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A Next-Generation IoT-Driven Robotic Rescue Paradigm for Borewell Emergencies with High-Torque Adaptive Manipulation

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ABSTRACT

Rescue operations in deep and narrow borewells are extremely challenging due to restricted access, poor visibility, and the inability of humans to directly reach victims in such confined vertical environments. To address these limitations, this work presents a compact and remotely operated Borewell Rescue Robot (BRR) developed using an Espressif Systems Processor (ESP32-CAM) Microcontroller Unit (MCU), designed to enable real-time monitoring and precise control during emergency situations. The system integrates live video streaming with mechanical actuation through a wireless interface, allowing operators to guide and control the robot safely from a remote location. A 32-bit embedded processor supported by Pseudo-Static Random Access Memory (PSRAM) ensures smooth and continuous Video Graphics Array (VGA) image transmission, providing clear visualization of the borewell interior. Communication is established using a Wireless Fidelity (Wi-Fi) Access Point (AP), while WebSocket-based protocols facilitate low-latency, bidirectional data exchange for synchronized control and monitoring. The robotic mechanism incorporates dual high-torque servo motors for accurate gripping and positioning, enabling effective manipulation within narrow shafts. To overcome low-light conditions, a Pulse Width Modulation (PWM)-controlled Light Emitting Diode (LED) system is integrated for enhanced illumination. The software architecture follows an asynchronous, event-driven model using the ESPAsyncWebServer framework, allowing concurrent handling of video streaming and control commands without delay. Additionally, a fail-safe mechanism is implemented to reset actuators and disable critical components in case of communication loss, ensuring system safety, reliability, and efficient deployment in real-world rescue scenarios.

Keywords: Borewell Rescue Robot (BRR), ESP32-CAM, Microcontroller Unit (MCU), Wireless Control (Wi-Fi AP), Real-Time Video Streaming, LED Illumination

1. INTRODUCTION

The extensive reliance on underground water sources across India has resulted in a sharp rise in borewell construction, where these deep and narrow vertical shafts are primarily deployed for agricultural irrigation and domestic water supply. Despite their importance in sustaining rural livelihoods and improving water accessibility, borewells present severe safety threats when they are left uncovered, loosely capped, or abandoned after depletion. Their extremely confined diameter combined with depths that frequently exceed 100 feet creates a highly hazardous environment, particularly in cases of accidental falls involving children, where immediate rescue becomes exceptionally difficult due to limited access, poor visibility, and lack of breathable air. Recognizing the urgency of this issue, the present work proposes a Borewell Rescue Robot (BRR) designed using an Espressif Systems Processor (ESP32-CAM) Microcontroller Unit (MCU), specifically tailored to operate within narrow vertical spaces and assist rescue operations through real-time monitoring and controlled mechanical intervention.

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The proposed system is built on a compact embedded architecture that integrates Pseudo-Static Random Access Memory (PSRAM), enabling continuous and stable Video Graphics Array (VGA) resolution streaming for clear visualization of the borewell interior. This visual feedback plays a crucial role in guiding rescue teams by providing situational awareness in an otherwise inaccessible environment. Communication between the robot and the operator is established using a Wireless Fidelity (Wi-Fi) Software Access Point (SoftAP), which allows direct device-to-device connectivity without relying on external network infrastructure. To ensure efficient and synchronized data exchange, the system employs the WebSocket protocol, which supports low-latency, bidirectional communication for real-time video streaming and control signal transmission. This architecture is particularly advantageous for deployment in rural or remote areas where internet connectivity may be unreliable or unavailable.

Traditional rescue techniques, such as excavating a parallel pit alongside the borewell, are not only time-consuming and labor-intensive but also highly dependent on soil conditions, machinery availability, and environmental constraints. These delays significantly reduce the chances of survival, as victims may suffer from oxygen depletion, dehydration, stress, and hypothermia over time. Numerous real-world incidents highlight the limitations of such conventional methods and underline the need for faster, more precise, and minimally invasive solutions. In response, the proposed robotic system integrates Pulse Width Modulation (PWM)-based actuator control along with high-torque servo motors, enabling precise positioning, gripping, and movement within the restricted borewell space. This allows the robot to carefully approach and secure the victim without causing additional harm. Furthermore, a high-intensity Light Emitting Diode (LED) illumination system is incorporated to enhance visibility in dark underground conditions, ensuring accurate operation even in complete absence of natural light.

