Journal of Science Engineering Technology and Management Science *ISSN:3049-0952*
Volume03, Issue04(1), April 2026 *www.jsetms.com*

A Low-Latency Visual Feedback Driven Robotic Mechanism for Rescue Operations in Restricted Vertical Structures

Md. Sharmila[1*], P. Tejaswini[1], B. Nandini[1], P. Aravindh[1], M. Shiva Parvathi[1], B. Vijay Kumar[1]
[1]Department of Electronics and Communication Engineering, Mother Teresa Institute of Science and Technology, Sanketika Nagar, Kothuru, Sathupally, Khammam, 507303, Telangana, India
*Correspondence: Md. Sharmila

To Cite this Article

Md. Sharmila, P. Tejaswini, B. Nandini, P. Aravindh, M. Shiva Parvathi, B. Vijay Kumar, "A Low-Latency Visual Feedback Driven Robotic Mechanism for Rescue Operations in Restricted Vertical Structures", Journal of Science Engineering Technology and Management Science, Vol. 03, Issue 04(1), April 2026,pp: 96-104, DOI: http://doi.org/10.64771/jsetms.2026.v03.i04(1).pp96-104

Submitted: 09-03-2026 *Accepted: 16-04-2026* *Published: 23-04-2026*

Abstract

Rescuing individuals trapped in deep, narrow borewells is an extremely complex task due to limited space, absence of light, and the impracticality of direct human involvement. This research presents a compact and wirelessly controlled Borewell Rescue Robot (BRR) designed to improve safety and efficiency during such emergencies. The system is built around an ESP32-CAM module, which combines processing capability with onboard imaging to deliver real-time video feedback from inside the borewell. The robot is capable of transmitting live video using a lightweight communication protocol, enabling operators to monitor conditions and guide actions with minimal delay. A pair of high-torque servo motors forms the core of the mechanical system, allowing precise movement and controlled gripping of the victim within confined vertical shafts. To address visibility challenges, an adjustable Light Emitting Diode (LED) lighting unit is integrated, providing sufficient illumination even in completely dark environments. The control system is developed using a non-blocking, event-driven architecture that allows simultaneous handling of motion commands and video streaming. This ensures smooth operation without lag or interruption. The robot functions through a self-contained wireless network, making it suitable for deployment in remote or infrastructure-limited areas. To enhance reliability, a safety mechanism is included that automatically stabilizes the system and halts movement if communication is disrupted. This solution offers a practical, scalable, and affordable approach to improving rescue operations in hazardous underground situations.

Keywords: Borewell Rescue Robot (BRR), ESP32-CAM MCU, Real-Time Video Streaming, Emergency Robotics, WebSocket Communication.

1. Introduction

The increasing dependence on groundwater resources in India has led to the widespread installation of borewells, which serve as a primary source of water for agricultural and domestic purposes. While these structures play a crucial role in supporting rural communities, they also pose serious hazards when not properly sealed or maintained. Unused or poorly covered borewells can turn into life-threatening traps, particularly because of their narrow diameter and extreme depth, which make conventional rescue efforts highly challenging and risky. In response to this issue, this research presents the development of a compact BRR that can be remotely operated to assist in emergency situations. The system is designed to descend into confined vertical spaces and provide continuous visual feedback, allowing rescuers to assess the condition of the trapped individual and guide the recovery process effectively. The core of the system is an ESP32-CAM module, which combines processing capability and onboard imaging to deliver real-time video streaming. Unlike traditional rescue approaches that often involve extensive excavation and prolonged delays, this robotic solution focuses on rapid deployment and minimal environmental disruption. The device incorporates precision-controlled actuators and servo-driven mechanisms that enable careful movement and secure handling within restricted spaces. To overcome visibility limitations in deep underground environments, an integrated lighting system ensures clear imaging even in complete darkness.

