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Design and implementation of QUADRESCUE: A ROS-based quadruped robot for disaster response support

Sanjay Deshmukh[1], Ojas Chanakya[1], Om Gabani[1], Kashish Patni[1], Asmita Deshmukh[2]
[1]Department of Electronics and Telecommunication, D. J. Sanghvi College of Engineering, Mumbai, India
[2]Department of Computer Engineering, K. J. Somaiya Institute of Technology, Mumbai, India

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ABSTRACT

Search and rescue (SAR) operations in hazardous environments demand robotic systems capable of traversing complex terrains while ensuring responder safety. Traditional wheeled platforms often fail in debris-laden areas, and fully autonomous quadrupeds remain financially out of reach for many rescue agencies. This paper presents the design and development of QUADRESCUE, a modular operator-assisted quadruped robot built to bridge the gap between affordability and capability in disaster response. QUADRESCUE delivers core SAR functionalities including remote visual inspection, real-time terrain mapping via an RGB-D camera, payload transport, and GPS-based survivor localization. Built with a robust three degrees of freedom (3DoF) per leg design, the robot uses inverse kinematics algorithms to precisely control twelve servo motors for stable locomotion across uneven terrain. The system integrates the robot operating system (ROS) for seamless operation, real-time joystick control for easy navigation, an IMU for orientation sensing, and a GPS module with 3-meter accuracy. Field evaluations demonstrate 80–94% success rates on challenging surfaces, substantially outperforming wheeled counterparts 19% to 39% with a 200-meter control range and 45 minutes of runtime. QUADRESCUE offers a lightweight, cost-effective, and repairable solution that combines practical usability with advanced performance, making it well-suited for real-world deployment in emergency rescue situations.

Corresponding Author:

Sanjay Deshmukh
Department of Electronics and Telecommunication, D. J. Sanghvi College of Engineering
Vile Parle 400056, Mumbai, Maharashtra, India
Email: sanjay.deshmukh@djsce.ac.in

1. INTRODUCTION

Search and rescue (SAR) operations are usually carried out in risky and unpredictable conditions where human access is restricted due to safety concerns, accessibility constraints, and operational limitations [1]. Disasters such as earthquakes, building collapses, or landslides require rapid assessment of affected areas to efficiently coordinate rescue efforts and locate survivors. The critical nature of these operations, combined with the inherent dangers to human responders, has driven the development of robotic platforms to assist in SAR missions [2]. Each of these platforms, however, possess inherent limitations that influence their performance in real-world rescue operation scenarios.

Wheeled robots, though energy efficient, face difficulties in navigating through debris, rubble, and uneven terrains due to their limited mobility [3], [4]. Tracked robots, though more capable of dealing with uneven surfaces, has lower speed, energy efficiency and also faces maneuverability issues, particularly in congested environments [5], [6]. Aerial platforms provide valuable reconnaissance capabilities but face payload constraints and environmental sensitivity to wind, smoke, or low visibility conditions [7], [8]. These limitations collectively highlight the inadequacy of traditional robotic platforms for the dynamic and unstructured nature of disaster environments.

Quadruped robots have emerged as a promising alternative, offering enhanced terrain adaptability through successful traversal of rough surfaces, obstacles, and confined spaces [9], [10]. The four legged design allows for increased stability, flexibility, and mobility on diverse terrain, making them highly suitable for such disaster response operations [11]. Unlike wheeled and tracked robots, quadruped robots have the ability to dynamically change gait patterns to maintain stability on rugged terrains [12].

Research over the past years has focused on improvement in quadruped locomotion, including variable stiffness control, bio-inspired leg mechanisms, and adaptive gait strategies, all improving terrain traversal capability [13]–[15]. Quadruped robots have the capability to handle payloads better, allowing them to transport essential supplies such as first aid kits, communications equipment, or light tools to places that would be inaccessible to human responders [16]. Despite advancements in autonomous quadruped systems, fully autonomous robots still struggle with serious challenges related to real-time decision-making like humans, adaptability, and environmental perception [17]–[20].

However, a critical gap exists in current quadruped robotics for SAR applications. While advanced autonomous systems like Boston Dynamics' Spot demonstrate impressive capabilities, their complexity and cost make them inaccessible to many rescue organizations, particularly in developing nations. Conversely, simple manual platforms lack the mobility and sensing capabilities required for effective disaster response. The fundamental research question addressed in this work is: Can a cost-effective, operator-controlled quadruped robot be developed that maintains essential SAR capabilities while remaining accessible to resource constrained rescue teams.

