Full Length Article

An Intelligent Robotic System For Borehole Child Rescue Operations

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Abstract

Borewell accidents remain a critical safety issue in rural and semi-urban regions, where abandoned or uncovered borewells pose life-threatening risks, particularly to children. The narrow diameter, significant depth, poor visibility, and limited oxygen availability inside borewells make rescue operations extremely challenging and time-sensitive. Conventional rescue approaches, including rope-based retrieval and excavation of parallel pits, are time-consuming, hazardous, and lack real-time monitoring, thereby reducing the chances of safe recovery. To address these limitations, an intelligent robotic solution is proposed to enhance the efficiency, safety, and success rate of borewell rescue missions.This paper presents the design and implementation of an intelligent borewell rescue robot capable of performing safe and controlled child rescue operations. The system incorporates an ESP32-CAM module for real-time video surveillance within the borewell. Track-based DC motors, controlled through motor drivers, facilitate smooth vertical movement, while a servo-actuated gripper mechanism is designed to securely hold the trapped child. High-intensity LED illumination is integrated to improve visibility in low-light conditions, enabling accurate positioning and monitoring. The ESP32-CAM transmits live video footage to the operator, allowing continuous observation of the child's condition and robot maneuvering.During operation, the robot is lowered into the borewell using a cable or rope while the operator observes the live video stream. After locating the child, the servo-controlled gripper carefully secures the child, and the robot is gradually lifted to safely bring the child to the surface.The proposed intelligent rescue system significantly improves operational speed, precision, and safety compared to traditional methods. By combining real-time monitoring, remote control capability, and a secure gripping mechanism, the system enhances the probability of successful rescue. Furthermore, the proposed design can be extended for additional applications such as confined-space inspection, underground exploration, and disaster-response operations.

Keywords:
Borewell Rescue Robot, ESP32-CAM, Real-Time Video Monitoring, Robotics, Embedded Systems, Child Rescue System, Remote-Controlled Robot, Servo Motor, DC Motors, Motor Driver, Gripper Mechanism, IoT-Based Surveillance, Confined Space Rescue, Disaster Response Robotics, Wireless Communication, LED Illumination System, Safety Engineering, Automation in Rescue Operations, Smart Rescue Technology.

INTRODUCTION

Borewell accidents continue to pose a significant safety challenge, particularly in rural and semi-urban regions where abandoned or improperly sealed borewells are common. Children are especially vulnerable to such hazards, and several incidents reported across India highlight the severity of this issue. The confined diameter, substantial depth, absence of light, and limited oxygen availability inside borewells make rescue operations highly complex and time-sensitive. Conventional rescue techniques, such as rope-based retrieval methods or digging adjacent pits, are often slow, labor-intensive, and risky. These approaches also lack proper monitoring capabilities, which reduces the chances of safe recovery. Furthermore, manual rescue attempts become increasingly ineffective as the borewell depth increases, due to positioning challenges and the distressed condition of the trapped child.Recent advancements in robotics and embedded systems have opened new possibilities for rescue operations in hazardous and confined environments. Robotic systems equipped with cameras, sensors, and remote-control mechanisms can operate in spaces where human intervention is impractical or dangerous. In borewell rescue scenarios, such robotic devices can be deployed into narrow shafts to identify the trapped child, monitor environmental conditions, and assist in extraction. Real-time video feedback further enables rescue teams to make informed decisions and perform controlled operations.To address the limitations of traditional rescue techniques, this work proposes an intelligent robotic system designed specifically for borewell child rescue operations. The system utilizes an ESP32-CAM module to provide live video streaming from inside the borewell, allowing operators to accurately determine the child's location. The robotic unit is equipped with motor-driven movement and a servo-controlled gripper mechanism that gently secures the child during extraction. By integrating real-time monitoring, precise control, and automated operation, the proposed system aims to enhance rescue efficiency and safety. Experimental evaluation under controlled conditions indicates improved performance compared to conventional manual methods, with reduced rescue time and higher success probability

