DESIGN AND IMPLEMENTATION OF A ROBOTIC SYSTEM FOR BOREWELL RESCUE

Namira Tarannum[1], V. Radha[2], Susmitha Dokur[3]

[1]*Department of Electronics and Communications Engineering, Stanley College of Engineering and Technology for Women, India*
E-mail: ariman810@gmail.com

[2]*Department of Electronics and Communications Engineering, Stanley College of Engineering and Technology for Women, India*
E-mail: radha@stanley.edu.in

[3]*Department of Electronics and Communications Engineering, Stanley College of Engineering and Technology for Women, India*
E-mail: susmitha@stanley.edu.in

Abstract

Borewell accidents are common occurrences particularly in the rural regions where the open wells prove to be hazardous to the children. The traditional methods of rescue are extremely difficult, consume time and can hardly be effective due to the narrowness and depth of borewells. In this paper, the author discusses a borewell rescue robot built on Arduino that could allow making rescue efforts, drilling directly down the borewell shaft. The overall idea is to make the rescue effort less dangerous and more regulated besides reducing the time it requires to execute it. The suggested system is comprised of mechanical arm gripper which are driven by a DC motor and controlled by an Arduino microcontroller. The wireless camera that is fitted on the robot enables the operators to monitor the welfare of the victim and also to precisely manage the rescue mechanism in real time. The robot is linked to the control station via Wi-Fi. ESP32 Cam module has an LED light unit that allows observing the conditions in the dark borewell and an ultrasonic sensor to detect the distance between the gripper and the victim to ensure that the positioning is accurate. The borewell also has a sound sensor that can determine the level of noise in it. The mechanism is used to determine the presence of the child and their responsiveness. Through this project, we learn to apply embedded systems and robotic actuation to develop a solution that is useful to society and is real-time rescue.

Keywords: Borewell Rescue Robot, Arduino-based System, Robotic Gripper Mechanism, Wireless Monitoring, Embedded Rescue System

1. INTRODUCTION

Borewell accidents are now emerging as a major safety issue in most developing locations with more of the rural regions having borewells that are not properly sealed, and thus left uncovered. These small shafts are particularly dangerous to those children who fall into the borewell. Due to the thin diameter, the oxygen amount is low, vision is impaired, and the dirt is unstable, which makes the rescue activities difficult and time-sensitive. It is far lengthier and far more dangerous when the rescuers excavate parallel pits or drop people into the borewell manually. In most cases, minutes can be lost, and there are less chances to save human life.

Several technological ways to make the rescue operation through the borewell more effective have been suggested in the recent studies. The system discussed in [1] involves the use of a gripper-based mechatronics mechanism for the movement of the victim in the narrow space of the borewell. The system is mechanical in operation with limited sensing support, which makes the process difficult to determine the exact position of the victim. The proposed system was influenced by this, as it also uses a small mechanical arm. In another study, [2] a rescue system is discussed, which can be controlled from a distance. The system is also not free from the drawback of possible delays in operation. The study discussed in [3] compares the various rescue operations with the drawbacks associated with the methods, including time consumption and safety, but does not discuss the method for real-time rescue operation. The automation-based rescue operations discussed in [4] try to make the rescue operation more efficient with the addition of the robotic system, but the operation is also dependent on the complexity of the system. The IoT-based rescue robot discussed in [5] is provided with basic monitoring facilities. It is also a complicated system, which is not suitable for real-time operation. The above-discussed methods prove that the situation is still not completely safe, even though the situation is better than before. Most of the works that there are operational are multi-component systems with complex components or do not have proper positioning mechanisms.

This paper tells you how to make an Arduino-based robot that can go down into a borewell and help pull the victim out. The system comprises a motorized mechanical arm with a gripper for accurate handling, a wireless camera for live video feedback, and LED lighting to help you see better. There is an ultrasonic sensor built in to check the distance and make sure the gripper is in the appropriate spot. There is also a sound sensor that can tell how loud the sounds are in the borewell. This helps find the victim and check to see if they are awake. The major purpose of the suggested system is to give emergency response teams an inexpensive, reliable, and real-time embedded rescue solution. The project demonstrates the application of embedded technology to address a significant societal issue through the integration of robotic control and wireless monitoring.

