International Journal of
AI Electronics and Nexus Energy
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0515 www.zesterapublications.com Original Research Paper

TorqueMax-RS: An IoT-Synchronized Deep-Shaft Robotic Extraction Framework for Borewell Emergency Intervention

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ABSTRACT

Rescuing victims trapped in deep and narrow borewells is highly challenging due to confined space, lack of visibility, and the inability of humans to access such environments directly. To overcome these limitations, this work proposes a compact and remotely operated Borewell Rescue Robot (BRR) developed using an Espressif Systems Processor (ESP32-CAM) Microcontroller Unit (MCU), designed to provide real-time monitoring and precise control during rescue operations. The system integrates live video streaming with mechanical actuation through a wireless interface, allowing operators to guide the robot safely from a remote location. A 32-bit embedded processor supported by Pseudo-Static Random Access Memory (PSRAM) enables smooth Video Graphics Array (VGA) image transmission, while WebSocket-based communication ensures continuous and low-latency data exchange. The robotic mechanism utilizes dual high-torque servo motors for gripping and positioning, enabling accurate manipulation within confined vertical shafts. To address poor lighting conditions, a Pulse Width Modulation (PWM) controlled Light Emitting Diode (LED) system is incorporated for effective illumination. The software follows an asynchronous, event-driven architecture using the ESPAsyncWebServer framework, allowing simultaneous handling of video streaming and control commands without delays. Additionally, a fail-safe mechanism is implemented to reset actuators and disable critical components in case of communication loss, ensuring safety and reliability. The system operates through a Wireless Fidelity (Wi-Fi) Access Point (AP), eliminating dependency on external infrastructure and enabling deployment in remote locations, making it a scalable and efficient solution for emergency 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 use of groundwater across India has led to the rapid increase in borewell installations, which are deep, narrow shafts primarily constructed for irrigation and domestic water supply. Although these structures are essential for supporting agricultural productivity and rural communities, they pose significant risks when left uncovered, partially sealed, or abandoned. Due to their small diameter and considerable depth, often exceeding 100 feet, accidental falls—especially involving children—create extremely dangerous situations where conventional human intervention becomes nearly impossible. To address this critical safety concern, this work presents the design of a Borewell Rescue Robot (BRR) built using an Espressif Systems Processor (ESP32-CAM) Microcontroller Unit (MCU). The system is specifically developed to operate in confined vertical environments and assist rescue teams by providing real-time visual feedback and controlled mechanical interaction for victim retrieval.

The robot integrates a compact embedded system equipped with Pseudo-Static Random Access Memory (PSRAM), enabling continuous Video Graphics Array (VGA) resolution streaming for clear and stable visualization of the borewell interior. A Wireless Fidelity (Wi-Fi) Software Access Point (SoftAP) is utilized to establish direct communication between the robot and the operator, while WebSocket protocol ensures uninterrupted, low-latency data transmission for synchronized control and monitoring. This eliminates dependency on external communication infrastructure, making the system suitable for remote and rural deployment.

Traditional rescue methods, such as excavating a parallel pit adjacent to the borewell, are highly time-consuming, labor-intensive, and often constrained by soil conditions and equipment availability. These delays significantly reduce survival chances due to factors such as oxygen depletion, dehydration, and hypothermia. Numerous incidents reported across different regions highlight the urgency of adopting faster and more reliable rescue mechanisms. In response, the proposed system incorporates Pulse Width Modulation (PWM)-controlled actuators and high-torque servo motors that enable precise gripping and positioning within the restricted borewell space. A high-intensity Light Emitting Diode (LED) illumination system is integrated to enhance visibility in dark underground conditions, allowing accurate operation.