LITERATURE SURVEY

Several researchers have proposed technological solutions to improve borewell rescue operations. S. Akhila, P. Lavanya, S. Pavithra, S. Yashwanth, and S.K. Umar Faruq (2025) presented an IoT-based borewell child rescue system incorporating ESP32 and ESP32-CAM modules for live monitoring. Their approach integrates environmental sensors and oxygen supply mechanisms to assist rescue teams by transmitting real-time data. Although the design improves monitoring capabilities, limited emphasis is placed on controlled robotic manipulation for safe child extraction. The present work focuses on improving this aspect through a simplified robotic mechanism with a servo-operated gripper and controlled movement for precise handling [1].

Nagashwini, Arun, Hemanth Kumar, Pradeep Kumar M., and R. Santosh Kumar (2024) developed a smart borewell rescue system that incorporates artificial intelligence and wireless communication for child detection. Their work enhances detection accuracy and monitoring efficiency; however, the mechanical rescue mechanism is not extensively addressed. The proposed system complements this limitation by incorporating direct robotic intervention supported by real-time video feedback and a secure gripping mechanism for extraction [2].

Prakash Rao and Rupa Devi (2022) introduced a smart borewell rescue mechanism using embedded control techniques. Their system integrates cameras, robotic arms, and communication modules for remote rescue operations. While their approach enhances monitoring and control, the design complexity increases deployment difficulty. The proposed work presents a compact and practical alternative using ESP32-CAM-based monitoring and a simplified mechanical structure suitable for narrow borewell environments [3].

Tejaswini S. Mane, Prashant A. Kale, Shreyas S. Karale, Neeraj S. Kamble, and Prathamesh B. Aher (2021) proposed a robotic device equipped with sensors and cameras to assist borewell rescue operations. Their system mainly focuses on environmental monitoring and robotic positioning. In comparison, the proposed design introduces an improved child-handling mechanism using a servo-based gripper, which enhances safety and reliability during extraction [4].

OBJECTIVE

The primary objective of this project is to design and develop an intelligent robotic system capable of performing safe and efficient child rescue operations in deep and narrow borewells. The system employs an ESP32-CAM module for real-time video surveillance, enabling rescue personnel to monitor the trapped child and accurately control the robot. Additionally, the robotic platform incorporates controlled movement and a servo-actuated gripping mechanism to ensure safe handling during extraction. The proposed design aims to reduce rescue time, improve operational safety, and increase the likelihood of successful rescue missions.

ORGANISATION OF THE REPORT

This report is organized as follows. Chapter 1 presents the introduction and overview of the proposed project. Chapter 2 discusses embedded systems, including their fundamentals, importance, and applications. Chapter 3 provides a detailed description of the hardware components used in the system. Chapter 4 explains the software implementation, including development using Arduino IDE and Android-based control. Chapter 5 presents the system block diagram and its operational flow. Chapter 6 describes the hardware modules, testing procedures, and experimental results of the proposed system.

Embedded Systems

An embedded system is a specialized computing system designed to perform a dedicated function within a larger mechanical or electrical system. Unlike general-purpose computers, embedded systems are optimized for specific tasks and often operate under real-time constraints. These systems integrate hardware and software components to provide efficient, reliable, and cost-effective solutions for particular applications. Embedded systems are widely used in modern electronic devices such as consumer appliances, industrial automation equipment, medical instruments, and robotic platforms.

Most embedded systems are built around microcontrollers, microprocessors, or digital signal processors (DSPs). These processing units control system operations by executing programmed instructions stored in memory. Because embedded systems are designed for specific tasks, engineers can optimize them for reduced power consumption, compact size, improved reliability, and lower production cost. In addition, many embedded systems operate continuously with minimal human interaction, making stability and real-time performance essential design considerations.

Embedded systems vary in complexity, ranging from simple single-chip controllers to sophisticated multi-processor configurations. Simple systems may control basic functions such as switching or monitoring, while complex embedded platforms manage advanced operations such as robotics, automation, and communication. In the proposed borewell rescue robot, the embedded system plays a crucial role in controlling movement, video streaming, lighting, and gripping mechanisms.