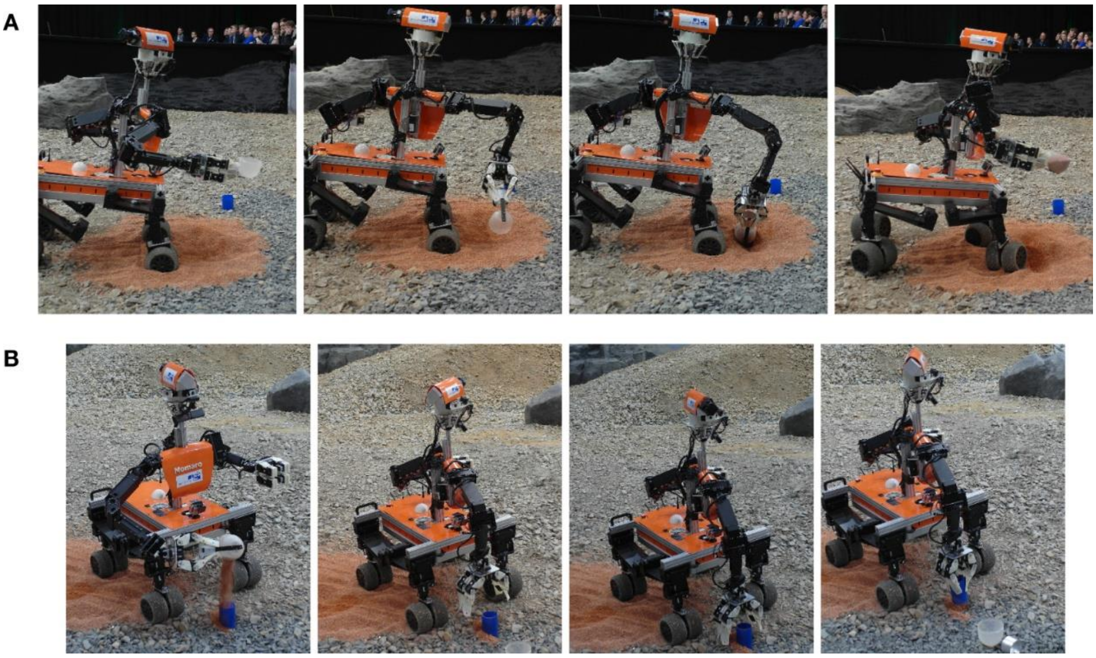

Figure. 1: Borewell rescue robot.

The system operates through a dedicated wireless network, eliminating reliance on external communication infrastructure and making it suitable for use in remote areas. Its software framework is designed to handle multiple operations simultaneously, ensuring smooth coordination between live video transmission and mechanical control. Safety is further enhanced through built-in protective measures that stabilize the system in case of signal interruption or malfunction. This project offers an innovative and efficient approach to borewell rescue operations, aiming to reduce response time, improve operational safety, and increase the chances of successful victim recovery.

2. Literature Survey

Sui, et al. [1] focused on the design and development of an enveloping soft gripper with high load-carrying capacity, emphasizing adaptability and safe interaction with objects of varying shapes and textures. Their study explored the use of flexible materials and compliant structures that allowed the gripper to conform around objects rather than relying on rigid grasping. This approach significantly reduced the risk of damage during handling, making it highly suitable for delicate rescue operations. The authors conducted detailed characterization experiments to evaluate gripping force, load capacity, and stability under different conditions. Their results demonstrated that the soft gripper could maintain a secure hold even under dynamic disturbances, highlighting its potential for applications in constrained environments such as borewell rescues where careful and adaptive manipulation is essential.