On the software side, the system adopts an asynchronous and event-driven architecture, allowing multiple processes such as video streaming, sensor feedback, and control command execution to run concurrently without blocking system performance. This results in a highly responsive and stable system capable of continuous operation during critical rescue missions. Additionally, a robust fail-safe mechanism is implemented to enhance safety and reliability; in the event of communication loss, hardware malfunction, or unexpected behavior, the system automatically resets actuators and disables high-power components to prevent accidental damage or unsafe movements. Overall, by combining real-time visual monitoring, precise mechanical control, efficient communication, and intelligent safety features, the proposed Borewell Rescue Robot offers a practical, scalable, and cost-effective solution that significantly improves rescue efficiency and increases the probability of successful victim retrieval in emergency scenarios.

2. LITERATURE SURVEY

Akash, et al. [1] developed a robotic system specifically designed for borewell rescue operations, focusing on achieving reliable performance within extremely confined vertical environments. Their work presented a detailed mechanical design that included a compact chassis, optimized actuator placement, and specialized gripping mechanisms capable of functioning in narrow shafts. The authors emphasized the importance of maintaining alignment and stability while the robot is lowered into deep borewells, as even minor deviations could affect rescue effectiveness. They also integrated sensing and control modules to improve positional accuracy and ensure safe interaction with the victim. Experimental observations demonstrated that such a structured robotic design could significantly reduce rescue time compared to conventional manual approaches, while also improving safety and precision.

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Sui, et al. [2] investigated the development of a soft robotic gripper with high load-carrying capability, focusing on adaptability and safe interaction with objects of varying shapes and sizes. Their design utilized flexible and compliant materials that allowed the gripper to envelop objects instead of applying rigid force, thereby minimizing the risk of damage during handling. The study included detailed characterization experiments to evaluate gripping force, deformation behavior, load capacity, and stability under different operating conditions. The results showed that the gripper maintained a secure hold even under dynamic disturbances, highlighting its effectiveness in uncertain environments. This makes it particularly suitable for rescue operations where delicate handling and adaptability are essential. Karthik, et al. [3] conducted an extensive investigation into existing borewell rescue systems, analyzing various technological approaches such as robotic mechanisms, sensing techniques, and communication frameworks. Their study compared different systems based on parameters including response time, operational efficiency, and reliability. They identified several critical limitations in traditional methods, such as slow deployment, lack of precision, and heavy reliance on manual labor. The authors also examined case studies to understand real-world challenges and concluded that there is a strong need for automated, fast, and reliable rescue solutions that can operate effectively in confined environments and improve survival outcomes. Ramkumar, et al. [4] proposed an Internet of Things (IoT)-based rescue system aimed at enhancing real-time monitoring and coordination during borewell emergencies. Their system architecture integrated multiple sensors to capture environmental conditions and the status of the trapped individual, with communication modules transmitting this data continuously to remote operators. This enabled rescuers to monitor critical parameters and make informed decisions quickly. The authors highlighted the importance of continuous data flow and connectivity in improving rescue efficiency and reducing response time. Their experimental analysis indicated that IoT-enabled systems could significantly enhance situational awareness and operational effectiveness in emergency scenarios.