History of Embedded Systems

The concept of embedded systems evolved from early computing machines developed in the mid-20th century. Initially, computers were large, expensive, and designed for single-purpose operations. As semiconductor technology advanced, compact and efficient computing devices became possible. One of the earliest modern embedded systems was the Apollo Guidance Computer, developed for NASA's Apollo space missions. This system used integrated circuits to reduce size and weight while providing reliable navigation control.

During the 1960s and 1970s, embedded systems began appearing in industrial and military applications. With the development of microprocessors and microcontrollers, embedded technology became more affordable and accessible. Today, embedded systems are integrated into nearly every electronic device, including robotics, smart appliances, communication systems, and safety equipment.

HARDWARE COMPONENTS

This chapter describes the hardware elements used in the proposed Intelligent Robotic System for Borewell Child Rescue Operations. Each component is selected based on reliability, operational safety, compact size, and suitability for deep and narrow borewell environments. The hardware setup includes power supply, vision system, motor driving unit, robotic gripping mechanism, sensing unit, lighting module, and wireless control interface. These components work together to ensure efficient monitoring and safe rescue operations.

The major hardware components used in the system are:

Battery Supply

Fig.1 Battery supply

The battery acts as the primary power source for the entire robotic system. It provides regulated DC voltage required for operating controllers, sensors, motors, and lighting components. A rechargeable battery is preferred to ensure portability and uninterrupted operation in remote rescue locations where external power sources may not be available. Compact size, stable output, and reliability make it suitable for mobile robotic applications.

Specifications

- Type: Rechargeable Sealed Lead Acid (SLA) Battery
- Rated Voltage: 12V
- Capacity: 1Ah
- Charging Voltage: 13.5V – 13.8V

ESP32-CAM Module

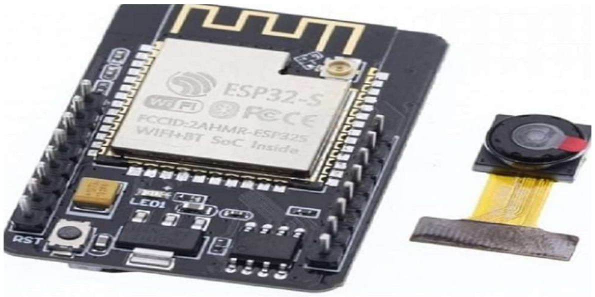


Fig.2 ESP32 Camera Module

The ESP32-CAM is a compact embedded vision module that integrates an ESP32 microcontroller with Wi-Fi connectivity and a camera interface. It is capable of capturing images and streaming live video over a wireless network. The module supports real-time monitoring and remote control, making it suitable for surveillance and robotic applications. Due to its small size and built-in communication capabilities, it is widely used in embedded monitoring systems.

DC Motor

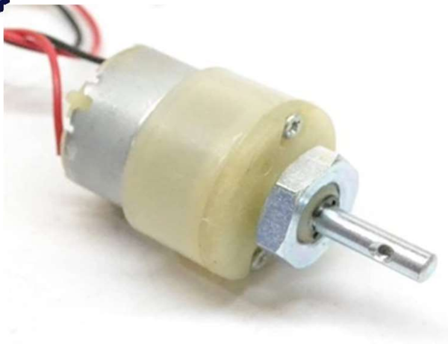


Fig.3 DC Motor

A DC motor is an electromechanical device that converts electrical energy into rotational mechanical motion. It operates based on electromagnetic principles, where current flowing through a conductor in a magnetic field generates torque. DC motors are widely used in robotic systems because of their simple control, reliability, and continuous rotation capability.

In the proposed system, DC motors are used to drive the movement of the robotic structure. They provide the required torque to perform mechanical operations smoothly and efficiently.

