

## SmartBoreRescue: A Semi-Autonomous Vertical Mobility Robot with Vision-Assisted Rescue Mechanism

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### ABSTRACT

Rescue operations in deep and narrow borewells present severe challenges due to restricted access, poor visibility, and the inability of humans to intervene directly. This work introduces a compact and remotely operated Borewell Rescue Robot (BRR) developed using an ESP32-CAM Microcontroller Unit (MCU) to enable safe and efficient victim retrieval. The system integrates real-time visual monitoring and precise actuation through a wireless control interface. A 32-bit embedded processor equipped with Pseudo-Static Random Access Memory (PSRAM) supports continuous Video Graphics Array (VGA) resolution streaming, which is transmitted using WebSocket-based communication to ensure minimal latency and stable feedback. The robotic mechanism employs dual high-torque servo motors responsible for gripping and positioning tasks, enabling controlled manipulation within confined vertical spaces. Illumination in low-light environments is achieved using a Pulse Width Modulation (PWM) controlled Light Emitting Diode (LED) module, enhancing visibility for accurate operation. The software architecture is implemented using an asynchronous, event-driven model through the ESPAsyncWebServer library, allowing concurrent handling of video transmission and control commands without blocking execution. Additionally, a fail-safe mechanism is incorporated to automatically reset actuators and deactivate critical components in case of communication loss, ensuring operational safety. The system operates through a Wireless Fidelity (Wi-Fi) Access Point (AP), eliminating dependency on external network infrastructure and enabling deployment in remote locations. This design demonstrates a reliable, scalable, and cost-effective robotic solution for emergency rescue scenarios, improving response efficiency in hazardous underground environments.

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

### 1. INTRODUCTION

The rapid decline in groundwater availability across India has resulted in the large-scale drilling of borewells, which are narrow, deep vertical shafts primarily used for irrigation and domestic water supply. Although these structures are essential for sustaining agriculture and rural livelihoods, they often become extremely dangerous when abandoned or left uncovered. In many cases, these borewells are only 10 to 12 inches in diameter but extend beyond 100 feet in depth, making them inaccessible for direct human rescue. This project proposes an ESP-based Borewell Rescue Robot (BRR), a compact and remotely operated system designed to safely navigate such confined environments and assist in victim retrieval through real-time monitoring and controlled mechanical interaction. The system is built around an ESP32-CAM Microcontroller Unit (MCU) integrated with Pseudo-Static Random Access Memory (PSRAM), enabling stable Video Graphics Array (VGA) streaming for continuous visual feedback. Communication is established using a Wireless Fidelity (Wi-Fi) Software Access Point (SoftAP) and WebSocket protocol, ensuring low-latency transmission without dependency on external infrastructure.

The need for such a system arises from the limitations of conventional rescue techniques, particularly the parallel excavation method, where a secondary pit is dug alongside the borewell. This process is slow, resource-intensive, and highly dependent on soil conditions, often taking several hours to days to reach the trapped individual. During this time, victims face severe risks such as oxygen depletion, dehydration, and hypothermia. Historical incidents across various regions in India have highlighted the urgency of faster and more reliable rescue solutions, especially as most victims are young children who accidentally fall into inadequately secured borewells. Data from national agencies indicates that such accidents have occurred repeatedly over the years, with a significant percentage resulting in fatalities due to delayed response.

To address these challenges, the proposed robotic system integrates Pulse Width Modulation (PWM)-controlled actuators and high-torque servo mechanisms for precise gripping and positioning within the narrow shaft. A high-intensity Light Emitting Diode (LED) illumination system is included to enhance visibility in dark underground conditions. The software architecture follows an asynchronous, event-driven model, allowing simultaneous handling of video streaming and control commands without blocking system performance. Additionally, a fail-safe mechanism is incorporated to ensure safety by resetting actuators and disabling high-power components in case of communication loss or system failure. By combining real-time visual feedback, precise control, and rapid deployment capability, this system offers a practical, cost-effective, and scalable solution for emergency rescue operations. It significantly improves response efficiency and provides a safer alternative to traditional methods, thereby contributing to better survival outcomes in borewell-related accidents.