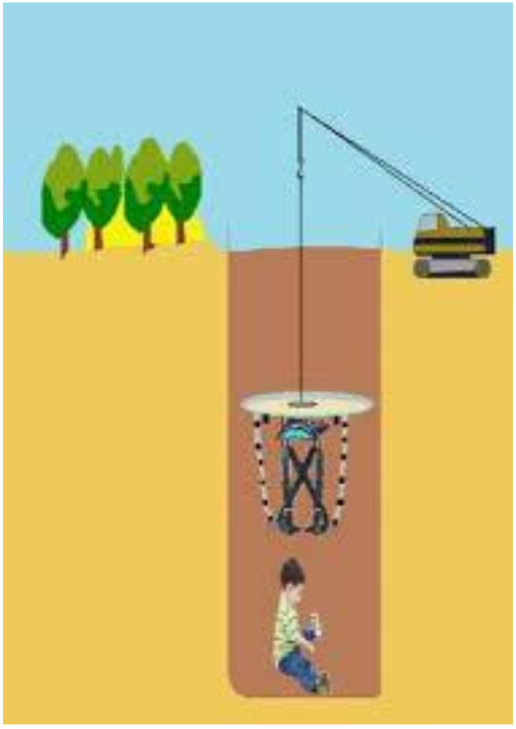

Fig. 1: Borewell Rescue System

The software architecture is based on an asynchronous, event-driven model, allowing simultaneous processing of video streaming and control commands without blocking execution. This ensures smooth and responsive system performance even during continuous operation. Additionally, a fail-safe mechanism is implemented to automatically reset actuators and disable high-power components in the event of communication loss or system malfunction, ensuring operational safety. By combining real-time monitoring, precise actuation, and rapid deployment capability, the proposed robotic system offers a practical, scalable, and cost-effective solution for borewell rescue operations, significantly improving efficiency and increasing the likelihood of successful victim recovery.

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

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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.
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

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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, 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 system architecture is designed as a tightly integrated, real-time embedded vision and control framework centered on the ESP32-CAM (AI-Thinker) module, which unifies camera acquisition, wireless networking, WebSocket-based communication, memory management, and hardware actuation into a single cohesive pipeline. The ESP32-CAM interfaces with the OV2640 camera sensor through a parallel camera bus (signals such as D0–D7, XCLK, PCLK, VSYNC, HREF, SIOD, SIOC), and image capture is handled via the esp_camera driver using configurations like PIXFORMAT_JPEG and FRAMESIZE_VGA to balance image quality and transmission efficiency as illustrated in Fig. 2. Captured frames are stored in frame buffers allocated in PSRAM using functions such as psram_malloc and heap_caps_malloc with external memory enabled, ensuring that continuous streaming does not exhaust internal SRAM. The system operates in Wi-Fi Access Point (SoftAP) mode, broadcasting a predefined SSID and password, allowing a mobile device or browser to connect directly and access the hosted web interface via a fixed IP address, thereby eliminating dependency on external routers and minimizing communication latency.

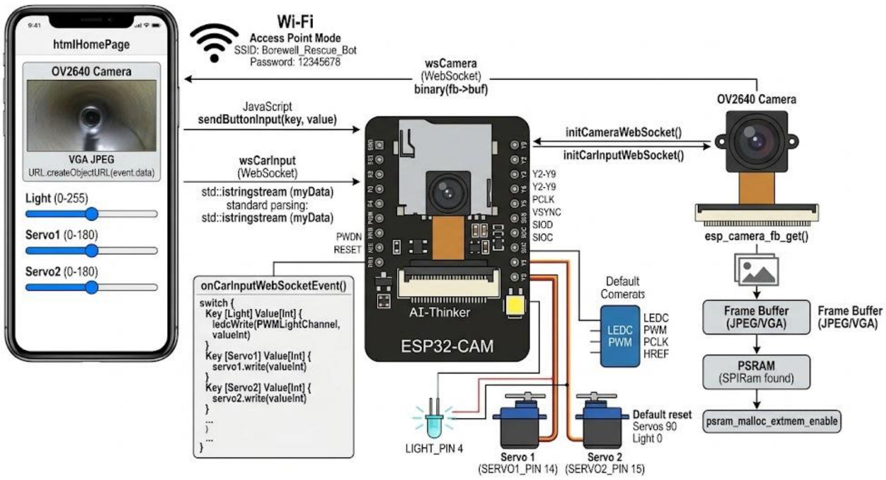

Fig. 2: Proposed system architecture

The web interface provides a live camera feed along with interactive controls for LED brightness (0–255 range) and servo motor angles (0–180 degrees), with user interactions captured through JavaScript functions such as sendButtonInput(key, value). These inputs are transmitted via a WebSocket channel (wsCarInput) as structured key-value strings, enabling low-overhead, event-driven communication. On the ESP32-CAM side, the onCarInputWebSocketEvent handler receives incoming data, performs parsing using string stream techniques, extracts control parameters, and validates them before execution. The control logic maps these parameters to hardware actions, where LED brightness is controlled using LEDC PWM channels (ledcWrite on LIGHT_PIN, typically GPIO 4), and servo motors (e.g., SG90) are driven using PWM signals generated through libraries such as ESP32Servo, connected to designated GPIO pins (e.g., GPIO 14 and GPIO 15). In parallel, a separate WebSocket