Specifications

- Type: Brushed DC Geared Motor
- Operating Voltage: 6V – 12V
- Speed: 100 – 300 RPM
- Current Consumption: 200 mA – 500 mA
- Output: Rotational Motion

Motor Driver (L298N)

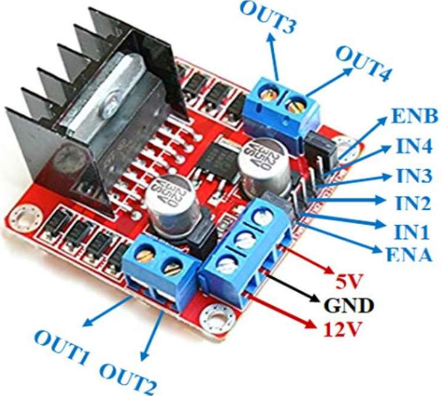


Fig.4 DC Motor driver (L298N)

A motor driver is required to control DC motors because microcontrollers cannot supply sufficient current directly. The L298N dual H-bridge motor driver acts as an interface between the controller and motors. It allows control of motor direction and speed through digital input signals and PWM control.

Specifications

- Driver IC: L298N Dual H-Bridge
- Operating Voltage: 5V – 35V
- Maximum Output Current: 2A per channel
- Logic Voltage: 5V
- Control Inputs: IN1, IN2, IN3, IN4
- Enable Pins: ENA, ENB

Pin Description

- VCC: Motor supply voltage input
- 5V: Logic power supply
- GND: Common ground connection
- ENA, ENB: Enable pins for motor speed control
- IN1, IN2: Motor A direction control
- IN3, IN4: Motor B direction control
- OUT1, OUT2: Motor A output terminals
- OUT3, OUT4: Motor B output terminals

The motor driver ensures safe and efficient motor control for robotic movement.

Robotic Arm with Gripper

Fig.5 Gripper Mechanism

The robotic gripper is a mechanical end-effector used to grasp and hold objects. It is mounted at the end of the robotic arm and acts as the main rescue component. The gripper opens and closes using a motor-driven mechanism. When the motor rotates in one direction, the jaws close to hold the object, and reverse rotation opens the jaws.

This mechanism allows gentle and controlled handling of the trapped child, ensuring safe extraction from the borewell.

Specifications

- Mechanism Type: Two-finger claw gripper
- Material: Lightweight aluminum/plastic
- Actuation: Servo motor / DC motor
- Load Capacity: 200 g – 1 kg
- Control Method: Motor driver / PWM

Gas Sensor

Fig 6 Gas Sensor

A gas sensor is used to detect harmful gases present inside the borewell. It converts gas concentration levels into electrical signals that can be processed by the controller. In rescue operations, monitoring air quality is important to ensure the safety of the trapped child.

If dangerous gases are detected, the system can generate alerts, enabling rescue teams to take appropriate precautions.

High Power LEDs

Fig 7 Power LEDs

High power LEDs provide bright illumination inside the borewell. Since borewells have very low visibility, proper lighting is required for clear video capture. These LEDs consume low power while producing high-intensity light. A driver circuit is used to regulate current and protect the LEDs.

The lighting system improves camera visibility and helps operators monitor the rescue process effectively.

Software Description

The software component plays a crucial role in controlling, coordinating, and integrating all hardware modules of the proposed borewell rescue robot. It acts as the backbone of the system, enabling communication between different components such as the camera, motors, lighting system, and gripper mechanism. The entire system is developed using Embedded C programming and implemented through the Arduino IDE, which provides a user-friendly platform for writing, compiling, and uploading code to the microcontroller. The ESP32-CAM module serves as the central controller of the system, responsible for handling real-time video streaming, wireless communication, motor control, LED lighting, and gripper operations. This integration ensures that the robot operates efficiently and responds accurately to user commands.