RenugaDevi, et al. [5] proposed an Internet of Things (IoT)-based preventive system that utilized drone-operated cameras to identify unclosed or abandoned borewell openings in remote and rural areas. Their approach combined aerial surveillance with image processing techniques to detect hazardous locations that could potentially lead to accidents. The system continuously transmitted real-time data to monitoring stations, enabling authorities to take immediate preventive actions. The authors emphasized the importance of early detection and proactive safety measures, demonstrating that such systems could significantly reduce the occurrence of borewell-related incidents by identifying risks before accidents happen. Rishab, et al. [6] presented a mechatronic robotic hand system designed to achieve human-like dexterity for life-saving applications. Their work focused on developing articulated joint mechanisms and coordinated actuation strategies that allowed precise control of finger movements and gripping force. This enabled the robotic hand to handle delicate objects safely without causing damage. The study included experimental validation to evaluate performance in tasks requiring fine manipulation, showing that the system could operate effectively in constrained environments where careful and controlled interaction is essential. Thota, et al. [7] developed a microcontroller-based rescue system using an Arduino platform, emphasizing simplicity, affordability, and ease of implementation. Their design integrated sensors and actuators to perform essential functions such as movement control, object detection, and gripping operations. The system demonstrated that low-cost hardware could be effectively utilized to build functional rescue mechanisms for controlled environments. However, the authors also discussed limitations related to processing power, scalability, and adaptability, indicating that more advanced systems are required for complex real-world rescue scenarios. Kavyasree, et al. [8] proposed a comprehensive robotic solution for borewell rescue operations, integrating mobility,

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sensing, and communication into a unified platform. Their system was designed to navigate narrow vertical shafts while maintaining stability and precise control. It incorporated sensing mechanisms for environment detection, real-time monitoring for operator awareness, and gripping mechanisms for safe victim extraction. The authors addressed challenges such as limited space, poor visibility, and the need for accurate manipulation, demonstrating that an integrated robotic system could significantly improve the efficiency, safety, and success rate of borewell rescue operations.

3. PROPOSED SYSTEM

The overall architecture is implemented as a unified, real-time embedded vision and control system built around the ESP32-CAM (AI-Thinker) module, which consolidates image capture, wireless connectivity, WebSocket communication, memory handling, and actuator control into a streamlined operational flow. The module communicates with the OV2640 image sensor through a parallel camera interface using signals such as D0–D7, XCLK, PCLK, VSYNC, HREF, SIOD, and SIOC, while frame acquisition is managed via the esp_camera driver configured with parameters like PIXFORMAT_JPEG and FRAMESIZE_VGA to achieve an optimal trade-off between visual clarity and transmission efficiency, as depicted in Fig. 1. Captured image frames are temporarily stored in buffers allocated within PSRAM using dynamic memory functions such as psram_malloc and heap_caps_malloc with external memory enabled, thereby preventing overload of internal SRAM during continuous streaming. The device functions in Wi-Fi SoftAP mode, broadcasting a predefined network identifier and password, allowing direct connection from a mobile device or browser through a fixed IP address, which removes reliance on external networking infrastructure and reduces communication delay.

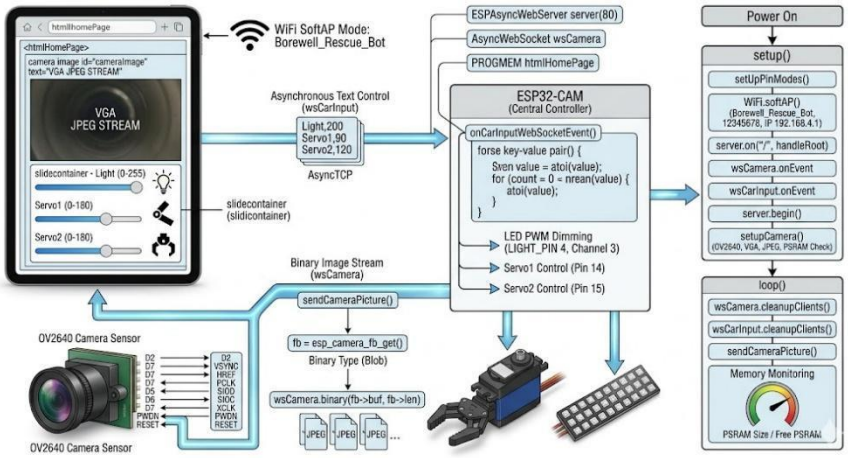


Fig. 1: Proposed system architecture

The user interface provides a live video stream along with control options for adjusting LED intensity (ranging from 0 to 255) and servo positions (0 to 180 degrees), where user inputs are captured through JavaScript functions like sendButtonInput(key, value) and transmitted via a WebSocket channel as structured key-value messages, ensuring efficient event-driven interaction. On the processing side, incoming data is handled by an event callback that parses and interprets commands using string processing techniques, validates inputs, and translates them into hardware actions. LED brightness is

