

A Safety-Oriented Multi-Functional Borewell Rescue Framework with a Stable Lifting Mechanism

B. Neeraja

Chaitanya Bharathi Institute of Technology, Hyderabad, India
bneeraja_ece@cbit.ac.in (corresponding author)

K. Vasanth

Chaitanya Bharathi Institute of Technology, Hyderabad, India
vasanthecek@gmail.com

Raja Kumari Chilukuri

Vallurupalli Nageswara Rao Vignana Jyothi Institute of Engineering & Technology, India
rajakumari_ch@vnrvjiet.in

T. Nagalaxmi

Stanley College of Engineering and Technology for Women, India
tnagalaxmi@stanley.edu.in

E. Chandrasekhar

Chaitanya Bharathi Institute of Technology, Hyderabad, India
chandrasekhar404@gmail.com

P. Udith Chandra Prasad

Chaitanya Bharathi Institute of Technology, Hyderabad, India
udithpulijala17@gmail.com

B. Bhavya Sree

Chaitanya Bharathi Institute of Technology, Hyderabad, India
bhavya4858@gmail.com

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ABSTRACT

Open borewells pose severe safety hazards due to their deep and narrow structure, making rescue operations challenging and time-sensitive. The rescuer faces difficulties due to the restricted location, low oxygen levels, and limited visibility, putting both the rescuer and the victim in peril. Therefore, the development and implementation of effective borewell rescue systems are crucial for improving safety measures and emergency response strategies. This study presents a novel borewell rescue system incorporating a multifunctional framework comprising air quality monitoring, a ventilation system, a robotic arm, and a support mechanism. The air quality monitoring system, equipped with sensors, a camera, and a communication device, assesses environmental conditions, enabling real-time interaction with the victim. Based on the collected data from sensors and cameras, a specially designed support mechanism is deployed, expanding upon reaching the victim's position to create a stable platform, preventing further descent, and minimizing injury risks. A robotic arm then carefully lifts the victim in a controlled manner, minimizing sudden movements and reducing injury risk. Additionally, a ventilation mechanism supplies fresh oxygen through narrow tubes, ensuring adequate air circulation. By incorporating automation, real-time analytics, and IoT-based monitoring, the measured values of gases,

humidity, and temperature at various depths indicate that as the depth of the borewell increases, the concentration of harmful gases rises. To address these challenges, the system supplies oxygen to the victim through narrow tubes, ensuring their survival until rescue is completed. These features make the system more effective and reliable compared to conventional rescue methods.

Keywords-borewell rescue system; Air quality monitoring; robotic arm; IoT; real-time monitoring; data visualization

I. INTRODUCTION

Borewells are crucial, especially in areas that lack surface water. They provide water that can be used for services such as drinking water supply, household use, agriculture, and industry. Borewells act as a significant water supply backup system in times of drought. However, there is a safety concern regarding children who fall into open or abandoned borewells. Borewells in India typically have diameters ranging from 6 to 8 inches and depths of approximately 300 to 500 feet. As a result, borewell rescue systems, specifically focused on dealing with the challenges of rescuing children stuck inside narrow and deep borewells, have emerged. Research has highlighted how these borewell accidents often happen in rural states of India, specifically agricultural states like Tamil Nadu, Gujarat, Madhya Pradesh, and Haryana.

When children accidentally fall into borewells, the need for instant rescue is of utmost importance for their survival. Authors in [1] proposed a preventive approach called Smart Child Rescue System (SCRS), which fits onto the top of the borewell to prevent children from falling inside by a closing mechanism, reducing the complexity of rescue; however, maintenance and cost are critical issues regarding this system. Authors in [2] proposed a prosthetic borewell rescue system integrating robotic arms and real-time monitoring to enhance safety. However, this system is still in a development stage: as automation and robotics advance, such systems will become more efficient, ensuring faster and more reliable emergency rescue operations.

Authors in [3] introduced an airbag-assisted pneumatic borewell rescue system for safety. This system is modular but relies on external power supplies for the airbags. Authors in [4] developed an Arduino-based smart borewell ambulance rescue system to detect and rescue children or animals trapped in borewells. However, its design faces challenges in terms of complexity, limited depth, and practical application in real life. Authors in [5] designed a robot-based system with real-time video monitoring and robotic arms to safely lift the child from the borewell. Although it has a very fast response and real-time surveillance, it faces challenges in the case of very narrow borewells and relies entirely on the durability of the robotic components. Most of the bores have harmful gases such as methane, carbon monoxide, and liquefied petroleum gas. Methane has a foul smell, and it displaces oxygen from confined spaces, resulting in asphyxiation. It also blocks the flow of oxygen in the body as carbon monoxide binds to the cytoglobin. LPG is often responsible for explosions or poisoning in confined spaces, even if it is mainly used for cooking and heating.