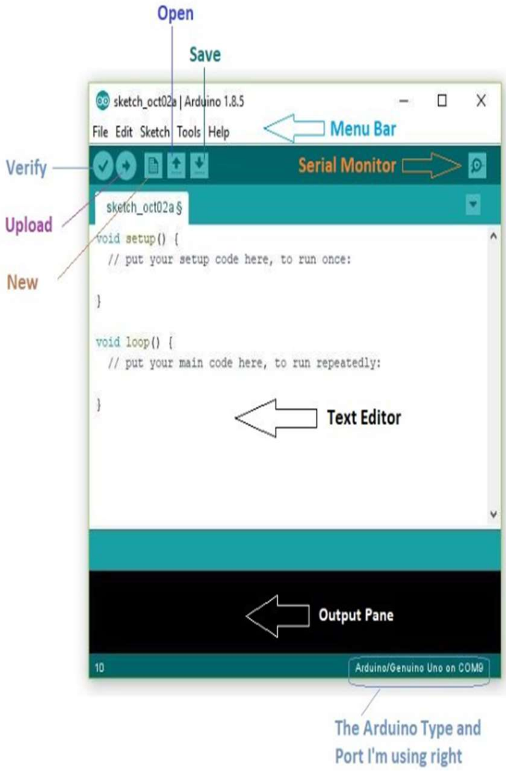
The software tools used in this project include Embedded C as the programming language, the Arduino IDE for code development and compilation, the ESP32 board package for enabling compatibility with the ESP32-CAM module, and a web browser interface that allows the operator to control the robot and monitor live video. The ESP32-CAM program is designed to establish a Wi-Fi connection and host a web server. Once connected, the operator can access this server through a mobile or computer browser, which acts as a control interface. At the same time, the onboard camera streams live video from inside the borewell, enabling real-time monitoring and precise control of the robot's movements.

Embedded C is a specialized version of the C programming language specifically designed for embedded systems and microcontroller-based applications. It allows direct interaction with hardware components such as GPIO pins, sensors, motors, and communication modules. Due to its efficiency, low memory consumption, and fast execution speed, Embedded C is widely used in real-time and IoT-based systems. In this project, Embedded C is used to program the ESP32-CAM microcontroller, enabling it to perform multiple tasks simultaneously. These tasks include establishing Wi-Fi connectivity, initializing the camera module, controlling DC motors for movement, operating LEDs for illumination, and processing commands received from the web interface.

The software architecture is designed to ensure smooth and reliable operation of the rescue robot. When the system is powered on, the ESP32-CAM initializes and connects to a Wi-Fi network. It then starts a web server that provides a user interface for the operator. Through this interface, the operator can send commands such as moving the robot up or down, activating the gripper, or turning on the LED lights. The microcontroller processes these commands and triggers the corresponding hardware components in real time. Simultaneously, the camera continuously captures and transmits video footage, allowing the operator to observe the borewell environment and make precise decisions during the rescue operation.

The use of Embedded C offers several advantages in this system, including efficient memory utilization, fast execution, direct hardware control, and high reliability for real-time applications. Additionally, the modular structure of the code allows easy modification and scalability for future enhancements. Overall, the software component ensures seamless coordination between hardware and user control, making the borewell rescue robot intelligent, responsive, and effective in performing safe rescue operations.

Arduino IDE



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Fig 8 Arduino IDE Programming Interface

Arduino IDE is an open-source development environment used for writing, compiling, and uploading programs to microcontroller boards. It provides a simple interface along with built-in libraries that simplify embedded system development.