Ramkumar, et al. [2] proposed an Internet of Things (IoT)-based child rescue system aimed at improving the efficiency of borewell rescue operations through real-time monitoring and communication. Their system architecture integrated multiple sensors to track environmental conditions and the status of the trapped victim, while communication modules transmitted this data to remote operators. The authors emphasized the importance of continuous data flow, enabling rescuers to monitor parameters such as position and surrounding conditions in real time. They also discussed the use of network connectivity to coordinate rescue efforts more effectively. Experimental evaluations suggested that such an IoT-enabled approach could significantly reduce response time and improve decision-making accuracy during critical rescue scenarios. Thota, et al. [3] developed an Arduino-based child rescue system that demonstrated a simple yet effective approach to implementing robotic assistance in borewell emergencies. Their design utilized a microcontroller to control sensors and actuators, enabling basic operations such as movement, object detection, and gripping. The system was structured to be low-cost and easily deployable, making it suitable for use in resource-constrained environments. The authors presented implementation details along with experimental validation, showing that the system could perform essential rescue tasks in controlled conditions. They highlighted the advantages of using Arduino, including ease of programming, modularity, and affordability, while also noting limitations in terms of processing capability and scalability for more complex operations.

Kavyasree, et al. [4] presented a comprehensive robotic system designed specifically for rescuing children trapped in borewells, addressing both mechanical and operational challenges. Their work detailed the design of a compact robotic platform capable of navigating narrow vertical shafts while maintaining stability and control. The system incorporated sensing mechanisms to detect the environment and locate the victim, along with a gripping mechanism designed for safe extraction. They also discussed communication systems that enabled real-time monitoring and operator control. The authors identified key challenges such as limited space, low visibility, and the need for precise manipulation, and proposed solutions to overcome these constraints. Their study demonstrated that integrating mobility, sensing, and communication into a single platform could significantly improve the effectiveness of borewell rescue operations. Rishab, et al. [5] presented a mechatronic puppet-based robotic hand system designed for life-saving applications, focusing on achieving human-like dexterity in constrained environments. Their work described the mechanical design of the hand using articulated joints and linkage mechanisms that mimicked natural finger movements. Actuation was implemented to allow precise control over gripping force and finger positioning, enabling safe interaction with fragile objects. The authors also discussed control strategies that allowed coordinated motion of multiple joints, improving adaptability in complex rescue scenarios. Experimental evaluations highlighted the system’s ability to perform delicate manipulation tasks, making it suitable for applications where careful handling, such as rescuing trapped victims, is essential.

Akash, et al. [6] presented the design and development of a robotic system specifically intended for borewell rescue operations, emphasizing structural stability and controlled mobility in narrow vertical shafts. Their study detailed the mechanical framework of the robot, including chassis design, actuator placement, and gripping mechanisms tailored for confined spaces. They also integrated sensors and control systems to enhance positioning accuracy and operational reliability. The authors discussed practical challenges such as alignment within the borewell, maintaining balance, and ensuring safe interaction with the victim. Their experimental results demonstrated that a well-designed robotic system could significantly improve rescue efficiency compared to traditional manual approaches. RenugaDevi, et al. [7] proposed an Internet of Things (IoT)-based detection system that utilized drone-operated cameras to identify unclosed borewell holes in remote areas. Their approach combined aerial surveillance with image processing techniques to detect hazardous openings that could lead to accidents. The system was designed to transmit real-time data to monitoring stations, enabling authorities to take preventive action before incidents occurred. The authors discussed the integration of communication technologies and automated detection algorithms, highlighting the importance of proactive safety measures. Their work demonstrated how combining IoT with drone technology could reduce the occurrence of borewell accidents by identifying risks at an early stage.

Karthik, et al. [8] conducted a detailed investigation and analysis of existing borewell child rescue systems, reviewing various technological approaches and their effectiveness. Their study examined components such as sensing mechanisms, communication systems, and robotic designs used in different rescue solutions. They also analyzed case studies and experimental models to evaluate performance in real-world scenarios. The authors identified key limitations in traditional rescue methods, including slow response time, lack of precision, and high dependency on manual intervention. Based on their findings, they emphasized the need for advanced, automated, and reliable systems that can operate efficiently in confined environments and improve survival outcomes in borewell rescue situations.