## 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 system architecture as illustrated in Fig. 1, is structured as a fully integrated, event-driven embedded vision and control framework that unifies real-time image acquisition, wireless networking, web-based interaction, and hardware actuation using the ESP32-CAM as the central processing and communication unit. The ESP32-CAM incorporates the OV2640 camera sensor, which captures image frames through the esp\_camera driver using configurations such as VGA resolution and JPEG compression to balance quality and bandwidth efficiency, with frame buffers managed in PSRAM to sustain continuous streaming. The device operates in SoftAP mode, creating a self-hosted Wi-Fi network with a defined SSID and IP configuration, allowing direct client connection via a web browser without external infrastructure, thereby reducing latency and improving reliability in standalone deployments. An asynchronous web server is deployed to handle HTTP requests for webpage delivery and routing, while a WebSocket server enables persistent, low-overhead, bidirectional communication for real-time control and telemetry exchange. Distinct endpoints are defined, such as “/Camera” for binary video stream transmission and “/CarInput” for receiving structured text-based control commands, ensuring separation of data flows and efficient request handling.

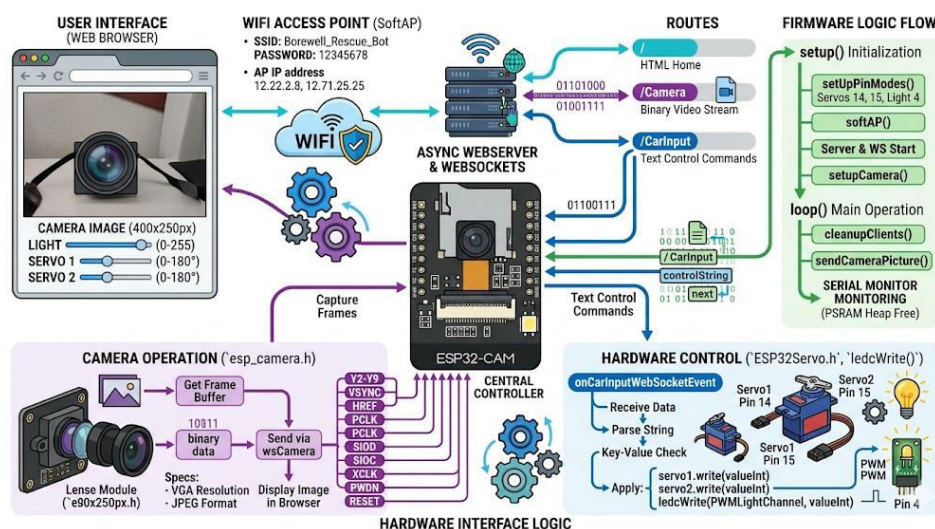


Fig. 1: Proposed system architecture

The user interface is designed as an interactive control dashboard that displays the live camera feed and provides adjustable controls for parameters such as illumination intensity and servo positioning, typically mapped to PWM ranges (e.g., 0–255 for LED brightness and 0–180 degrees for servo angles). These inputs are encoded into compact command strings and transmitted via WebSocket, where the ESP32-CAM processes them through an event-driven handler (onCarInputWebSocketEvent), performing parsing, key-value extraction, and validation before execution. The hardware control subsystem translates these commands into PWM signals using LEDC channels, enabling precise control of servo motors (e.g., SG90 or MG996R) and lighting elements connected to designated GPIO pins. The firmware architecture follows a structured lifecycle with a setup phase that initializes GPIO configurations, camera parameters, Wi-Fi SoftAP, and server instances, followed by a continuous loop phase that manages client connections, streams image frames, processes incoming commands, and performs memory housekeeping such as client cleanup and PSRAM monitoring.

The system ensures efficient concurrency by leveraging asynchronous communication, minimizing blocking operations and enabling simultaneous streaming and control execution. The routing and control logic maintain internal state variables for tracking current servo positions, light levels, and connection status, supporting consistent and responsive operation. Additionally, binary encoding of image data and optimized WebSocket transmission reduce communication overhead, enhancing frame rate and responsiveness. The architecture demonstrates a cohesive integration of perception, networking, processing, and actuation layers, providing a scalable and low-latency solution for real-time remote monitoring and control of robotic or embedded vision systems.