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regulated using PWM signals generated through LEDC channels, while servo motors are controlled via PWM outputs mapped to designated GPIO pins. Simultaneously, a dedicated WebSocket stream handles transmission of binary image frames obtained using esp_camera_fb_get(), enabling uninterrupted real-time video display on the client side. Initialization routines establish communication channels, and the main execution loop manages client connections, streams video frames, processes control inputs, and clears inactive sessions without blocking system performance. The design leverages asynchronous event handling to support concurrent operations, while efficient memory utilization through PSRAM and buffer reuse ensures stability under continuous data flow. By separating control and streaming pathways, the system minimizes latency and enhances responsiveness, resulting in a reliable, scalable, and high-performance embedded solution that effectively integrates sensing, communication, processing, and actuation components.

4. RESULTS AND DISCUSSION

4.1 SOFTWARE IMPLEMENTATION

Fig. 2 illustrates the CAD-based robotic assembly highlighting the integrated structural frame, linkage elements, and mounting configurations developed using a parametric design approach. The model demonstrates precise geometric constraints applied to ensure accurate alignment and positioning of components within the assembly. The visualization includes kinematic relationships that define the motion behavior of interconnected parts under actuator influence. The feature tree structure reflects organized design elements such as sketches, extrusions, and constraints for efficient modification. The assembly layout supports evaluation of spatial clearances and mechanical fit between components

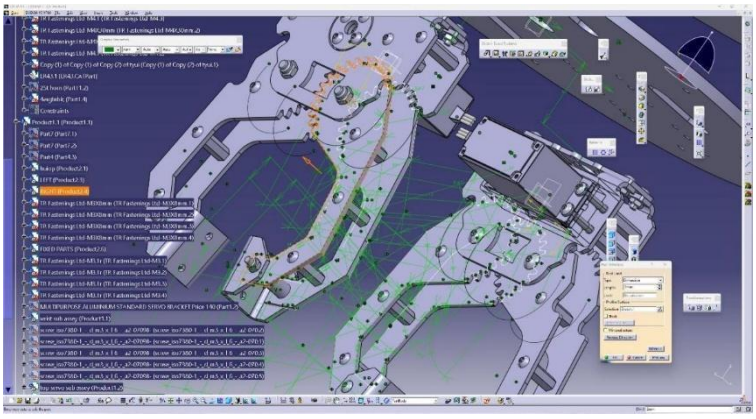
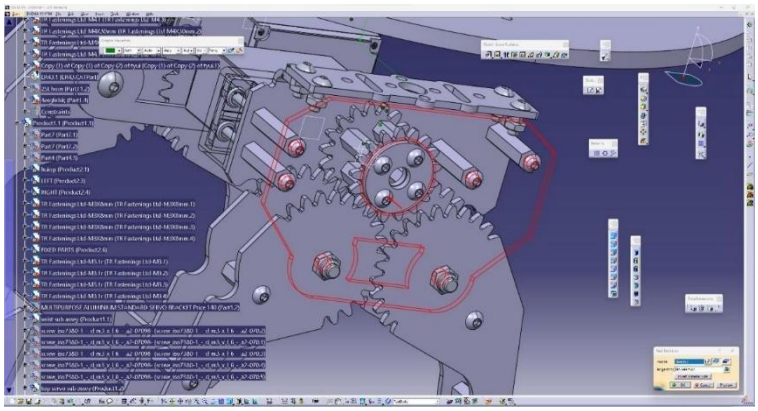


Fig. 2: CAD-Based Robotic Assembly and Kinematic Design



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Fig. 3: CAD Model of Gear-Driven Robotic Linkage Mechanism

Fig. 3 depicts the CAD model of a gear-driven robotic linkage mechanism designed to convert rotational motion into controlled mechanical actuation. The arrangement includes intermeshing gears, linkage arms, and fastening components configured to ensure synchronized motion transmission. The constraint definitions establish precise rotational relationships between gear elements, enabling accurate motion simulation. The design supports analysis of torque transfer, mechanical efficiency, and load distribution across the system. The structural configuration ensures stability and alignment of moving parts during operation.