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channel (wsCamera) is responsible for transmitting binary image data (frame buffer content) to the client, ensuring continuous real-time video streaming. The function esp_camera_fb_get() retrieves frame buffers, which are then sent as binary payloads over the WebSocket, allowing efficient rendering of live video in the browser. Initialization routines such as initCameraWebSocket() and initCarInputWebSocket() configure these communication channels, while the main loop continuously handles client management, cleans up inactive connections, streams frames, and processes incoming commands without blocking execution. The architecture ensures concurrency through asynchronous event handling, enabling simultaneous streaming and control operations. Memory optimization techniques, including PSRAM utilization and buffer reuse, are critical for maintaining stability during high-frequency data transfer. The separation of streaming and control pathways reduces latency and improves responsiveness. Overall, the system demonstrates a robust integration of sensing, networking, processing, and actuation layers, delivering a scalable, low-latency, and efficient real-time embedded control solution.

4. RESULTS AND DISCUSSION

4.1 SOFTWARE IMPLEMENTATION

Fig. 3 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

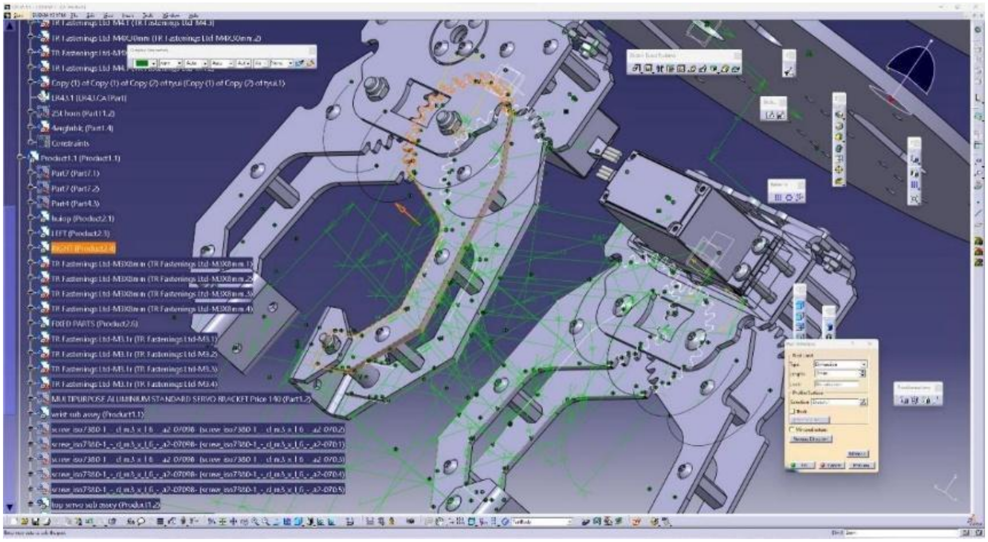

Fig. 3: CAD-Based Robotic Assembly and Kinematic Design

Fig. 4 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.