### 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 WebSockets rather than a traditional linear loop.

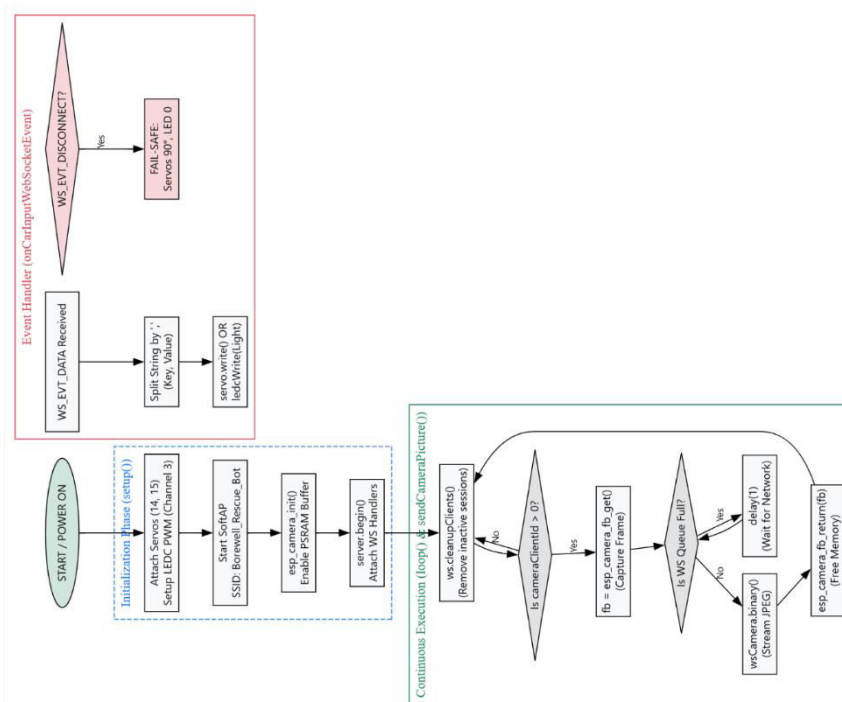


Fig. 2: Proposed operational flow and logic analysis.