Fig. 4 represents the CAD model of a multi-layer robotic platform integrated with a dual gripper assembly for manipulation tasks. The design features stacked circular plates that provide structural support and space for component integration. The dual gripper mechanism is mounted symmetrically, enabling coordinated object handling and improved operational balance. The assembly incorporates linkage structures and actuator mounting points to facilitate precise gripping actions. The layered configuration allows efficient organization of electronic and mechanical subsystems within a compact form factor.

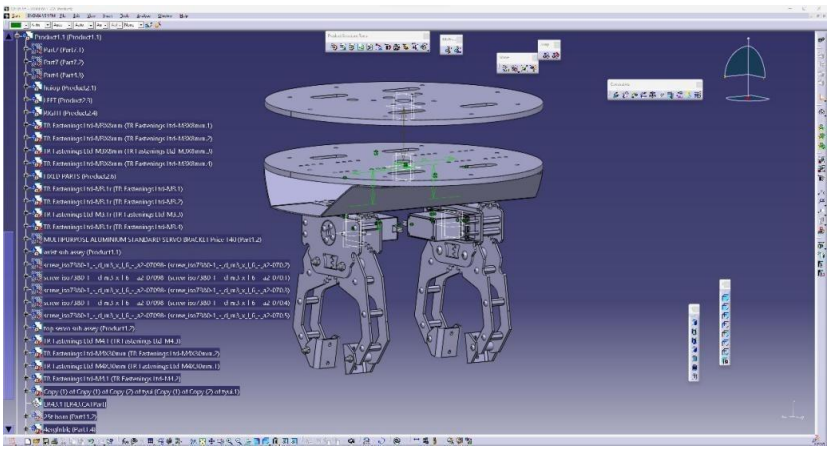
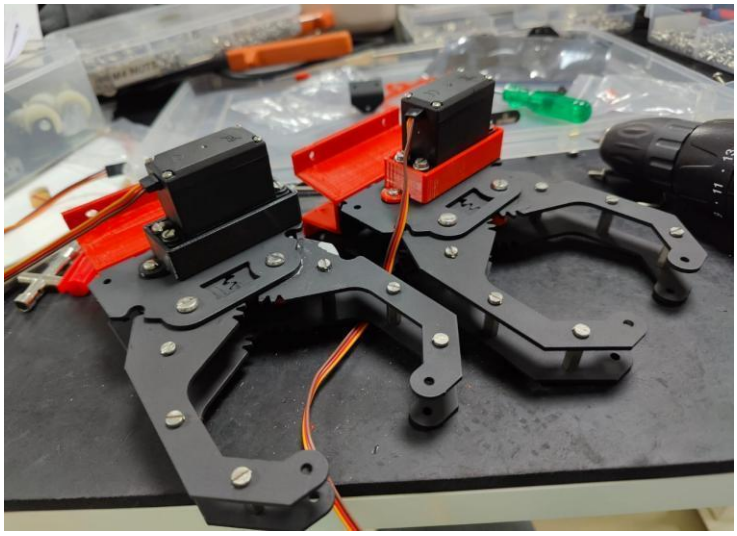


Fig. 4: CAD Model of Multi-Layer Robotic Platform with Dual Gripper Assembly

4.2 HARDWARE IMPLEMENTATION



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Fig. 5: Dual Servo Motor Gripper Mechanism for Robotic Manipulation

Fig. 5 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.

Fig. 6 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.

