carrying out the stages of the cascade classification.

•Locating human faces and analyzing frame differences for motion detection.

•Detection rectangles are drawn, and visual feedback is sent to the operator.

•This process loops continuously until the system is manually shut down. The full step-by-step workflow of this victim detection pipeline is defined in Figure 3.

The main reason for choosing Haar Cascade detectors over deep learning ones like YOLO is that Haar Cascade detectors require only minimal computational power and can run fast. This is particularly important when you want real-time operation on low-powered, lightweight embedded platforms like the Raspberry Pi without having a GPU for acceleration.

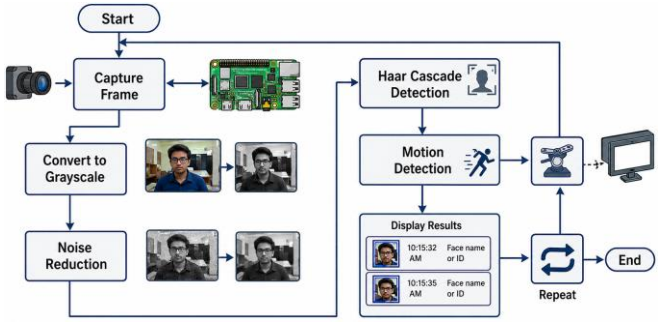


Figure 3. Workflow of the proposed victim detection algorithm

4. EXPERIMENTAL RESULTS

4.1 Experimental environment and setup

The test experiments were conducted in simulated disaster areas that simulate real-world disaster scenarios, such as fallen concrete, cramped corridors, uneven floors, and dimly lit conditions.

The robot trials were based on the criteria for estimating the robot's effectiveness, capability to move around, accuracy in victim detection, stability in communication, duration of system reaction, and power consumption. Performance analysis was conducted under various environmental conditions to verify the trustworthiness and capability of the rescue robot proposed for disaster response operations. Figure 4 shows the physical prototype of the robot, which was placed amongst rubble and debris during the testing stage.

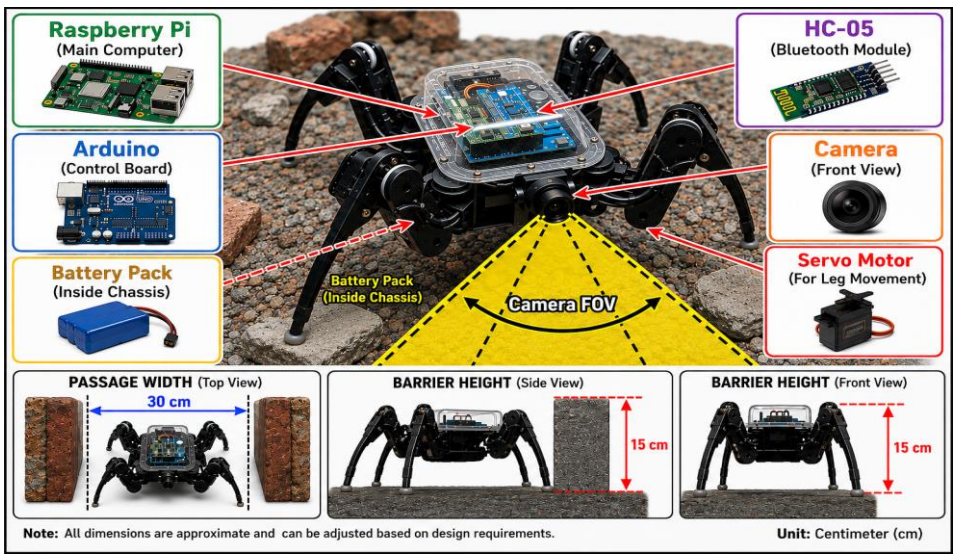


Figure 4. Prototype of the spider-inspired quadruped robot and embedded hardware configuration

Note: The figure includes annotated views of the embedded hardware components and schematic top and side views of the experimental testing setup, including a 30 cm passage width and a 15 cm obstacle height.