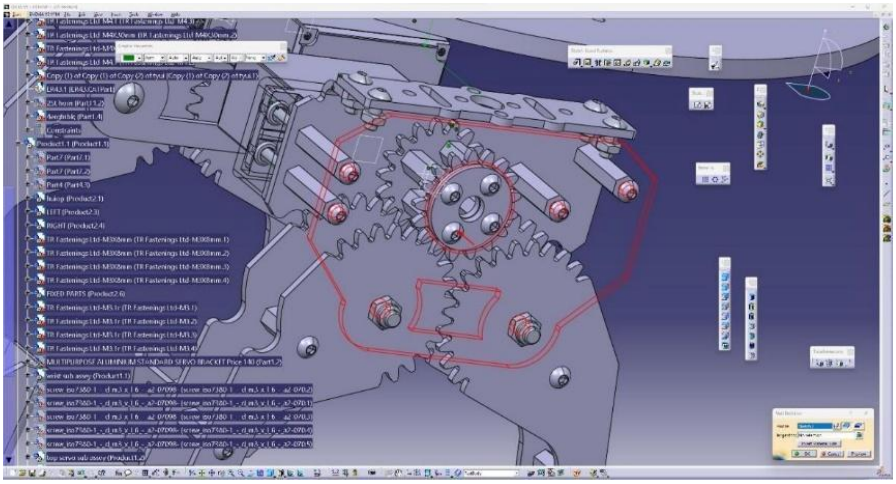

Fig. 4: CAD Model of Gear-Driven Robotic Linkage Mechanism

Fig. 5 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.

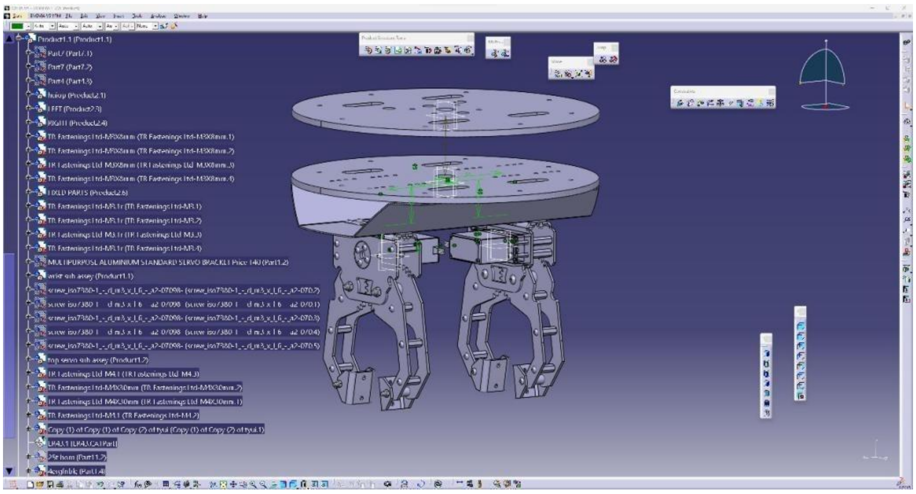

Fig. 5: CAD Model of Multi-Layer Robotic Platform with Dual Gripper Assembly

4.2 HARDWARE IMPLEMENTATION

Fig. 6 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.

Received: 09-03-2026 | Accepted: 16-04-2026 | Published: 23-04-2026

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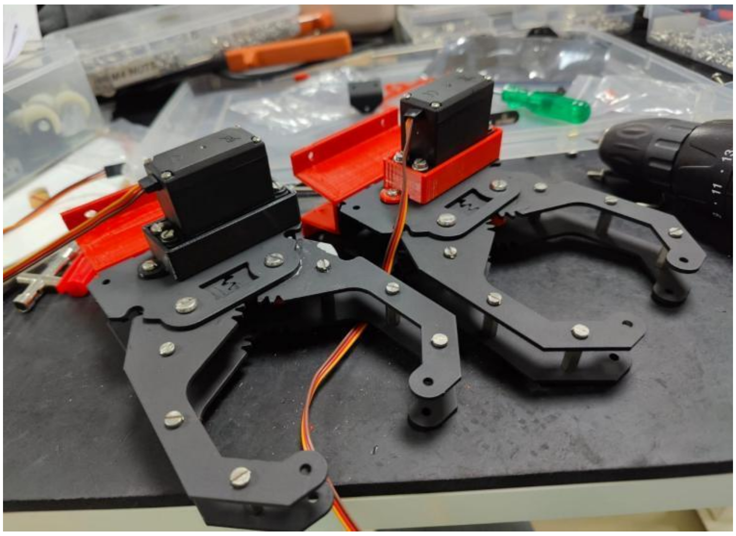

Fig. 6: Dual Servo Motor Gripper Mechanism for Robotic Manipulation

Fig. 7 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.