Many systems have emerged as solutions for borewell rescues by improving efficiency, safety, and reliability in

operations through technology. Authors in [6] presented an IoT-based borewell monitoring and child rescue system based on multi-sensor fusion. However, it depends heavily on sensor accuracy and cloud connectivity, which can cause delays in emergencies due to connectivity failures. Authors in [7] proposed a method for rescuing children through borewells using Arduino. The main feature of their system is an arm clipper mechanism, which can be utilized to rescue children from borewells quickly and safely. Though effective in quick rescue operations, the system's performance degraded due to high power requirements, distance scaling, and dependency on sensors. Furthermore, authors in [8] built an Octobot for versatile, cost-effective child rescue using real-time monitoring. However, this system has some limitations, including the need for manual control.

Authors in [9] designed a robot module with LED lights, sensors, and a video feed to safely lift the child from borewells. Authors in [10] proposed a multi-sensor borewell system to monitor well surroundings, water quality, and potential natural disasters. Authors in [11] focused on autonomous subsurface exploration and extraction systems. Their system integrates LiDARs to create real-time 3D models of the borewell environment, with robotic arms and vacuum pumps enabling accurate control of operations during the rescue. Despite being advanced, automated, and versatile, the system suffers from complexity arising from the integration of various components such as LiDAR and real-time data processing. Authors in [12] designed a sensor-based streetlight monitoring and maintenance system using wireless communication networks, while authors in [13] reported that integrating embedded sensors significantly enhances the control performance of robotic systems.

Despite advancements in technology, there is no well-established system that integrates both real-time air quality measurement and borewell rescue operations. Developing such a system would significantly improve rescue efforts and increase the chances of saving lives in these critical situations. Thus, the present study proposes a multi-component system incorporating robotic, environmental monitoring, and a stable structural support mechanism to address the complexities of confined space rescues into a borewell rescue system.

II. INTEGRATION OF COMPONENTS

The proposed system consists of three major parts: air quality monitoring, a support mechanism, and a robotic hand.

A. Air Quality Monitoring

This subsystem works as an advanced monitoring device that incorporates a camera, an array of environmental sensors, and a microcontroller for assessing the air and other environmental parameters inside a borewell. It consists of various sensors to measure harmful gases and air pollutants, as

presented in the table. I. A DHT11 sensor measures relative humidity (%) and air temperature ($^{\circ}\text{C}$), and an ultrasonic sensor measures distance from the child (in m). These sensors work together to periodically monitor important atmospheric and geographical parameters, creating enhanced situational awareness during rescue operations. The system is implemented using Embedded C.

TABLE I. SENSORS FOR MEASURING DIFFERENT GASES

Sensor	Measured parameters	Description
MQ-6	Methane and LPG (ppm)	Measures methane and LPG gases
MQ-7	Carbon monoxide (ppm)	Measures carbon monoxide levels
MQ-135	Air pollutants	Detects air pollutants

B. Support Mechanism

The support system is designed specifically to be accommodated within the small space beside the victim. It is triggered by the measurement values of the well and the camera view. The support system descends at the bottom of the borewell and spreads out to form a platform that provides support by arresting further descent and fixing the position of the victim within the closed region. The support system consists of Arduino UNO R3 and NRF24L01 transceivers, three servos, and an ultrasonic sensor. The NRF24L01 enables wireless communication, while the ultrasonic sensor assists in the measurement of distance. The servos are programmed to spread out properly to provide stability and support to the victim within the closed region.

C. Robotic Hand

The robotic hand is another primary subsystem, with flex sensors and microcontrollers. It is worn as a glove so that basic natural data can be collected and wirelessly disseminated. With bend sensors placed on the glove, there is guidance along with indications of the amount of bend or deflection, permitting accurate digitization of finger and hand movements. Input from these sensors transmits to an Arduino UNO R3 microcontroller, which operates as the system's brain and allows it to execute its functions based on the sensor inputs and interface with the other components. The NRF24L01 transceiver module allows wireless connection to the central transmitter, enabling real-time data sharing. Wireless data transmission is very important for external control and feedback.

III. METHODOLOGY

The proposed system consists of three major parts: air quality monitoring, a support mechanism, and a robotic hand. The air quality monitoring subsystem continuously monitors atmospheric conditions to provide the right environment, while the support mechanism provides stability, and the robotic hand is designed for remote handling of trapped individuals during rescue operations. The workflow of the borewell rescue system is illustrated in Figure 1.