3. Proposed System

The proposed methodology presents a systematic framework for enabling safe and efficient rescue operations in deep borewells using an embedded robotic system. The process begins with system initialization and hardware configuration, followed by real-time image acquisition, wireless communication, and controlled mechanical actuation. A compact imaging unit continuously captures visual data from inside the borewell, which is transmitted to the operator through a low-latency wireless interface. Based on the received visual feedback, control commands are issued to guide the robotic mechanism for precise movement and victim handling, as shown in figure 2. The architecture also incorporates safety monitoring and automatic recovery features to ensure reliable operation under uncertain conditions. A user interface allows seamless interaction with the system for monitoring and control, while the overall framework supports continuous observation and responsive actuation during rescue procedures.

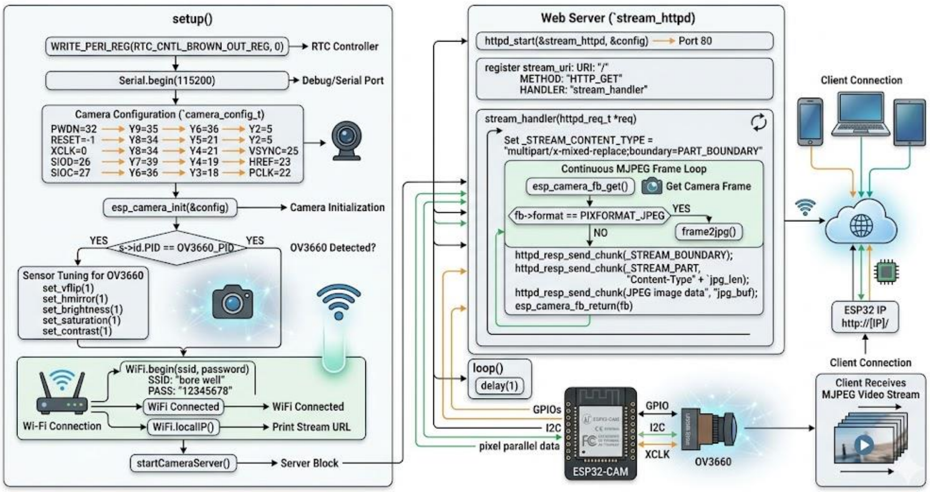

Figure. 2: Proposed system architecture

User Interface (Control Panel)

- The operator interacts with the system through a control interface designed for monitoring and command input.
- It provides access to live video streaming, movement controls, and actuator operation.
- Users can observe the internal borewell environment in real time and make decisions accordingly.
- Control inputs from the interface are transmitted wirelessly to the embedded system.

Embedded Controller (ESP32-CAM Unit)

- The ESP32-CAM acts as the central processing and control unit of the system.
- It handles image capture, wireless communication, and actuator control simultaneously.
- The module processes incoming commands and executes corresponding mechanical actions.
- Its integrated camera enables continuous visual monitoring inside the borewell.

Wireless Communication Module

- Communication is established through a Wi-Fi-based access point created by the embedded system.
- This eliminates dependency on external internet infrastructure.
- Real-time data exchange occurs between the control interface and the embedded unit.
- The system ensures low-latency transmission for responsive operation.

Image Acquisition and Streaming

- The onboard camera continuously captures images from inside the borewell.
- Captured frames are compressed and transmitted as a live video stream.
- The streaming mechanism provides uninterrupted visual feedback to the operator.
- This enables accurate assessment of the victim’s position and surrounding conditions.

Mechanical Actuation System

- The robotic mechanism includes high-torque servo motors for movement and gripping.
- These actuators allow controlled positioning within narrow vertical spaces.
- The system is capable of performing delicate handling operations required during rescue.
- Precision control ensures minimal risk to the trapped individual.

Illumination System

- A high-intensity LED module is used to provide lighting in dark underground environments.
- The brightness can be controlled to enhance visibility based on conditions.
- This improves the clarity of captured images for better decision-making.

Control and Processing Logic

- The system operates using a non-blocking, event-driven programming approach.
- It allows simultaneous handling of video streaming and control commands.
- This ensures smooth and uninterrupted system performance.
- The architecture supports real-time responsiveness during critical operations.