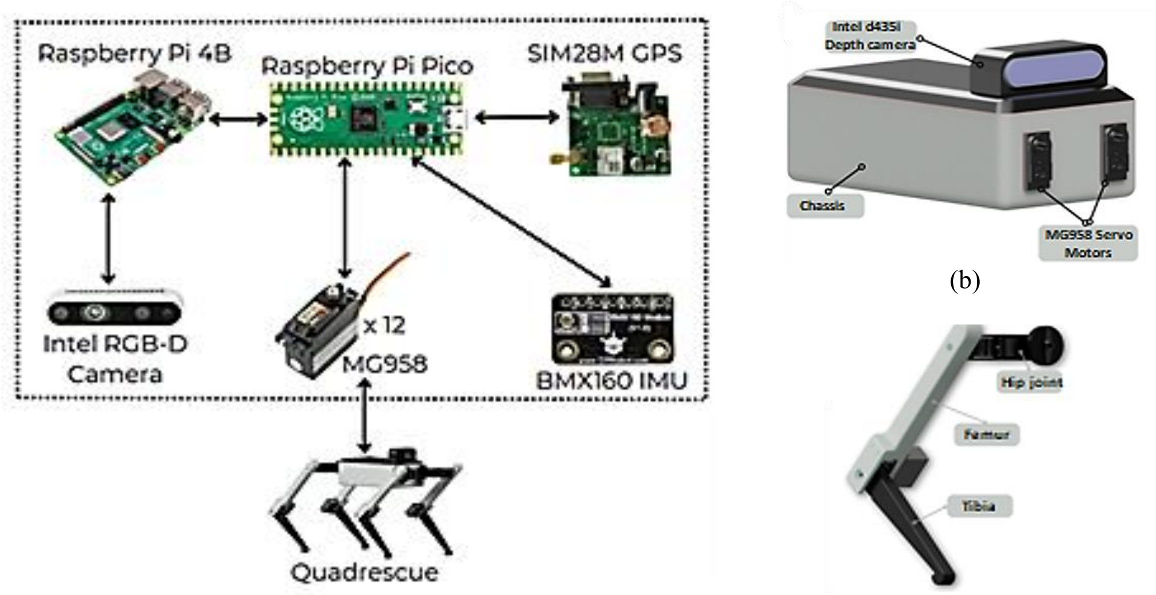
This paper presents QUADRESCUE, a novel quadruped robot that addresses this gap through three key innovations: First, a modular design philosophy that prioritizes field repairability and component replacement over complex autonomous systems [21]. Second, operator-assisted control that preserves human decision making while providing enhanced mobility and sensing capabilities [22], [23]. Third, cost-effective implementation using standard components and 3D-printed parts without compromising functional performance [24]. Unlike existing platforms that focus on full autonomy or basic mobility, QUADRESCUE balances affordability, capability, and practical deployment considerations specifically for disaster response scenarios.

QUADRESCUE provides essential SAR capabilities including remote visual inspection through RGB-D cameras, real-time terrain mapping, GPS based victim localization, and payload delivery across challenging terrains. The system integrates a biomimetic four-legged design with inverse kinematics control, IMU-based orientation sensing, and ROS based communication architecture to deliver a comprehensive yet accessible SAR platform [25]. A ROS based modular quadruped robot was successfully developed and validated, demonstrating effective mobility and adaptability for disaster response tasks in unstructured environments.

The remainder of this paper is organized as follows: section 2 details the mechanical design, electronics architecture, and control algorithms. Section 3 presents experimental validation, including terrain adaptability testing and functional capability demonstrations, and discusses the implications of the results along with directions for future development. Section 4 presents the conclusions.

2. METHOD

The main components of QUADRESCUE are the chassis, four articulated legs, IMU sensor, RGB-D stereo camera, GPS module and Raspberry Pi central processing unit. Mechanical architecture prioritizes functional resilience in adverse environments through a balanced design approach that maintains structural integrity while minimizing complexity. Figure 1 illustrates the key hardware components and design of the QUADRESCUE robot developed for disaster response applications. Figure 1(a) presents complete electronic architecture, showing how the Raspberry Pi 4B serves as the central processing unit running ROS, connected to the Raspberry Pi Pico microcontroller which interfaces with 12, MG958 servo motors, the BMX160 IMU for orientation feedback, and the SIM28M GPS module for localization. The Intel RGB-D camera connects directly to the Raspberry Pi 4B for environmental perception and mapping. Figure 1(b) depicts the central chassis design, featuring a compact enclosure that houses the electronic components while providing mounting points for the depth camera and servo motors. The chassis is designed for durability while maintaining a lightweight profile suitable for field deployment. Figure 1(c) shows the biomimetic leg design with clearly labeled components including the hip joint, femur, and tibia segments, reflecting the mammalian inspired three degree of freedom configuration that enables the quadruped’s enhanced mobility across uneven terrains compared to wheeled or tracked alternatives. Each leg uses three MG958 servo motors to achieve the required articulation for complex locomotion patterns.