#### 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.

### 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

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

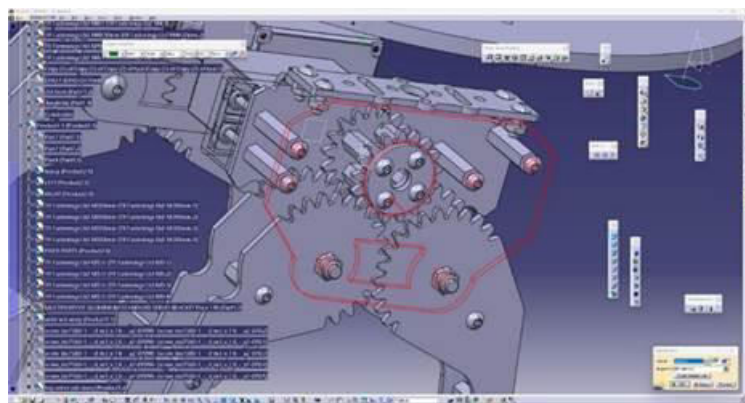


Fig. 4: CAD Model of Gear-Driven Robotic Linkage Mechanism

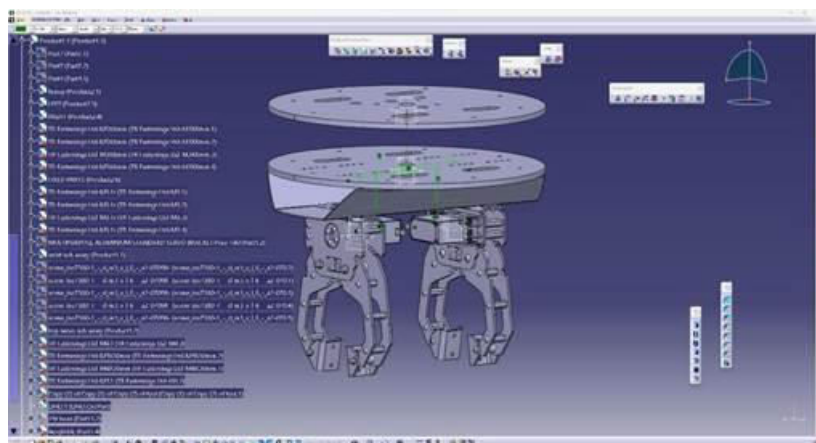


Fig. 5: CAD Model of Multi-Layer Robotic Platform with Dual Gripper Assembly

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.

## 4.2 HARDWARE IMPLEMENTATION

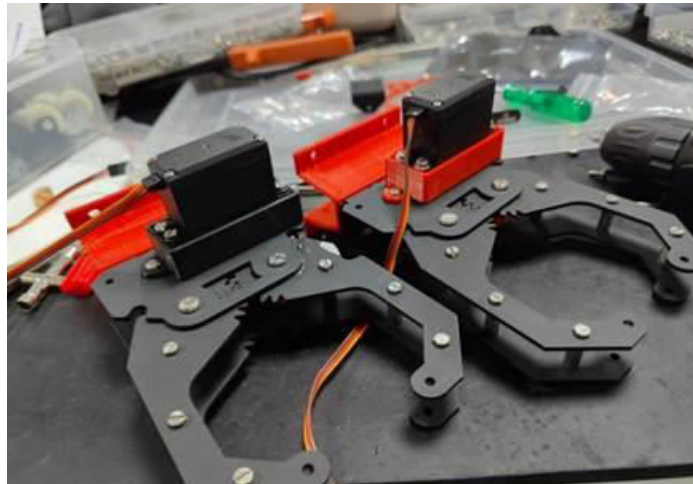


Fig. 6: Dual Servo Motor Gripper Mechanism for Robotic Manipulation

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.

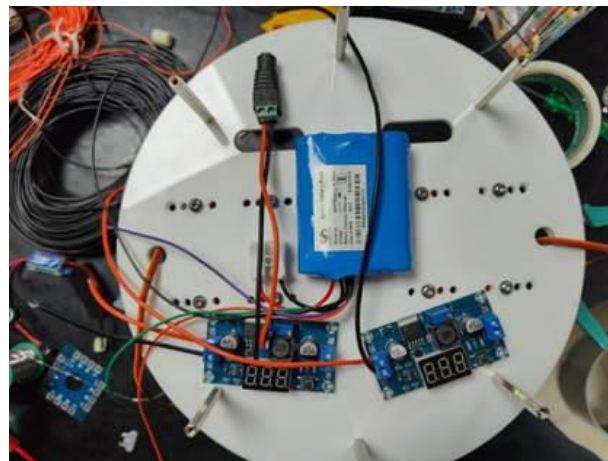


Fig. 7: Power Distribution Module with Battery Pack and Voltage Regulation Units

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

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.



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

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.

## 5. CONCLUSION

The ESP32-CAM based Borewell Rescue Bot demonstrates a modern shift toward safe and technology-driven rescue operations, replacing slow and risky excavation methods. The system integrates real-time Video Graphics Array (VGA) streaming with mechanical actuation in a compact and cost-efficient design suitable for narrow borewell environments. By using WebSocket communication and Pseudo-Static Random Access Memory (PSRAM), it delivers low-latency visual feedback essential for quick decision-making during emergencies. A Pulse Width Modulation (PWM)-controlled lighting setup and high-torque servo grippers improve visibility and enable stable victim handling. The inclusion of a fail-safe mechanism ensures operational safety by maintaining control even during signal interruptions. Compared to traditional methods, this approach offers faster deployment with minimal environmental disturbance. The system provides a scalable and practical solution for improving rescue efficiency and outcomes.

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