Safety and Fail-Safe Mechanism

- A safety module continuously monitors communication and system status.
- In case of signal loss or malfunction, the system automatically halts movement.
- Actuators are reset to a safe state to prevent unintended actions.
- This enhances operational reliability and protects both the system and the victim.

Data Output and Monitoring

- Live video output is displayed on the control interface for continuous observation.
- Operators receive immediate feedback on system actions and environmental conditions.
- This enables precise coordination during rescue operations.

Operational Workflow

- The system is deployed into the borewell and initialized.
- Real-time video is transmitted to the operator interface.
- Based on visual input, control commands are issued to guide the mechanism.
- The actuators perform movement and gripping actions as required.
- The process continues until safe retrieval is achieved.

System Adaptability and Improvement

- The framework allows future enhancements such as additional sensors or automation features.
- Performance can be improved by optimizing communication and control algorithms.
- The design supports scalability for different borewell depths and conditions.

3.1 Proposed System Workflow

The operational workflow of the Borewell Rescue Bot is designed as a non-blocking, event-driven system. Because the ESP32 must simultaneously stream video and process motor commands, the logic relies on Asynchronous WebSocket’s rather than a traditional linear loop, as shown in figure 3.

1. System Operational Flow & Logic Analysis

The workflow is divided into three distinct logical phases:

Phase I: Initialization (Setup)

- **Hardware Pinning:** The system initializes PWM via the ledc library for the LED and attaches the Servo objects to pins 14 and 15.

- **Networking:** The ESP32 configures itself as a SoftAP. It assigns itself a static IP address (usually 192.168.4.1).
- **Camera Prep:** The code checks for PSRAM. If detected, it allocates a large buffer to handle VGA frames. The camera is initialized with JPEG compression set to a quality of 10.
- **Server Start:** The AsyncWebServer begins listening on Port 80, and two WebSocket endpoints (/Camera and /CarInput) are opened.

Phase II: The Execution Loop (Real-Time Stream)

- **Frame Acquisition:** The sendCameraPicture() function attempts to capture a frame from the sensor.
- **Client Verification:** The logic checks if a client is connected to the camera socket (cameraClientId != 0). If no one is watching, it skips the heavy task of frame processing to save power.
- **Binary Transmission:** The raw JPEG buffer is sent as a binary blob.
- **Congestion Control:** A while loop checks clientPointer->queueIsFull(). This is the "Traffic Cop" logic—it prevents the ESP32 from crashing by waiting until the network buffer has room for the next frame.

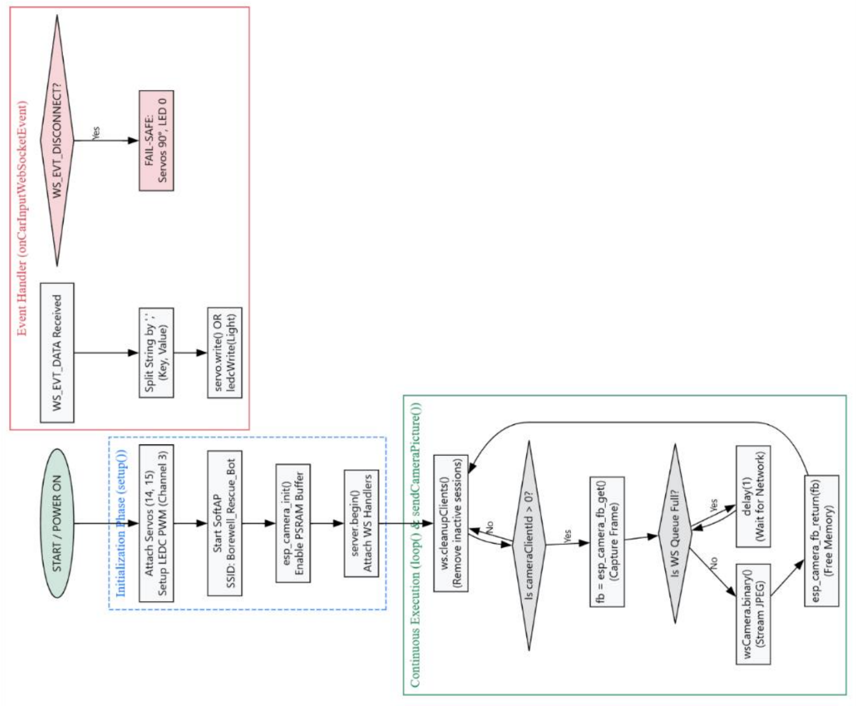

Figure. 3: Proposed operational flow and logic analysis.