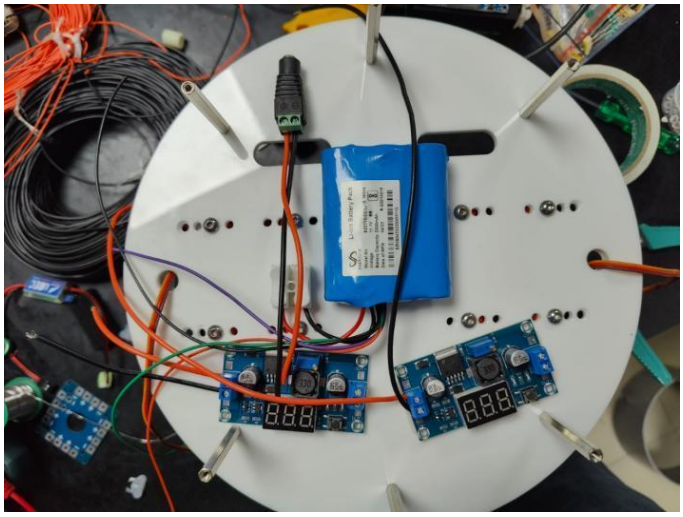


Fig. 6: Power Distribution Module with Battery Pack and Voltage Regulation Units

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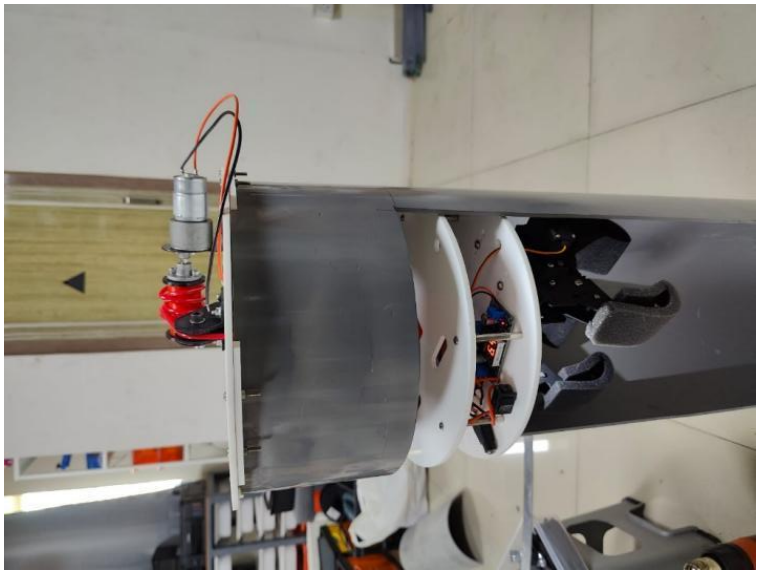
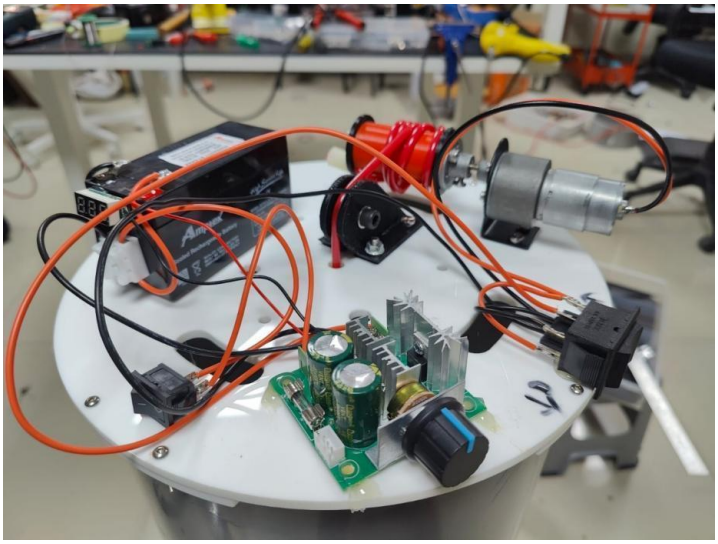


Fig. 7: Cylindrical Robotic Assembly with DC Motor-Driven Mechanism and Multi-Level Structural Platform

Fig. 7 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.

Fig. 8 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.



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Fig. 8: Integrated Control and Actuation Module with DC Motor, Servo Assembly, and Power Regulation Circuit.

5. CONCLUSION

The ESP32-CAM–based borewell rescue system introduces a faster and safer alternative to traditional excavation methods. It combines real-time VGA video streaming with a compact mechanical design suitable for narrow environments. Low-latency communication using WebSocket and PSRAM enables quick decision-making during rescue operations. A PWM-controlled lighting system enhances visibility in dark conditions. High-torque servo grippers ensure secure and stable victim handling. The system also includes a fail-safe mechanism to prevent unintended actions during signal loss. Compared to conventional techniques, it reduces rescue time and environmental disruption. Overall, it provides an efficient and scalable solution for modern rescue operations.

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