4.2 Mobility performance

To thoroughly test the locomotion capabilities, the robot went through 20 separate trials for each environmental setting in the simulation of a catastrophe. Thanks to the spider-mimicking way of locomotion, the robot demonstrated a great capacity for adjusting to various terrains different from those of regular wheeled vehicles. It was able to get through narrow passages and stay balanced on irregular surfaces. As can be seen in Table 2, the navigation and stability components of the system yielded high success rates, whereas overcoming obstacles at raised heights posed a moderately difficult challenge because of servo motor torque limitations.

Table 2. Quantitative robot mobility performance

Test Scenario	Success Rate (Attempts)	Performance Assessment
Uneven Surface Navigation	95% (19/20)	Excellent
Narrow Passage Traversal	90% (18/20)	Excellent
Obstacle Crossing	70% (14/20)	Moderate
Balance Stability	95% (19/20)	Excellent

4.3 Vision, communication, and power performance

In addition to locomotion, a practical deployment scenario of SAR robots mostly relies on the efficiency of their vision subsystem, the reliability of the control link, and the overall energy demands of the robot, including power consumption. That's why this section describes in detail the victim detection score (Table 3), communication stability and communication delay (Table 4), and power consumption in each module (Table 5) to give a full view of the embedded system's operational performance.

Table 3. Quantitative victim detection performance

Detection Test	Precision	Recall	F1-Score	Average Processing Speed
Face Detection in Normal Lighting	93.2%	92.0%	92.6%	18 FPS
Face Detection in Low Light	84.3%	81.0%	82.6%	18 FPS
Motion Detection (Overall)	93.6%	88.0%	90.7%	18 FPS

Table 4. Communication and system performance

Parameter	Measured Value
Communication Range	10 meters
Average Response Time	0.8 seconds
Connection Stability	High

Table 5. System power consumption

Component	Power Consumption
Arduino Uno	0.25 W
Raspberry Pi 4	5 W
Servo Motors (Total for 12 servos)	2–4 W
Camera Module	1 W

To quantitatively measure the victim detection performance, we tested the system on a custom dataset made up of 500 video frames taken in the simulated disaster setting. The dataset contains 500 video frames: 150 frames with human faces, 200 frames of human movement, and 150 negative control frames containing only background rubble and debris without any human presence, used to evaluate the false-positive rate of the system. The evaluation relied on the popular object detection metrics: Precision (the proportion of correctly detected victims out of all detected victims), recall (the proportion of correctly detected victims out of all actual victims present in the frames), and F1-score (the harmonic mean of precision and recall). As presented in Table 3, the Haar Cascade technique yielded a remarkable F1-score of 92.6% for face detection under regular lighting, demonstrating its high dependability. Although the accuracy was reduced in dark settings, the system was still executing with a minimal processing load. The algorithm was executed in real time on the Raspberry Pi device even without GPU acceleration, and the average speed was 18 FPS.

The Bluetooth communication facilitated by the HC-05 module helped to maintain stable robot control when operations were carried out at short distances. During the robot movement and the video signal processing, the communication system stayed in good condition.

Due to its minimal power consumption features, the embedded architecture is perfectly suitable for rescue operations using portable devices. Using a rechargeable battery pack, the equipment's total operating time was about 90 minutes. To be specific, a 3-cell 11.1V Li-Po battery that has a capacity of 1200 mAh provides around 13.3 watt-hours of energy, which mathematically aligns closely with the system's average power consumption range of 8.25 to 10.25 W.

5. DISCUSSION

The experimental results indicate that the proposed quadruped robot is a very affordable tool for reconnaissance and victim localization in collapsed building environments and, at the same time, highly efficient. Quadruped bio-inspired locomotion offered the best adaptability to the terrain compared with traditional wheeled robots, mainly because it can navigate through narrow and irregular openings. Besides that, using Arduino Uno and Raspberry Pi brought about a well-balanced embedded system architecture. Separating motion control from image processing greatly reduced computational load and made the whole system more stable.

The computer vision framework, using OpenCV with Haar Cascade classifiers, delivered adequate real-time detection performance with minimal computational resources. Although deep learning detectors, like YOLO, have much better detection performance, they are too computationally demanding and high-wattage, requiring GPU acceleration. The lightweight technique detailed here is significantly more appropriate for embedded rescue systems.