Phase III: Event-Driven Interrupts (Control Logic)

- **Command Parsing:** When a user moves a slider, a string like "Servo1,120" is sent. The onCarInputWebSocketEvent triggers.
- **Tokenization:** The code uses std::istringstream to split the "Key" (Servo1) from the "Value" (120).
- **Actuation:** Depending on the key, the system calls servo.write(valueInt) or ledcWrite(channel, valueInt).
- **Fail-Safe:** If the WS_EVT_DISCONNECT event is detected (signal lost in the borewell), the logic immediately executes a safety override: Light = 0, Servos = 90°.

4. Results And Discussion

The results and discussion section presents the performance and effectiveness of the developed system under various operating conditions. The study evaluates key aspects such as real-time video transmission, responsiveness of control mechanisms, and overall system stability. Observations are made based on experimental testing in confined environments similar to borewell conditions. The accuracy and reliability of visual feedback play a crucial role in guiding the operation process. The response of actuators and their precision in movement are also analyzed. Any limitations encountered during testing are discussed along with possible improvements.

Figure 4 illustrates the dual servo motor gripper mechanism designed for robotic manipulation, incorporating high-torque servo motors (such as SG90/MG996R), mechanical linkage arms, and a precision claw assembly for controlled gripping operations. The configuration demonstrates coordinated actuation of the servo motors through PWM signals generated by a controller such as the ESP32, enabling accurate angular positioning of the gripper jaws. The linkage system ensures uniform force distribution during grasping, improving stability and object retention. The integration of mounting brackets, fasteners, and structural plates supports mechanical rigidity and repeatable motion. This setup highlights the role of servo-driven actuation in achieving precise pick-and-place functionality within robotic systems.