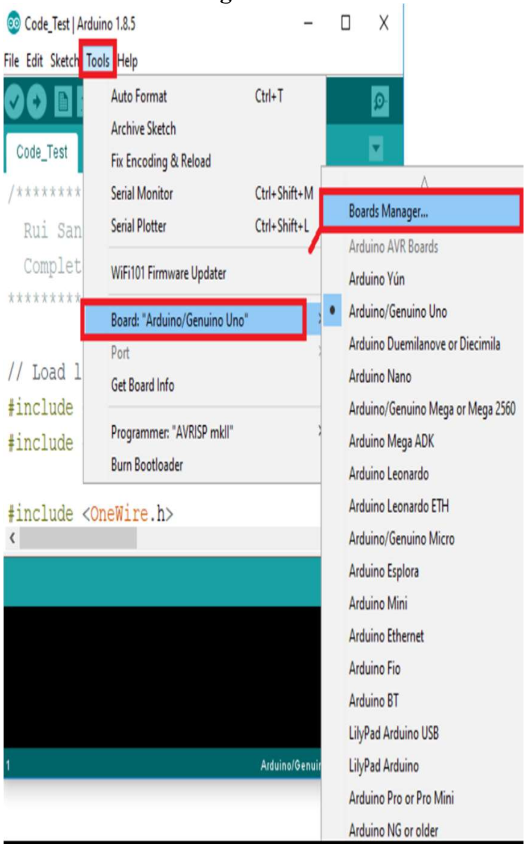
In this project, Arduino IDE is used to program the ESP32-CAM module. The code written in Embedded C controls the camera, motors, LED lighting, and communication system. After writing the program, the IDE compiles the code and uploads it to the ESP32-CAM using a USB-to-TTL converter.

Key features of Arduino IDE include:

- Built-in compiler
- Syntax error detection
- Serial Monitor for debugging
- Board Manager for hardware support
- Cross-platform compatibility

The Serial Monitor is used to verify Wi-Fi connectivity and monitor debugging messages during program execution. This helps in testing and troubleshooting the system