(a) (b) (c)

Figure 1. Hardware architecture of QUADRESCUE robot (a) component level overview showing electronics integration, (b) 3D model of the central chassis with mounted depth camera, and (c) 3D model of an articulated leg showing biomimetic design

This optimization yields reduced mass properties. The chassis functions as the primary housing for electronic subsystems, and mission payload, while simultaneously providing the structural foundation for the quadrupedal locomotion system. It has a ground clearance of 210 mm in its default position, which can be dynamically modified to navigate through tight spaces with low ceiling heights. The quadrupedal limbs of QUADRESCUE as shown in Figure 1(c) implement a biomimetic design based on mammalian anatomy, featuring a two-link structure with femur and tibia segments. Each leg incorporates three degrees of freedom through individual actuators at the hip, femur, and tibia joints. Table 1 represents the dimensional parameters of the leg structure. MG958 servo motors were selected as actuators based on their optimal torque due to internal metal gearbox, mass efficiency, and control characteristics. The design architecture prioritizes structural integrity while optimizing for manufacturing simplicity and efficiency of assembly, contributing to overall system cost reduction. The modular architecture of QUADRESCUE facilitates rapid field maintenance and component replacement during deployment in hazardous environments, minimizing system downtime and enhancing operational resilience. The electronics system comprises three subsystems, namely, power distribution, data acquisition, and actuation control.

Table 1. Leg parameters

Parameter	Symbol	Value (mm)
Hip offset	$l1$	67
Femur length	$l2$	180
Tibia length	$l3$	163

2.1. Power distribution

The power distribution system is responsible for distributing sufficient power to the whole electronics system. It utilizes 24V Lithium-Polymer battery and DC to DC step-down converters are used to provide specific voltage levels of 6.5V and 5V to various components. A 6.5V is used to power servo motors while a 5V is used to power a microcomputer and sensors. The microcomputer further powers the camera and microcontroller.

2.2. Data acquisition

The data acquisition system gathers and processes data from the BMX160 IMU sensor, SIM28M GPS module and Intel D435i RGB-D stereo camera. Initially, the sensor's data is processed by the Raspberry Pi Pico microcontroller to determine orientation of the QUADRESCUE and GPS coordinates of the victims and this data is then transmitted to the onboard Raspberry Pi 4B microcomputer via serial communication. The microcomputer processes and transmits the visual feed and terrain maps from the depth camera to the rescue team via Wi-Fi communication.

2.3. Actuation control

The actuation control system is responsible for various joint actuation and leg movements of the QUADRESCUE. It comprises 12 MG958 servo motors whose angular positions are controlled by the signals from Raspberry Pi Pico.

Figure 2 presents the detailed circuit schematic for QUADRESCUE’s low-level control system centered on the Raspberry Pi Pico microcontroller. The diagram illustrates the microcontroller’s pin connections to twelve 3-pin JST connectors (C1-C15) that interface with the MG958 servo motors controlling the robot’s four legs. Each servo requires three connections: signal (M1-M12), power (VCC), and ground (GND). The circuit includes power regulation components with multiple ground connections ensuring proper electrical reference points throughout the system. Communication interfaces are visible with dedicated pins for I2C (SDA/SCL connections on pins 11-12) for sensor communication with the BMX160 IMU, and UART (RX/TX on pins 6-7) for serial communication with the main Raspberry Pi 4B microcomputer.