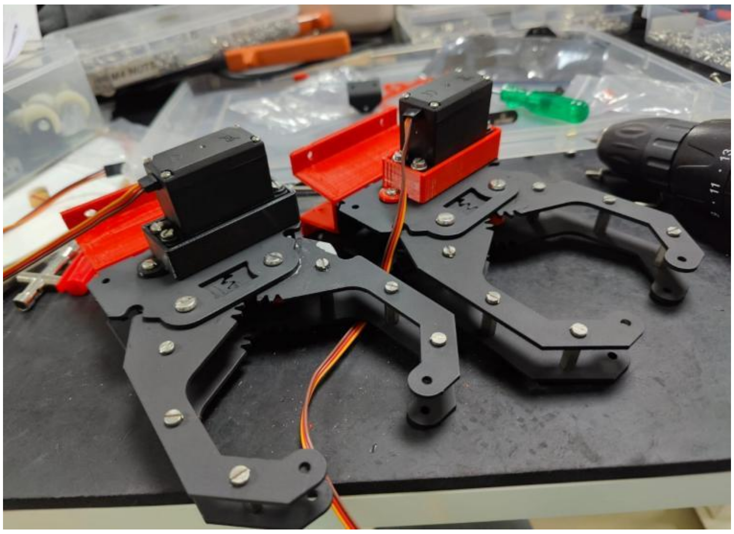

Figure. 4: Dual Servo Motor Gripper Mechanism for Robotic Manipulation

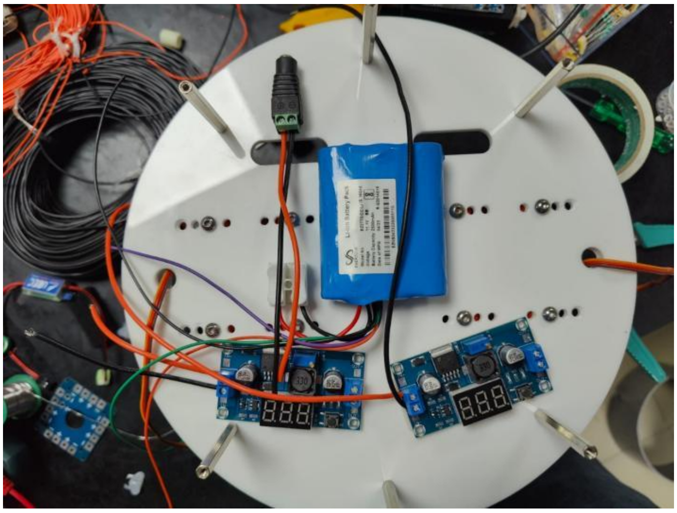

Figure. 5: Power Distribution Module with Battery Pack and Voltage Regulation Units

Figure. 5 depicts the power distribution module consisting of a lithium-ion battery pack (typically 12V), DC-DC buck converter modules (such as LM2596 voltage regulators), and supporting power connectors for efficient energy management. The architecture regulates voltage levels required for different subsystems including the ESP32 microcontroller, sensors, and motor driver modules. The presence of onboard digital voltage displays enables real-time monitoring of output levels, ensuring system safety and stability. The wiring configuration demonstrates organized distribution of power to multiple loads while minimizing voltage fluctuations.

Figure 6 represents the cylindrical robotic assembly integrating a DC geared motor, shaft coupling mechanism, and multi-level circular platforms for housing electronic and mechanical components. The DC motor provides rotational motion, typically controlled via a motor driver such as L298N or similar H-bridge modules, enabling actuation of attached mechanical elements. The layered structure accommodates control units like ESP32, sensor interfaces, and wiring assemblies within a compact vertical design. Structural supports and spacers ensure alignment and stability of stacked components.

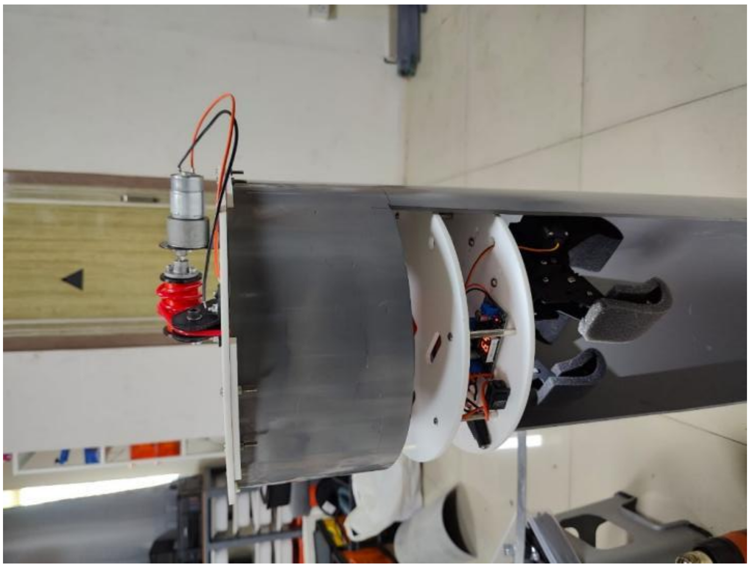

Figure. 6: Cylindrical Robotic Assembly with DC Motor-Driven Mechanism and Multi-Level Structural Platform