The rescue begins with locating the victim using a high-resolution, waterproof camera equipped with night-vision capability. This camera operates effectively in the narrow and

dark environment of a borewell, providing real-time visual feedback that helps assess the victim's condition and guide the positioning of the robotic hand and support mechanism. Visual data also play a crucial role in risk assessment before any physical intervention. For the evaluation of safety conditions within the borewell, the system continuously tracks the level of oxygen and harmful gases. A phone module has also been added to enable continuous communication with the victim, who can then be monitored by the rescue team. In the case of low oxygen, an external supply of oxygen is provided to the victim to stabilize them until the rescue operation.

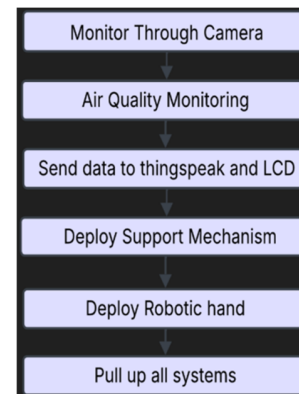


Fig. 1. Workflow of the proposed borewell rescue system.

The air quality analysis module uses NodeMCU, along with the ESP8266 wi-fi module, to wirelessly transmit the data of the sensor, as shown in Figure 3. NodeMCU processes these raw sensor readings into meaningful values such as gas concentrations in ppm. The NRF24L01 transceiver then transmits these data with low latency and long-range capability, ensuring uninterrupted communication with the rescue system. On the receiver end of the subsystem, an Arduino microcontroller controls the interface with the rescue team. Data transmitted from the TX side are received through the NRF24L01 module and then processed by the Arduino. The processed data are displayed in real time on an LCD screen form of gas concentrations, temperature, and humidity.

Sensors and communication modules are connected to power, ground, and input/output pins of the Arduino. For full connectivity, the RF module or NRF24L01 uses five wires (CE, CSN, MOSI, MISO, and SCK pins), which are attached to specific digital pins of the Arduino. The robotic arm and support mechanism operate in synchronization, ensuring a stable rescue process that minimizes sudden movements and reduces the risk of injury to the victim. Figure 4 presents the circuit general diagram of the system, showing how the Arduino, NRF24L01, ultrasonic sensor, servo motors, LED, and button are connected. The ultrasonic sensor senses the distance between the system and the child. The distance data are wirelessly sent over an NRF24L01 module to another NRF24L01 receiver, which in turn is connected to an LED and a button.