ESP32 Board Package



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// Load l
#include
#include

#include <OneWire.h>
```

Fig 9 ESP32 Board Manager in Arduino IDE

The ESP32 board package enables Arduino IDE to support ESP32-based microcontrollers. It contains device drivers, libraries, and configuration files required for programming ESP32 modules.

After installing the ESP32 board package, the Arduino IDE can recognize the ESP32-CAM module. The AI Thinker ESP32-CAM board option is selected before uploading the program.

Features supported by the ESP32 board package:

- Wi-Fi connectivity
- Bluetooth communication
- Camera interface support
- GPIO control
- Real-time processing capability

To install the ESP32 board package, the following URL is added in Arduino IDE preferences:

https://dl.espressif.com/dl/package_esp32_index.json

Once installed, the ESP32-CAM module can be programmed directly from the Arduino IDE.

Web Browser Interface

Fig 10 Web Browser Interface for Robot Control

The web browser interface allows wireless control of the rescue robot. The ESP32-CAM acts as a web server and hosts a control webpage. The operator accesses this page through a smartphone or computer browser.

When the ESP32-CAM connects to Wi-Fi, it generates an IP address. Entering this IP address in a browser opens the control interface. The webpage includes buttons for controlling robot movement, gripper operation, and LED lighting.

Control options available:

- UP – moves robot upward
- DOWN – moves robot downward
- OPEN – opens gripper
- CLOSE – closes gripper
- STOP – stops movement
- HEADLIGHT ON – turns LED on
- HEADLIGHT OFF – turns LED off

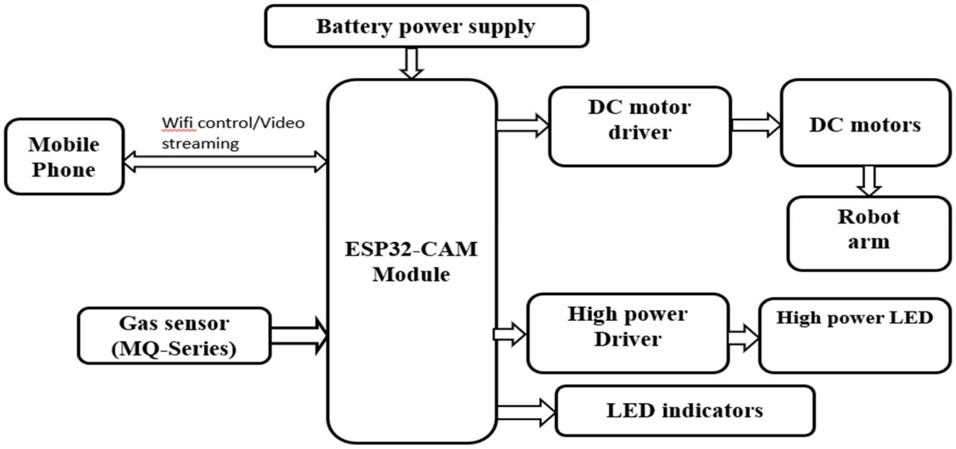
The interface also displays live video streaming from the camera, enabling real-time monitoring of the rescue process.

The webpage is created using HTML and JavaScript embedded inside the ESP32 program. When a button is pressed, an HTTP request is sent to the ESP32-CAM. The controller interprets the command and activates the respective hardware component.

This web-based control eliminates the need for a dedicated mobile application and simplifies system operation.

TECHNICAL ARCHITECTURE

Block Diagram



Block diagram

The block diagram shown in Fig. 5.1 illustrates the overall architecture of the intelligent robotic system designed for rescuing a child trapped inside a borewell. The system integrates sensing, control, communication, and actuation modules to perform rescue operations efficiently. The major components of the system include the ESP32-CAM module, motor driver circuit, DC motors, robotic arm mechanism, gas sensor, power LED, status LEDs, mobile control unit, and battery power supply.

The ESP32-CAM module acts as the central controller of the system. It receives commands from the mobile interface through Wi-Fi communication and controls the movement of the robotic arm using the motor driver. The camera attached to the ESP32-CAM provides live video streaming, enabling real-time monitoring of the borewell environment.

Power Flow

The power flow of the proposed rescue robot is designed to ensure stable and reliable operation of all modules. The battery serves as the primary energy source and distributes regulated DC power to each subsystem.

1. The battery power supply provides the main DC voltage required for operating the complete rescue robot. It ensures portability and independent operation in remote locations.
2. The supplied power is distributed to major hardware components including the ESP32-CAM module, gas sensor, motor driver, high-power LED, and LED

indicator circuits. This centralized power distribution simplifies system design.
3. The ESP32-CAM module receives regulated power from the battery and performs control operations such as wireless communication, video streaming, and command processing.
4. The gas sensor is powered continuously to monitor the borewell atmosphere and detect hazardous gases in real time. This improves operational safety.
5. The motor driver circuit receives power directly from the battery and supplies the required current to the DC motors. This allows smooth operation of the robotic arm.
6. The DC motors convert electrical energy into mechanical motion, enabling movement of the arm and gripper for rescue tasks.
7. The high-power LED unit obtains power from the battery supply and provides illumination inside the borewell, improving camera visibility.
8. LED indicators are powered to display system conditions such as power status, connectivity, and operational activity.
9. Overall, the battery power supply ensures efficient energy distribution and stable functioning of all subsystems within the borewell rescue robot.

Hardware Module

Fig. 11 Hardware Module

The hardware module of the intelligent borewell rescue robotic system, illustrated in represents the fully integrated prototype developed for rescue operations. The system combines mechanical, electronic, and communication components to enable remote monitoring and controlled manipulation inside a borewell environment.

Initially, the system is powered using a battery pack that supplies regulated DC voltage to all electronic modules. Once the power is switched ON, the ESP32-CAM module initializes and establishes a wireless connection for communication and video transmission. The initialization process activates all subsystems, including the motor driver, servo motor, camera module, and indicator LEDs.