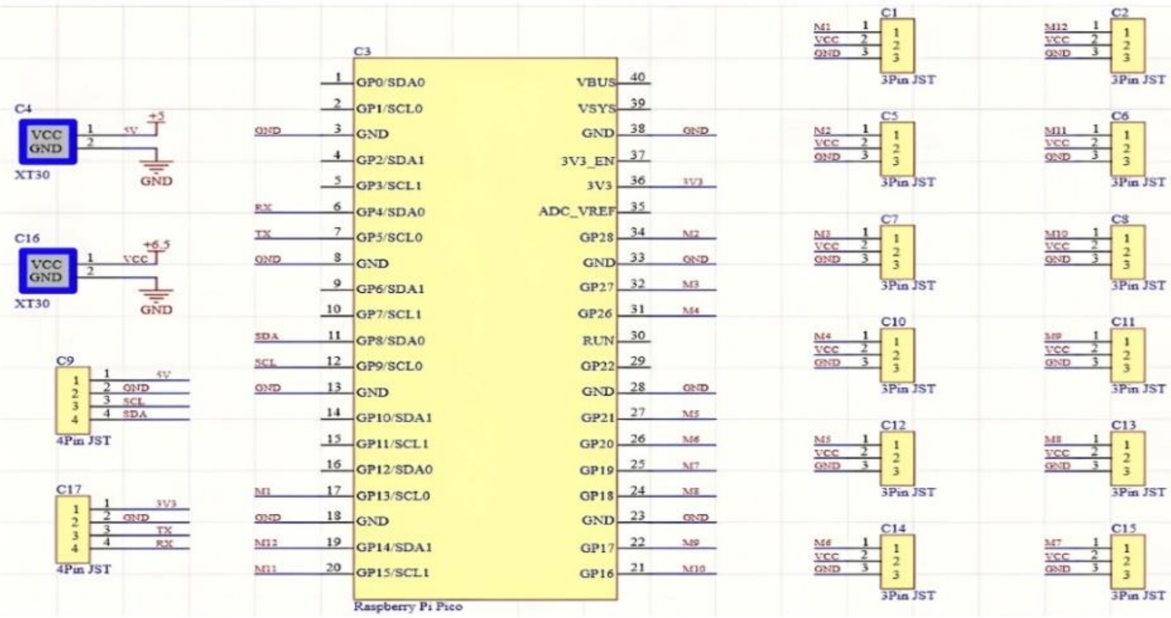
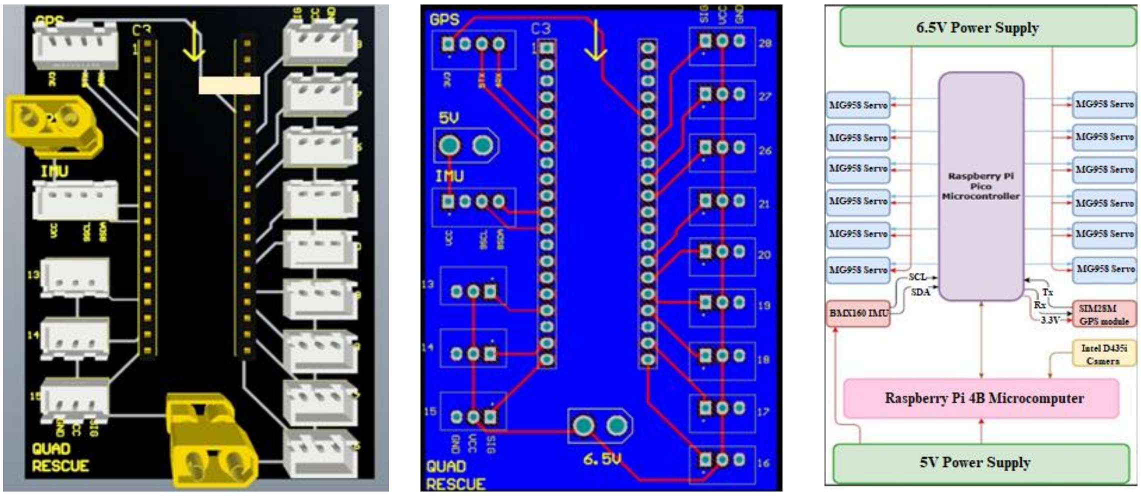


Figure 2. Circuit schematic of QUADRESCUE’s servo control system based on Raspberry Pi Pico microcontroller

Figure 3 illustrates multiple aspects of the QUADRESCUE robot’s implementation. Figures 3(a) and 3(b) show the custom PCB designed for the robot. Figure 3(a) depicts the physical 3D layout with labeled JST connectors for servo connections and power input, while Figure 3(b) presents the electrical schematic highlighting key connection paths between components, including both 5V and 6.5V power rails.

Figure 3(c) provides a system level block diagram illustrating the complete electronic architecture, with the Raspberry Pi Pico microcontroller at the center controlling twelve MG958 servo motors (six on each side) while communicating with the BMX160 IMU via I2C (SDA/SCL) and the SIM28M GPS module via UART (Tx/Rx). The robot’s software stack is built around ROS running on a Raspberry Pi 4B, which acts as the central computing unit. ROS nodes are configured for sensor data acquisition, servo motor control, and operator interface communication. This modular and scalable architecture enables efficient debugging, sensor fusion, and future expansion toward semi-autonomous navigation.