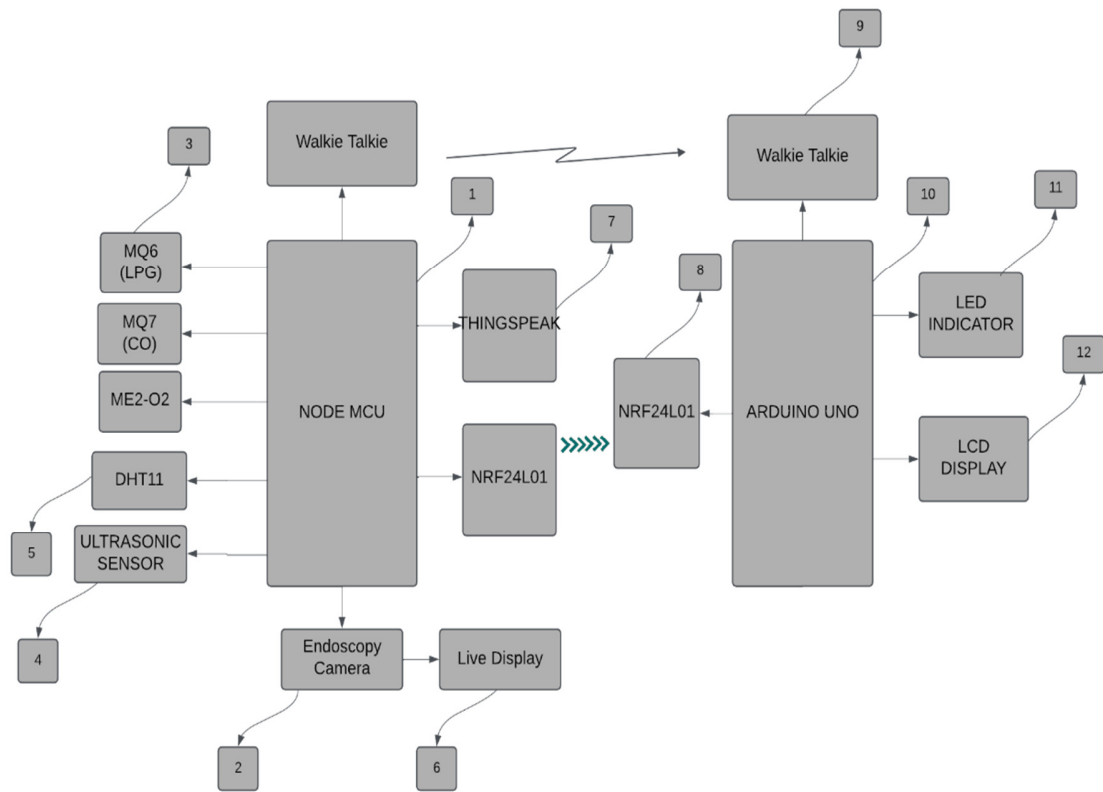


Fig. 2. System architecture of the borewell rescue monitoring system, illustrating the integration of sensing, communication, and display modules: (1) NodeMCU, (2) Endoscopy camera, (3) gas sensors, (4) ultrasonic sensor, (5) DHT11 temperature and humidity sensor, (6) live display unit, (7) ThingSpeak IoT platform, (8) NRF24L01 transceiver, (9) wireless communication modules, (10) Arduino Uno, (11) walkie-talkie modules, and (12) LCD.

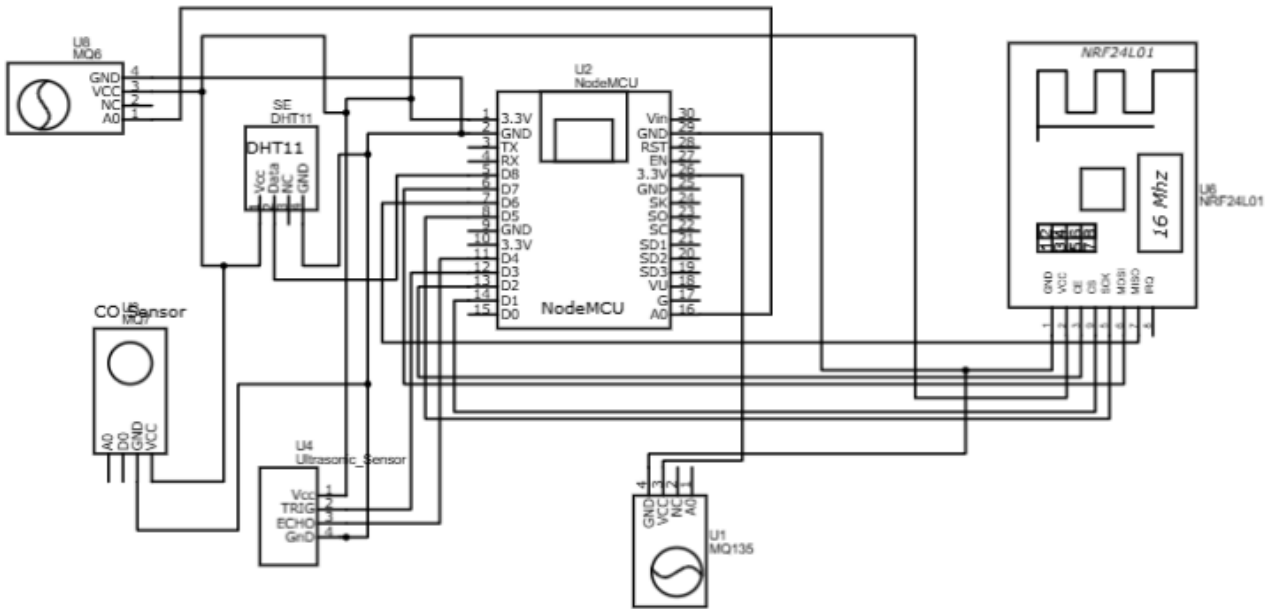


Fig. 3. Schematic diagram of the experimental setup of air quality monitoring.