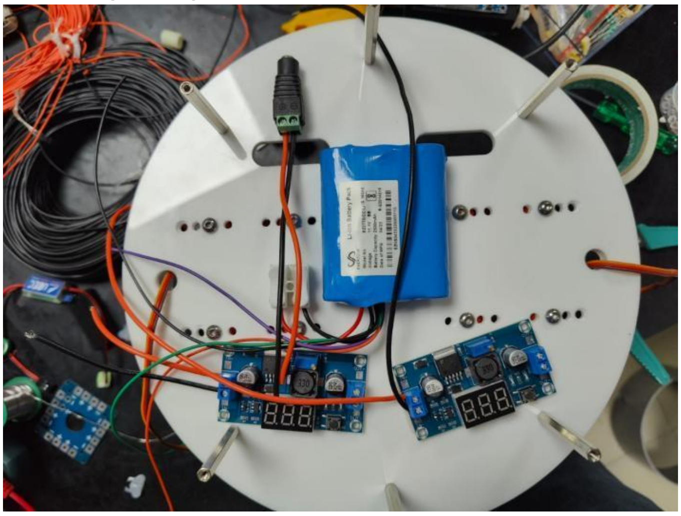

Fig. 7: Power Distribution Module with Battery Pack and Voltage Regulation Units

Fig. 8 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.

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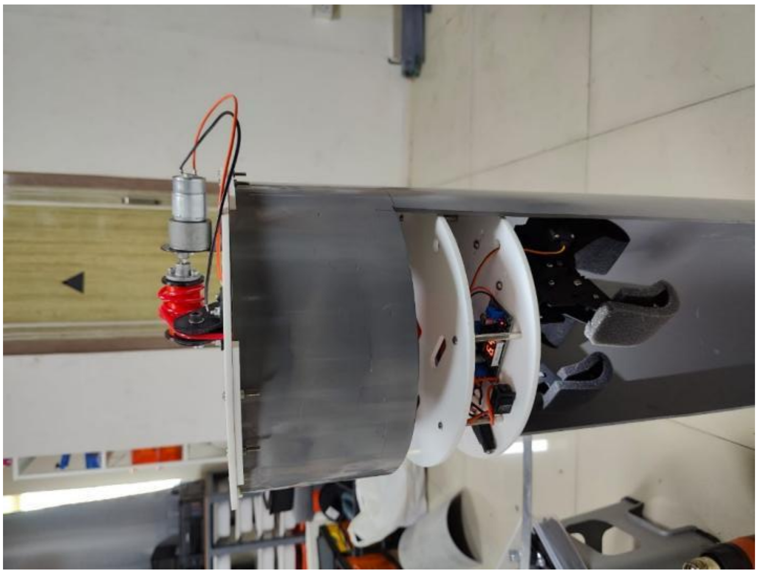

Fig. 8: Cylindrical Robotic Assembly with DC Motor-Driven Mechanism and Multi-Level Structural Platform

Fig. 9 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.

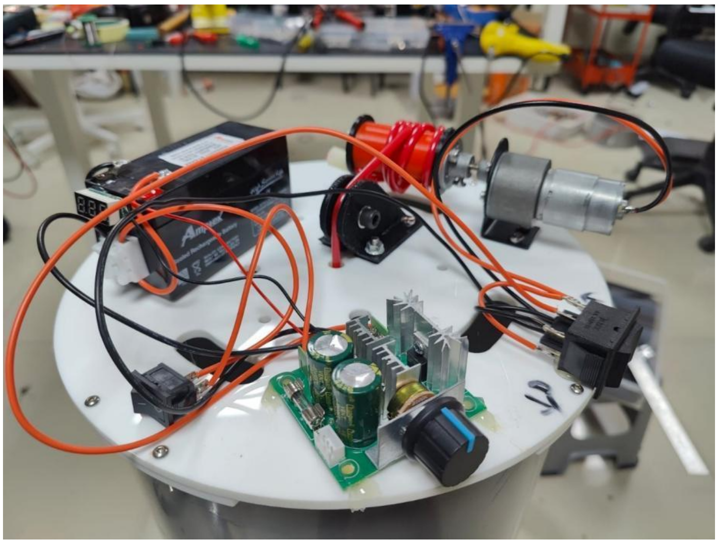

Fig. 9: Integrated Control and Actuation Module with DC Motor, Servo Assembly, and Power Regulation Circuit.

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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