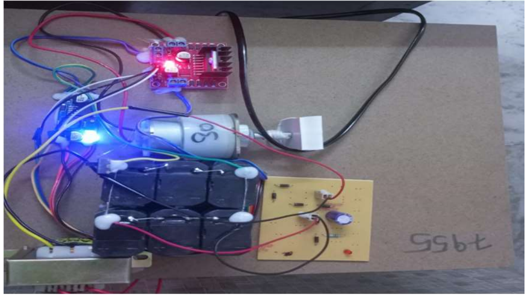


Fig. 12 Top View of Robotic Arm Assembly

The ESP32-CAM captures live video from inside the borewell and transmits it to a remote device such as a smartphone or laptop. This live feed allows the operator to observe the surroundings and determine the position of the trapped child in real time. Based on this information, control commands are issued from the mobile interface.

These commands are received by the ESP32-CAM module, which processes them and sends appropriate signals to the motor driver and servo motor. The motor driver controls the DC motors responsible for adjusting the vertical position of the robotic structure. This enables precise alignment of the robotic arm with the target location.

The robotic arm incorporates a gripper mechanism controlled by a servo motor. The servo provides accurate angular motion, allowing smooth opening and closing of the gripper. After proper positioning, the gripper is carefully closed to securely hold the child or object. Once the grip is established, the system can be gradually lifted to perform the rescue operation.

Indicator LEDs provide visual feedback regarding system status, such as power availability and operational mode. The integrated hardware module ensures safe, controlled, and efficient rescue operations through real-time monitoring and precise mechanical actuation.

Testing and Results

Fig. 13 System Power ON and Initialization

The intelligent borewell rescue robotic system was evaluated under different operational conditions to assess its performance, accuracy, and reliability. The testing procedure included validation of power supply, wireless communication, video monitoring, robotic movement, and gripping functionality. The results of these test cases demonstrate the effectiveness of the proposed design.

Case 3: Remote Control and Robotic Movement

Fig. 14 Robotic Arm and Gripper Operation

The third test focused on remote control functionality and movement of the robotic structure. Commands such as UP and DOWN were sent through the mobile interface to adjust the robot position.

The ESP32-CAM received these commands and transmitted control signals to the motor driver. The DC motors responded accordingly, enabling smooth upward and downward movement. This allowed accurate alignment of the robotic arm with the target. During this test, only positioning was evaluated, and the gripper mechanism remained inactive.

Case 4: Gripping and Rescue Operation

The final test examined the complete gripping and rescue process. Initially, the gripper remained in the open position, with the fingers expanded outward. After aligning the robotic arm with the target object, a CLOSE command was issued.

The servo motor rotated to close the gripper fingers, firmly holding the object. Once secured, the system was lifted gradually. The object remained stable during lifting without slipping, demonstrating effective gripping and controlled motion. This test confirmed the system’s capability to perform rescue operations safely

Results

The outcomes of the hardware testing are summarized in Table

Case	Test Performed	Input Command	System Response	Status
1	System Initialization	Power ON	All modules initialized	Successful
2	Live Video Streaming	Camera ON	Real-time video displayed	Successful
3	Remote Movement Control	UP / DOWN	Smooth vertical movement	Successful
4	Gripping and Rescue	OPEN / CLOSE + UP	Object gripped and lifted	Successful

The experimental results indicate that the proposed system performed reliably under all test conditions. The initialization process confirmed proper hardware setup. Real-time video streaming enabled effective monitoring of the borewell environment. Remote control commands provided smooth and accurate positioning of the robotic structure. The gripper mechanism successfully secured and lifted the object without slippage.

Overall, the developed borewell rescue robotic system demonstrated stable operation, precise control, and reliable performance, making it suitable for assisting in rescue operations.

Conclusion

The intelligent borewell child rescue robotic system was developed to provide a safer and more efficient approach for rescuing children trapped in borewells. The proposed system integrates real-time monitoring, wireless control, and a robotic manipulation mechanism to assist in rescue operations. The ESP32-CAM module enables live video streaming, allowing the operator to observe the borewell environment and guide the rescue process remotely using a mobile device.

The robotic arm equipped with a gripper mechanism demonstrated smooth and reliable operation during testing. The gripper was capable of securely holding and lifting the target object without slipping, ensuring stable handling. The system also successfully performed essential functions such as wireless communication, real-time monitoring, movement control, positioning, and gripping.

By minimizing direct human involvement, the proposed system reduces the risks associated with manual rescue attempts. The integration of real-time video feedback and precise mechanical control improves operational accuracy and safety. Based on experimental evaluation, the developed prototype proved to be reliable, practical, and suitable for real-time borewell rescue applications.

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