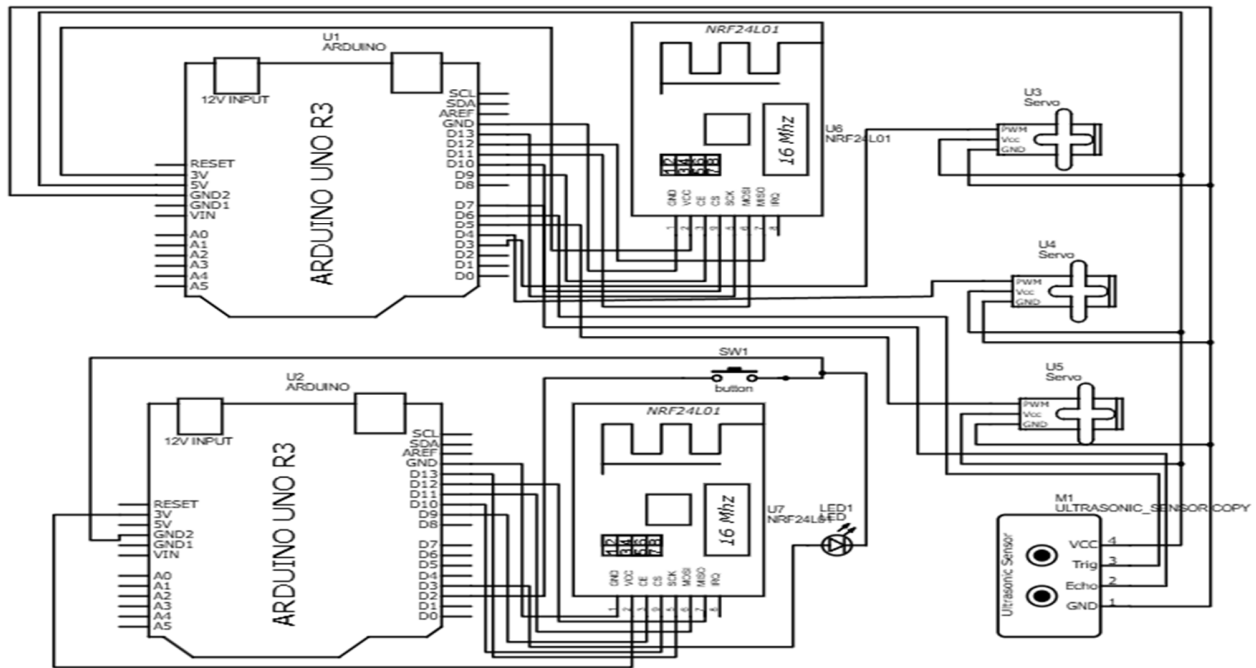


Fig. 4. Schematic diagram of support mechanism.

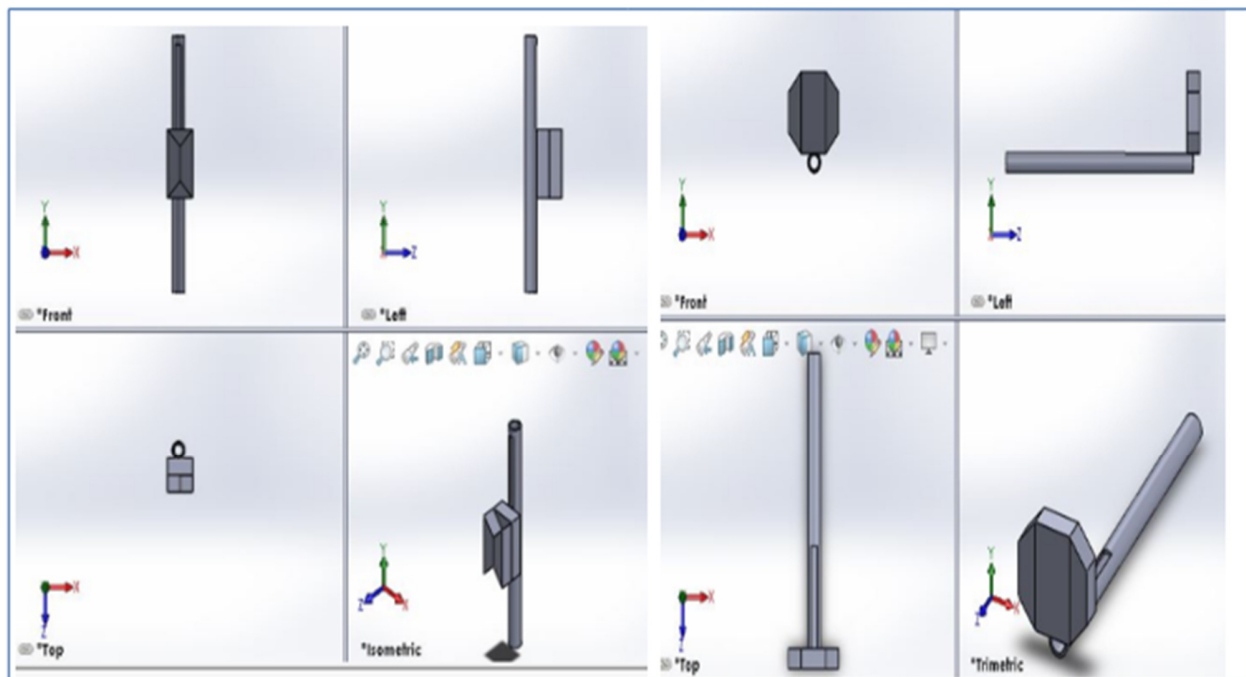


Fig. 5. Support mechanism base system movement along with the pole.