(a) (b) (c)

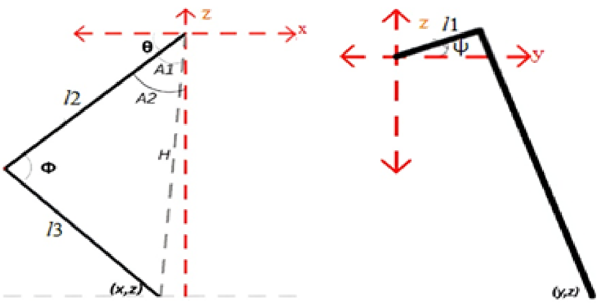
Figure 3. QUADRESCUE control system implementation and mechanical design (a) 3D component layout of the custom PCB, (b) PCB schematic showing electronic connections, and (c) overall block diagram of system connections

2.4. Inverse kinematics

The inverse kinematics algorithm takes into account the geometry and morphology of the robot's leg to generate optimal trajectory for each joint. The leg's geometry is depicted from the side view in Figure 4(a), while the front view is provided in Figure 4(b). As illustrated in Figure 4(a), the algorithm treats the foot (end of the tibia) as the end effector and computes joint trajectories based on its Cartesian position. The coordinate system shown in Figure 4(a) places the origin at the hip joint of the leg. As shown in Table 1, *l*1 represents the hip joint, *l*2 denotes the femur, and *l*3 corresponds to the tibia. The angles ψ, θ, and ϕ represent the joint angles at the hip, femur, and tibia, respectively. The inverse kinematics algorithm calculates these angles based on the current coordinates of the leg's end-effector within its local coordinate frame.

The value of ψ can be calculated using (1).

$$\Psi = tan^{-1}\left(\frac{y}{z}\right) \quad (1)$$



(a) (b)

Figure 4. QUADRESCUE leg geometry views (a) side view of leg geometry and (b) front view of leg geometry

In order to calculate the values of θ and ϕ in Figure 4(a), first the value of H is calculated as (2).

$$H = \sqrt{x^2 + y^2} \quad (2)$$

Now, the angle between femur and tibia denoted by ϕ is calculated using the cosine rule as

$$\cos(\Phi) = \frac{l2^2+l3^2-H^2}{2*l2*l3} \tag{3}$$

$$\Phi = cos^{-1}\left(\frac{l2^2+l3^2-H^2}{2*l2*l3}\right) \tag{4}$$

In order to calculate θ we must first calculate the angle A1. By cosine rule

$$\cos(A1) = \frac{H^2+l2^2-l3}{2*l2*H} \tag{5}$$

$$A1 = cos^{-1}\left(\frac{H^2+l2^2-l3^2}{2*l2*H}\right) \tag{6}$$

The angle A2 made by the femur with the vertical can hence be calculated as

$$\mathrm{A2} = tan^{-1}\left(\frac{x}{z}\right) + \mathrm{A1} \tag{7}$$

Hence the angle θ can be calculated as

$$\theta = \frac{\pi}{2} - A2 \tag{8}$$

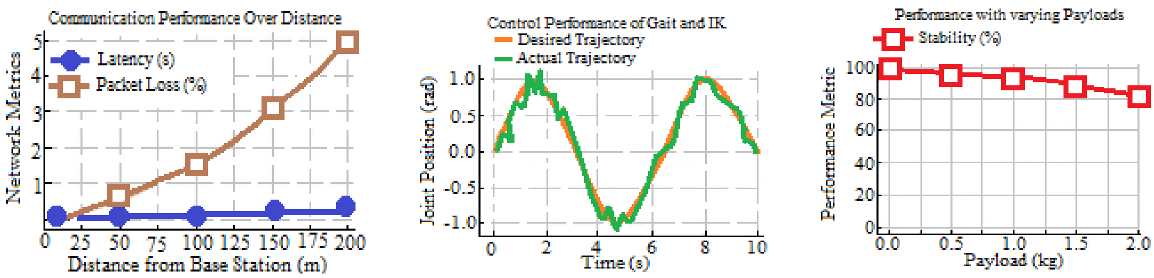
Hence the angles ψ, θ and ϕ are calculated according to the coordinates of the leg's end effector.

2.5. Gait planning

The gait planning in QUADRESCUE is implemented through a custom ROS node that generates leg trajectories based on specific gait patterns to achieve effective locomotion. During a gait cycle, each leg transitions between two phases, in first phase stance, where the leg is in contact with the ground, and in second phase swing, where the leg moves through the air. The robot supports two primary gaits walk and trot each defined by parameters such as step height, stride length, duty factor, and phase offsets. These parameters were tuned experimentally through iterative testing on different terrains to optimize stability and minimize energy consumption. The controller dynamically adjusts the duty cycle and stride frequency based on terrain feedback from the IMU and depth camera. This adaptive tuning allows QUADRESCUE to maintain balance and consistent locomotion performance across varied disaster-prone environments, making it more robust for real-world SAR applications. The inverse kinematics module is implemented as a ROS service that computes joint angles based on target leg positions received from the gait planner node. ROS topics facilitate real-time communication between modules, and RViz was used for live monitoring of sensor data. Figure 5 presents three critical performance metrics that assess QUADRESCUE's operational effectiveness in SAR scenarios.