Despite the encouraging results, experimental tests indicated that the Haar Cascade classifier has significant limitations in performing real-world disaster applications. The detection rate went down dramatically in dimly lit conditions, as these classifiers react strongly to lighting variations. More importantly, even though the method performs effectively for detecting straight-on faces, it is completely unable to find the victim's face when it is at an extreme angle, turned, or facing

away from the camera (profile or back views). In fact, in real-life scenarios of collapsed buildings, victims are often covered with dust or debris or partially hidden by rubble. Thus, these conditions destroy the distinct facial features that the system depends on, resulting in a total failure to detect the victim. The dependence of the system on clear facial features rather than the overall human shape is still a major limitation in finding unconscious or severely hidden victims. Therefore, the system will be best used as a preliminary visual screening tool for finding responsive or moving people only and not as a standalone option for finding unconscious or totally buried individuals. Besides, relying on Bluetooth communication caused the operational range to be much shorter than Wi-Fi or LoRa-based systems. Still, given the package's mini size, affordability, capability of streaming video live, and low power consumption being quite low, the suggested robot can be of great help to the civil defense team in the initial stage of the reconnaissance mission.

In comparison with the rescue robotic paradigms currently available, the proposed system brought to you by us presents a rather unique and suitable trade-off for very specific use cases and operational constraints. Deep learning approaches (e.g., YOLO) are known to deliver strong results when it comes to detection robustness, but these systems often require high-wattage GPUs or specialized edge AI hardware, which drives up cost and power demands. As for hardware, our robot is fully compatible with standard CPUs. On the flip side, we have traditional wheeled mobile machines that may be very power-efficient but, on their own, are insufficiently terrain-adaptive to cope with uneven debris found in collapsed buildings. Because of these limitations, the idea for the quadruped-type rescue robot was developed. It represents a very low-power, cost-effective, and highly mobile platform that can perform simple visual recognition in situations where heavy GPU-based systems are deemed neither feasible nor cost-effective to implement, acknowledging that this approach comes at the cost of reduced detection versatility compared to deep learning models.

6. CONCLUSION

In this study, lightweight computer vision techniques were used to construct and implement a smart quadruped robot that serves as a first-line visual screening tool for identifying the frontal faces and motion of conscious individuals inside collapsed buildings. The suggested solution integrated a spider's four-legged locomotion system with the incorporation of image processing techniques to aid in disaster response efforts. The robot incorporated an Arduino Uno for locomotion control and a Raspberry Pi 4 for victim detection through OpenCV using Haar Cascade classifiers. The test results have shown that the system can successfully navigate uneven surfaces, deliver video from a live stream, and spot front-facing human faces as well as movement quite accurately during disasters simulated as training scenarios.

This proposed method has various merits such as low cost, lightweight processing requirements, high energy efficiency, and superior terrain adaptability, among others, when compared with traditional wheeled rescue robots. Using the Haar Cascade classifiers not only helped in reducing the complexity of the computations but also helped in maintaining the practical real-time performance on the embedded hardware platforms. The data reveal that rescue robots modeled on biological systems with computer vision systems that are of low weight can be extremely helpful in enhancing the ability to perceive the environment and in decreasing the exposure of emergency teams to the hazards during disaster activities.

7. FUTURE WORK

There is a list of potential features that could be introduced in future investigations, which would be beneficial to the proposed rescue robot. For example, some planned features are the following:

(1) Instead of Bluetooth, the communication medium might be changed to Wi-Fi or LoRa, which offers a longer operating range.
(2) Victim detection in dark environments could be enhanced through the use of thermal camera integration.
(3) Autonomous navigation could be done by following Simultaneous Localization and Mapping (SLAM) algorithms and using obstacle avoidance.
(4) The use of deep learning algorithms like MobileNet-Single Shot Detector (SSD) could greatly help detection accuracy.
(5) There could be other kinds of sensors apart from environmental ones, e.g., gas detection, temperature, structural stability, etc.
(6) The idea of cloud-based monitoring systems is also floated for real-time rescue operations. Overall, these modifications could help a great deal in making future SAR robotic systems more effective and smarter.

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NOMENCLATURE

D	communication range, m
F1	F1-score, dimensionless
f	average processing speed (frame rate), fps
Pcon	power consumption, W
Pr	precision, dimensionless
R	recall, dimensionless
Sr	success rate, dimensionless
tr	average response time, s

Subscripts

1	F1-score
con	consumption
r	rate/response