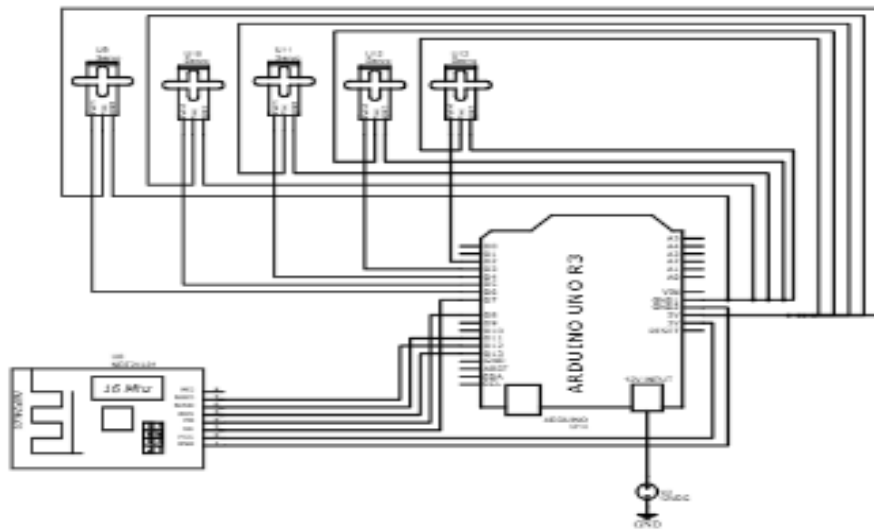


Fig. 6. Schematic diagram of the robotic hand.

LED turning on after receiving the distance information indicates that the system is well-positioned. After this, the button is pressed to activate the support mechanism, which makes the three servo motors move the support mechanism from behind and under the child by unfolding. This movement prevents any further fall when an Arduino sends a signal, as displayed in Figure 4. The structure enables reliable real-time monitoring and control of the system. Once the support mechanism is in place, a robotic arm is carefully deployed to safely lift the victim. Figure 6 illustrates the connections and components of the robotic hand subsystem. All power pins for the flex sensor are connected to 5V and ground pins of the microcontroller, while connecting the sensors' output pins directly to the analog input pins of the microcontroller. The air quality monitoring system integrates IoT technology, enabling real-time data transmission to a centralized monitoring station. By combining IoT technology, real-time analytics, and air quality monitoring, the proposed system offers an effective solution for borewell rescues, significantly improving both the safety and success rates during these challenging emergency operations.

IV. RESULTS

The borewell rescue system prototype provides an integrated view of confined space rescue operations and enables the real-time monitoring of air quality, precision control of the robotic hand, and a support mechanism to ensure the safety and stabilization of the victim. During the trials, the waterproof camera module with LED lights provided clear high-resolution visual feedback for detailed investigations of the borewell interior and victim conditions.

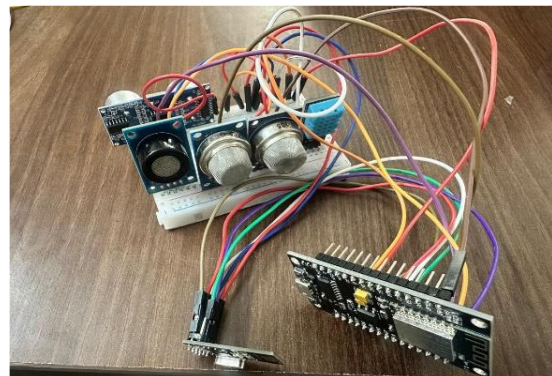


Fig. 7. Setup of air quality monitoring showing sensors MQ6, MQ7, MQ135, and DHT11.

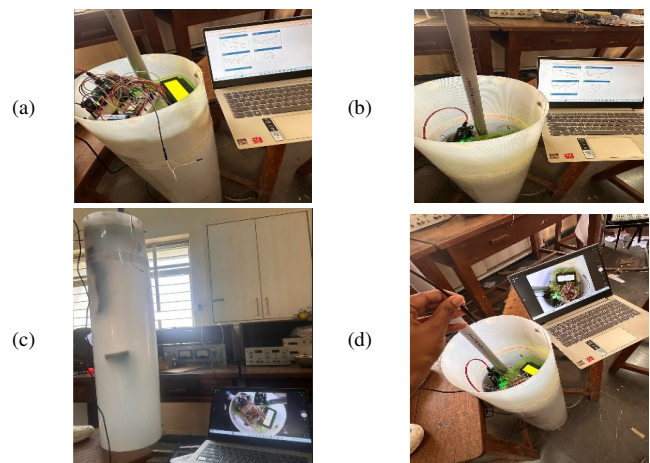


Fig. 8. Air quality monitoring at: (a) the top position, (b) 3 feet below the top surface, (c) the entire setup at the top, and (d) at 3 feet depth in the borewell.

A. Air Quality Monitoring

The experimental arrangement for air quality monitoring in a borewell rescue system is shown in Figure 3. The MQ-6, MQ-7, MQ-135, and DHT-11 sensors are properly positioned at the top of the borewell system to detect the gases in the borewell air. Figure 8 displays an air quality monitoring system positioned at various locations during a trial run. The MQ-6 detects methane, the MQ-7 monitors the levels of carbon monoxide, and the MQ-135 is used to detect hazardous gases. In addition, a DHT-11 sensor is used for humidity and temperature level measurement, as depicted in Figure 7. The sensors are interfaced with Arduino, which processes the data and sends them through the NRF24L01 module to the receiver.