Figure 5(a) demonstrates the system's wireless communication reliability over increasing distances. While latency rises gradually, packet loss remains under 1%, validating the system's capability to maintain effective control and feedback up to 200 meters. The inverse kinematics-based gait control accuracy is highlighted in Figure 5(b) through a comparison of desired and actual joint motions. The small tracking error confirms that the gait controller and IK solver are well-synchronized for precise limb movement. Figure 5(c) evaluates the robot's robustness under varying payloads, revealing that stability remains above 90% even with added weight. This underscores QUADRESCUE's capability to carry small payloads without significant compromise in mobility. The digital model and physical implementation of the QUADRESCUE robot are depicted in Figure 6. In Figure 6(a), the complete 3D model is illustrated, featuring an overlaid coordinate system with clearly marked X (red), Y (yellow), and Z (blue) axes, which are essential for navigation and control algorithm development.

The model illustrates the final design with four articulated legs featuring the biomimetic two segment structure (white femur and black tibia components) attached to a central chassis housing the electronic components. The Intel D435i depth camera is visible mounted on top of the chassis. Figure 6(b) displays the actual working prototype constructed according to the design specifications, demonstrating physical implementation using 3D-printed components for the legs and a wooden chassis painted black for durability. The prototype shows exposed wiring connecting the servo motors to the internal control systems and the mounted depth camera providing visual and depth perception capabilities. The comparison between the model and the prototype highlights the transition from design to implementation. The physical robot preserves the core structural elements required for quadrupedal mobility over uneven terrain, while integrating the computational and sensing components essential for disaster response scenarios. The compact design allows the robot to navigate through confined spaces while maintaining the 210 mm default ground clearance specified in the design requirements.



(a) (b) (c)

Figure 5. Evaluation of QUADRESCUE's performance under realistic conditions (a) communication performance over distance (b) control performance of gait and inverse kinematics and (c) locomotion performance under varying payloads

(a) (b)

Figure 6. QUADRESCUE robot design implementation (a) 3D model of complete assembly with coordinate system (b) actual working prototype

3. RESULTS AND DISCUSSION

This section presents the outcomes of the design and implementation process, along with the key functional capabilities demonstrated by the QUADRESCUE prototype during testing. The successful integration of the mechanical, electronic, and software components resulted in the assembled QUADRESCUE prototype. The prototype features the central chassis constructed from wood, housing the electronics, and the four articulated legs fabricated using 3D printing technology, equipped with the MG958 servo motors for actuation. This combination of materials proved effective in balancing structural integrity with weight considerations, while the 3D-printed components facilitated rapid prototyping and iterative improvements throughout the development process. Figure 7 demonstrates the dual visual outputs provided by QUADRESCUE's perception system during operation. A dedicated ROS node processes data from the Intel D435i RGB-D camera to generate real-time depth maps and point clouds

Figure 7(a) shows the standard RGB color video feed captured by the Intel RealSense D435i camera. It displays a cluttered indoor environment with blue walls, simulating the type of confined space typically encountered during search and rescue operations. The color feed provides operators with visual information necessary for identifying objects, assessing structural elements, and potentially locating victims. The corresponding real-time depth feed generated from the same camera's depth sensor is shown in Figure 7(b). In this visualization, brightness values indicate proximity as lighter areas represent objects closer to the camera, while darker regions signify greater distances. This depth visualization is crucial for terrain mapping and obstacle detection, allowing operators to perceive the three-dimensional structure of the environment even when color and lighting conditions are sub optimal. The system processes this depth data to generate point clouds and elevation maps that assist in navigation planning and structural assessment. QUADRESCUE sends both RGB and depth video feeds to the base station at the same time, helping operators make better decisions during rescue missions. This is useful for moving through debris and checking the safety of damaged structures, while keeping a reliable communication range of up to 200 meters.

(a) (b)

Figure 7. QUADRESCUE perception system output (a) original RGB feed from Intel D435i camera and (b) real-time depth feed visualization

Figure 8 illustrates the operator interface displaying the GPS-based navigation and victim localization capabilities of the QUADRESCUE system. One dedicated ROS node is used for parsing and visualizing GPS data. The image shows a satellite view of an operational area with an overlaid green path representing the robot's traversed route during a search and rescue mission simulation. Three red location markers labeled "victim" indicate points where potential survivors were identified by the operator through the robot's visual feed, with their precise GPS coordinates automatically logged and displayed on the map.