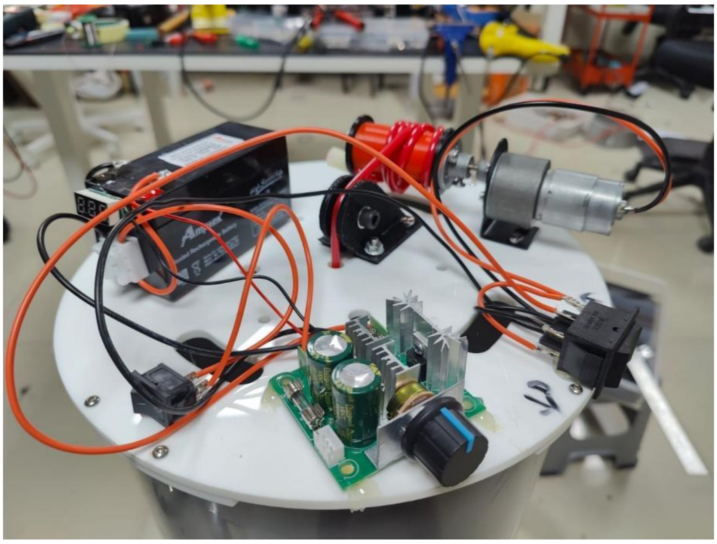

Figure. 7: Integrated Control and Actuation Module with DC Motor, Servo Assembly, and Power Regulation Circuit

Figure 7 illustrates the integrated control and actuation module combining a DC geared motor, servo motor assembly, lithium battery pack, power switch, and LM2596-based voltage regulation circuit. The system demonstrates interconnection between control electronics and actuation components, where the ESP32 microcontroller generates control signals for both servo and DC motor operations. The motor driver module facilitates bidirectional control and speed regulation of the DC motor, while the servo motor enables precise angular movements. The voltage regulator ensures stable power delivery to sensitive components, preventing fluctuations and ensuring reliability.

5. Conclusion

The developed system highlights a significant advancement in handling rescue situations within deep and confined borewell environments. By combining compact hardware with wireless control capabilities, it enables safer and more efficient intervention compared to conventional manual approaches. The integration of real-time visual monitoring allows operators to continuously observe internal conditions and make informed decisions during critical moments. The design ensures smooth coordination between image transmission and mechanical operations, resulting in responsive and precise control. The inclusion of effective illumination enhances visibility in low-light conditions, while the actuator mechanism supports careful handling within restricted spaces. Reliability is further strengthened through built-in safety measures that prevent unintended actions during communication loss or system instability. This approach reduces the time required for rescue operations and minimizes risks associated with traditional excavation techniques. Its flexible and scalable nature makes it suitable for deployment in various emergency scenarios, offering a practical and efficient solution for improving rescue success rates in hazardous underground conditions.

References

[1] D. Sui, et al., "An Enveloping Soft Gripper With High-Load Carrying Capacity: Design, Characterization and Application," IEEE Robotics and Automation Letters, vol. 7, no. 1, pp. 373–380, 2021.

[2] M. Ramkumar, K. Jana, J. Babu, and G. Bharathi, "IoT-based Child Rescue System from Borewell," in Proc. 6th Int. Conf. Electronics, Communication and Aerospace Technology, 2022, pp. 456–459.

[3] B. Thota, et al., "Innovative Child Rescue System from Borewell using Arduino," in Proc. Int. Conf. Innovative Data Communication Technologies and Application, 2023.

[4] A. Kavyasree, B. Bhargavi, M. Shabbar, U. Neerajapatel, and M. Vucha, "Borewell child rescue robot system," in AIP Conf. Proc., vol. 2492, no. 1, 2023.

[5] S. K. Rishab, D. S. Thinoj, and H. U. Prabhu, "Mechatronic Puppet Based Robotic Hand System For Life Saving Application," in Proc. 9th Int. Conf. Electrical Energy Systems, 2023.

[6] B. Akash, et al., "Design and development of robot for rescue operations for bore-well victims," in Proc. Int. Conf. Futuristic Technologies in Control Systems & Renewable Energy, 2020.

[7] S. RenugaDevi, et al., "IoT based detection of bore-well unclosed holes using automated drone operated cameras in a remote area," J. Phys.: Conf. Ser., vol. 1767, no. 1, 2021.

[8] S. Karthik, et al., "Investigation and analysis on child rescue system from open bore well," IOP Conf. Ser.: Mater. Sci. Eng., vol. 912, no. 2, 2020.