Figure 9 demonstrates the resulting air-quality data on the ThingSpeak cloud platform. ThingSpeak displays the data in

graphs, allowing rescue teams remote access and analysis of trends over time. The information concerning the air quality in this operation can now be obtained from anywhere, thus promoting informed decision-making and improved safety and effectiveness for the recovery efforts.

Finally, measured values are shown on the LCD display, which informs the operators in real-time about the safety of the borehole, as illustrated in Figure 10. An NRF24L01 wireless module is also employed to send the information to an external receiver, ensuring seamless communication in areas with minimal network coverage. The measured values of gases, humidity, and temperature at different distances from the ground levels are presented in Table II.

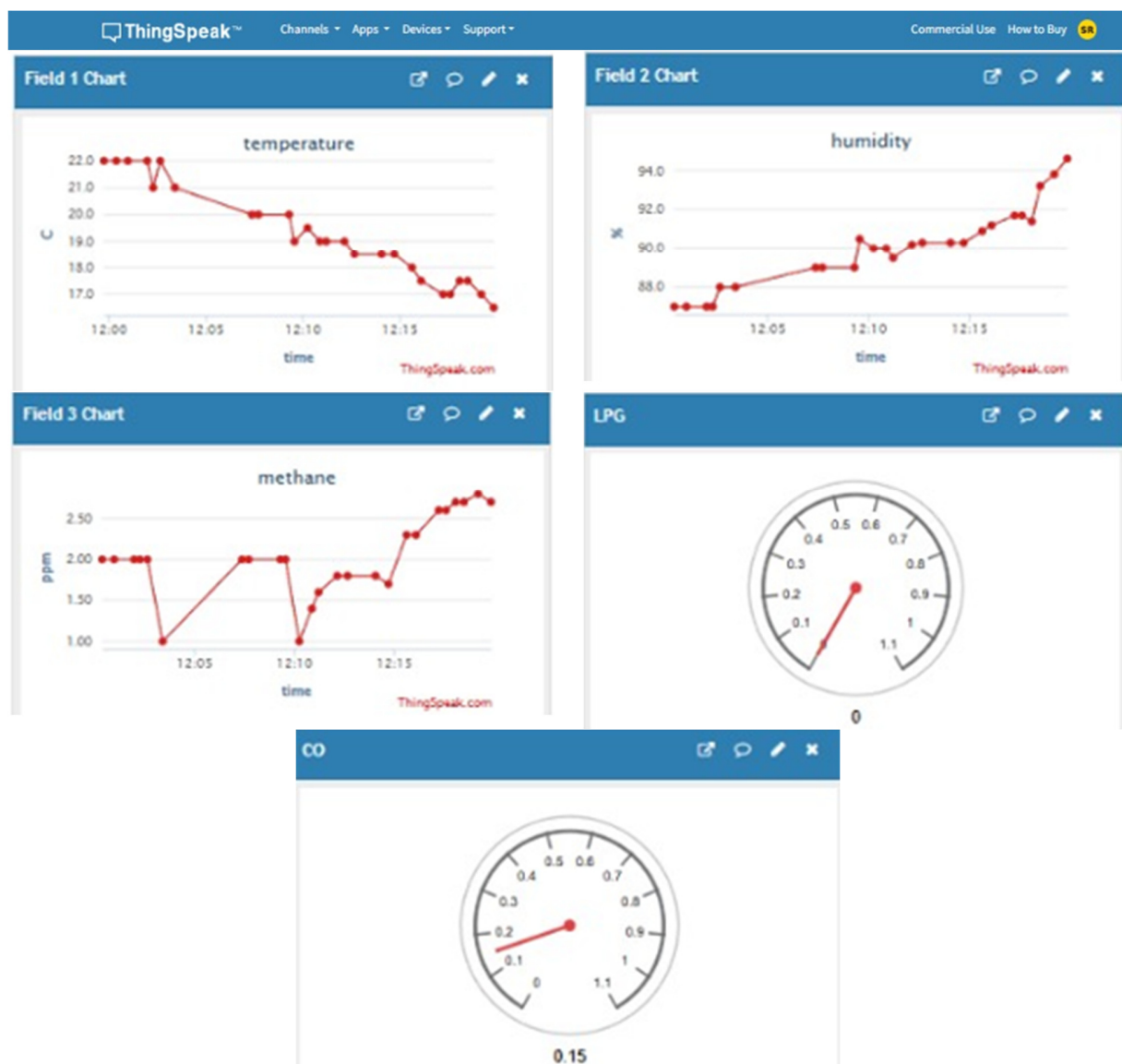


Fig. 9. Air quality monitoring via cloud data with temperature, humidity, methane, LPG, and CO levels at the top of the borewell system.