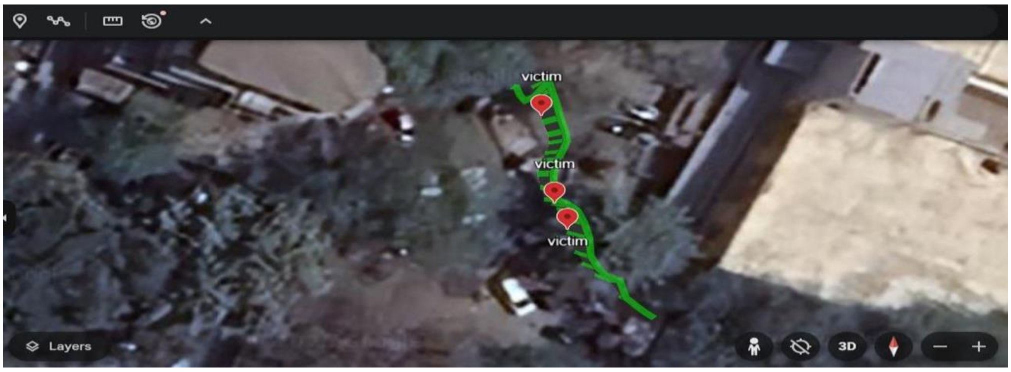


Figure 8. QUADRESCUE navigation and victim localization interface

This mapping functionality represents a critical feature of QUADRESCUE, allowing rescue teams to efficiently coordinate efforts by precisely locating survivors within the disaster zone. The interface utilizes standard mapping controls to enable operators to adjust the view, change map layers, or zoom as needed during operations. This visualization demonstrates that the SIM28M GPS module in QUADRESCUE provides location data with approximately 3 meters accuracy, as confirmed during testing. It also helps create a useful map of the robot's path and any important points it finds. This location data is invaluable for guiding human rescue teams directly to survivor locations, particularly in large or complex disaster areas where traditional navigation might be challenging due to altered landscapes or compromised infrastructure. The tested battery life of the quadruped is 45 minutes after which the battery needs to be replaced. It features a reliable communication system with a range of approximately 200 meters for seamless real-time data transmission.

Figure 9 presents quantitative results from terrain adaptability testing, comparing the performance of QUADRESCUE against a conventional wheeled robot platform across five distinct terrain types relevant to disaster scenarios. The bar chart displays success rates in terms of percentage of successful traversals. The data clearly demonstrates QUADRESCUE's superior mobility across challenging environments, particularly in disaster relevant terrains. While both platforms perform comparably on flat surfaces (100%), QUADRESCUE maintains consistently high performance across all tested conditions, with success rates ranging from 80% on stairs to 94% on gravel. In contrast, the wheeled robot shows dramatic performance degradation as terrain complexity increases, dropping to only 19% on stairs and 39% on rubble environments commonly encountered in disaster zones. The rubble and stairs categories highlight the most significant performance difference between the platforms, with QUADRESCUE outperforming the wheeled alternative by more than 50 percentage points in both cases. These results clearly show that the quadrupedal design works well for search and rescue tasks. These findings support the main idea that legged movement offers significant advantages in rough and uneven environments commonly encountered during disaster response.

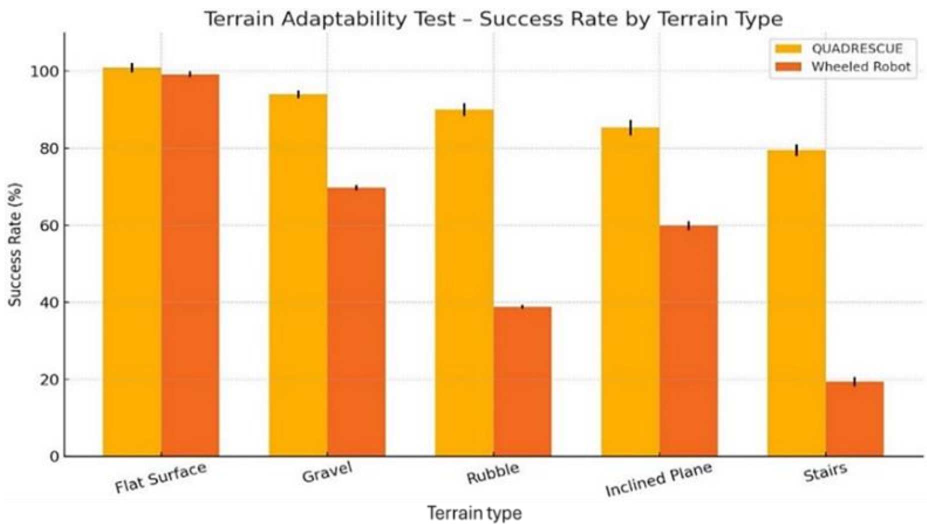


Figure 9. Comparative terrain adaptability performance between QUADRESCUE and wheeled robot platforms