TABLE II. MEASURED VALUES OF GASES, HUMIDITY, AND TEMPERATURE AT DIFFERENT DISTANCES

Distance below the ground	Temperature (°C)	Humidity (%)	Methane (ppm)	CO (ppm)	LPG (ppm)
Normal setup at room temp	27	31	1.8	0.2	0
1 feet	22	88	1.8	0.2	0
3 feet	19	90.4	1.8	0.2	0
5 feet	17.5	94.2	2.8	0.5	0



Fig. 10. LCD Displaying with the measured values of methane, CO, and LPG levels at the top of the borewell system.

B. Support Mechanism and Robotic Hand

The retractable support mechanism was positioned beside the victim and automatically deployed upon command, forming

a stable base beneath them. Its open and closed configurations are portrayed in Figure 11.

The robotic hand setup, shown in Figure 12, was designed to replicate the operator's finger movements using a glove equipped with flex sensors. These sensors detect finger bending and convert it into resistance values, which are transmitted wirelessly to the robotic hand through the NRF24L01 module. The motors in the robotic hand move each finger in real time, enabling smooth, intuitive, and precise control during borewell rescue operations, as demonstrated in Figure 13.

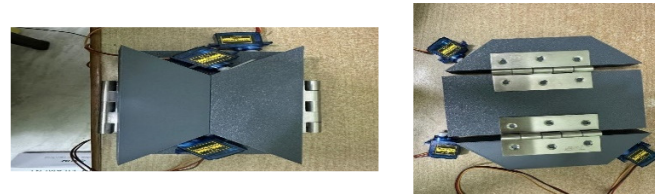


Fig. 11. 3D printed hexagonal base support.

TABLE III. COMPARISON OF THE PROPOSED SYSTEM WITH AVAILABLE LITERATURE

Method	Robotic hand	Support mechanism	Air quality monitoring	Camera	Sensor accuracy	Cost effectiveness	Response time	Ref.
Pneumatic borewell rescue system	-	Airbag	-	-	-	-	Fast	[3]
Arduino-based smart borewell ambulance rescue system	Very complex principle	-	-	-	Moderate	High	Moderate	[4]
Child rescue system	High-power clippers	-	Does not detect LPG, methane	Real-time monitoring	Low	Moderate	Moderate	[7]
Robot-based rescue system	Robotic arms	Air bag	-	Real-time monitoring	Moderate	Moderate	Moderate	[9]
Kid rescue system	Robotic modules	-	-	Real-time monitoring	Moderate	Moderate	Moderate	[11]
Aqua Deep Earth Probe (ADEP)	-	-	-	Used multiple sensors	High	Moderate	Moderate	[10]
IoT-based Borewell Monitoring and Child Rescue System using multi-sensor fusion	Robotic arm mechanism	Mechanical support system	Monitors gases and environmental parameters	Real-time monitoring	High	Moderate	Moderate	[6]
SCRS from the borewell	Robotic gripping mechanism	-	Monitors temperature and gas levels	Real-time monitoring	Moderate	Moderate	Moderate	[1]
Multi-purpose prosthetic borewell system – an invincible arm	Prosthetic robotic arm	Mechanical stabilization mechanism is used	-	Real-time monitoring	Moderate	Moderate	Moderate	[2]
Proposed borewell rescue system	Robotic hand	Hexagonal support is used	Detects harmful gases	Real-time monitoring	High	High	Fast	-



Fig. 12. Experimental setup of robotic hands.



Fig. 13. Robotic hand grasping a toy.

The coordination between camera lifting, robotic hand, and support mechanism ensures system reliability and helps maintain structural integrity during the rescue operation. It also prevents any further downward movement of the victim. The proposed system outperforms other similar systems presented in Table III.

V. CONCLUSION

The proposed borewell rescue system enabled continuous monitoring and real-time monitoring for ensuring a safe rescue. The system protects the operator as well as the victim by ensuring a safe rescue environment. The retractable support system provides a stable support platform, which arrests the further downward movement of the victim, while the glove-operated robotic hand with the ultrasonic feedback system allows precise handling and retrieval from the borewell. In addition, the system can be easily repurposed for other applications, such as in mining shafts with improved ultrasonic filtering and rugged sensors. Overall, the combination of environmental sensing and mechanical precision demonstrates the system's robustness and flexibility in lifesaving rescue operations.

DECLARATION OF COMPETING INTERESTS

The authors have no competing interests to declare that are relevant to the content of this article.

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DATA AVAILABILITY

Not applicable to this work.

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