Future development of QUADRESCUE should focus on improved power management, enhanced terrain mapping with hazard detection, and continued use of its modular design for easy maintenance. The experimental results confirm QUADRESCUE's effectiveness as a practical disaster response solution, outperforming wheeled platforms with a 94% success rate on rubble and 80% on stairs, compared to just 39% and 19% respectively. This validates the choice of quadrupedal locomotion for SAR operations. Equipped with real-time RGB-D mapping, GPS localization, a 200 meters communication range, and 45 minutes operational time, the system supports effective initial exploration and data collection in disaster zones. QUADRESCUE’s modular, cost-effective design using standard components and 3D-printed parts bridges the gap between expensive high-end robots and limited mobility wheeled platforms. It offers a robust yet affordable option, making SAR robotics more accessible to resource constrained rescue teams.

4. CONCLUSION

This work presents the design and implementation of QUADRESCUE, a ROS based quadruped robot tailored for disaster response operations. Emphasizing operator assisted control, modularity, and affordability, the system effectively bridges the gap between low-cost, manually operated systems and high-end autonomous platforms. It demonstrates strong terrain adaptability, robust sensor integration, and practical capabilities such as remote visual inspection, real-time terrain mapping, and GPS-based victim localization. The testing performed across various simulated disaster terrains highlights the advantages of the quadrupedal design, particularly in environments where wheeled robots fail to navigate effectively. The paper provides quantitative evidence through comparative terrain adaptability testing showing QUADRESCUE's superior performance (80-94% success rates) versus wheeled robots (19-39% on challenging terrain). Also, functional demonstrations of key capabilities including GPS localization (3 meters accuracy), dual RGB-D visual feeds, 45 minutes battery life, and 200 meters communication range. Despite the limitations in battery life and communication range, the results affirm the system’s potential to enhance the effectiveness of SAR missions, especially in resource constrained settings. Future work will focus on extending operational time, integrating semi-autonomous features, and incorporating feedback from first responders to fine-tune the system for practical deployment. The system ultimately contributes a versatile and accessible tool to the growing field of disaster robotics, offering a platform that is both technically capable and practically deployable in life saving scenarios.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sanjay Deshmukh	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Ojas Chanakya	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	
Om Gabani	✓	✓	✓	✓			✓			✓	✓		✓	
Kashish Patni	✓	✓				✓	✓	✓	✓					
Asmita Deshmukh	✓	✓			✓	✓			✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors declare that they have no conflict of interest and there are no competing interests.

ETHICAL APPROVAL

Authors have obtained all necessary permissions from the institutional ethical committee to conduct this work, and no human participant were involved in this study.

DATA AVAILABILITY

Specific data required can be made available upon reasonable request to the corresponding author. All materials belong to the authors and cannot be sold to anyone. Code will be made available upon reasonable request to the corresponding author.

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BIOGRAPHIES OF AUTHORS

Sanjay Deshmukh is an assistant professor at D. J. Sanghvi College of Engineering, Mumbai, India. He received his Ph.D. (electronics telecommunication engineering) from the University of Mumbai in 2022, Master of Engineering (digital electronics) in 2006, and Bachelor of Engineering (electronics and telecommunication) from Amravati University in 1994. His primary research interests include microstrip antennas, embedded systems, and communication networks. He can be contacted at sanjay.deshmukh@djsce.ac.in.

Ojas Chanakya was a student of the Department of Electronics and Telecommunication Engineering at Dwarkadas J. Sanghvi College of Engineering affiliated with the University of Mumbai, Vile Parle, Mumbai, India. He completed his B.Tech. in electronics and telecommunication engineering in 2025. His research interests include robotics, automation, and embedded systems. He can be contacted at chanakyaojas@gmail.com.

Om Gabani completed his bachelor's in technology in electronic and telecommunications engineering from Dwarkadas J. Sanghvi College of Engineering affiliated with Mumbai University in 2025. His research interests include embedded systems, power electronics, and hardware design. He can be contacted at omgabani23@gmail.com.

Kashish Patni was an undergraduate student at Dwarkadas J. Sanghvi College of Engineering, affiliated with the University of Mumbai. She completed her bachelor's degree in electronics and telecommunication engineering. Her research interests include Internet of Things and robotics. She can be contacted at kashishpatni2003@gmail.com.

Asmita Deshmukh is an assistant professor at KJSIT, Mumbai, India. She received her Ph.D. (computer science engineering) from Sant Gadge Baba Amravati University in 2025, Master of Engineering (computer engineering) from the University of Mumbai in 2012, and Bachelor of Engineering (computer science engineering) from Amravati University in 1996. Her primary research interests include natural language processing and deep learning. She can be reached via email at asmitadeshmukh7@gmail.com.