This contribution contains the issues regarding the traditional borewell rescue practices, i.e. the time lag in response, absence of visibility, and inability to work in tight constrained areas. In order to surmount these constraints, the small and lightweight robotic rescue system is developed based on embedded and wireless technology. The proposed system aims at enhancing real-time checking, managed actuation and secure managing of the victim during rescue missions. The rest of the paper will be structured as follows; Section 2 will provide the literature review of available borewell rescue systems, Section 3 will introduce the methodology and system design, Section 4 will comment on the results and performance assessment, and Section 5 will provide the conclusion of the work with future scope.

2. LITERATURE REVIEW

In this section, some borewell rescue systems are reviewed and the design approaches of these systems are compared with the proposed Arduino-based rescue robot. In [6], another previous rescue system is concerned with detection and alert systems based on the IoT, but do not have a proper gripping and extraction system. The octobot system presented in [7] proposes the use of more sophisticated stabilization methods with the help of sophisticated mechanisms, yet its architecture can be more complicated to use in practice. The system presented in [8] is an example of an IoT based design which illustrates embedded monitoring and control, but it requires constant connectivity and can be constrained in its real-time responsiveness. The gripper system [9] aims to create a mechanical gripping device designed for use in borewell rescue operations. The paper provides significance of secure holding in extraction, however, primarily focuses on the mechanical design features and does not integrate sensing or real-time monitoring features. The robotic rescue system, described in the [10], proposes a camera-based system for monitoring and controlling the rescue operation inside the borewell. Even though the system enhances the visual awareness, its reliance on manual control and poor sensing support could influence positioning accuracy. Similarly, the semi-autonomous rescue robot [11] is also semi-automated to help with rescue missions. The degree of automation is however not so high and the system still needs a lot of operator intervention that can affect the response time and accuracy. The two-step mechanism in [12] is a combination of the prevention and retrieval system which identifies a child who is close to the borewell opening. Although it enhances safety awareness, it is more on prevention, as opposed to effective in-depth rescue. The extraction of the embedded supervision and motor control in [13] is an IoT-based rescue system, which lacks a strong focus on the exact positioning. Likewise, the robotic rescue system in [14] employs controlled operation by use of servo-driven mechanisms, but lack of stability in small spaces is an issue. A simple rescue framework is presented in [15], implemented on an Arduino platform and has monitoring features, but does not have sophisticated sensing to locate a position of accuracy. The IoT system in [16] is a robotic system with remote operation and control, though there is more dependency between modules in the system. The proposed system adopts wireless communication and live streaming, which is supported by supporting technologies like IoT switching systems [17] and cloud-based monitoring based on ESP32-CAM [18] to prove its effectiveness and use in a simplified and application-specific fashion. The conceptual model that is used in [19] is aimed at enhancing maneuverability by using stabilization and rotating control. The proposed robot is compact and balanced, as these principles are demonstrated in its design. A real-time data visualization and control are noted in monitoring systems like [20] and web-based control applications in [21], but neither is specifically aimed at the rescue operations. The robotic rescue system in [22] illustrates implementation of the dual-arm gripper and internalized control, however, such designs have the tendency of making the mechanical systems more complicated. Sophisticated robotic hand systems such as [23] propose the flexible gripping systems though the application may not be applicable in narrow borewell settings. Equally, the environmental sensing and extraction in [24] is integrated with the robotic arm system; however, the system needs a lot of care to operate safely. The rescue system incorporated in [25] offers a structured solution, but it does not offer the real-time monitoring capability. The lifting force analysis presented in [26] consists of the analysis of the force requirements required to safely extract a trapped child out of a borewell. In [27], the analytical study explores various techniques of borewell rescue and indicates the difficulties of using the traditional and semi-automated systems. The paper [28] suggests an IoT-based smart rescue system that will enhance the safety of borewell accidents by monitoring and warning in real time. Although the method improves the communication and tracking abilities, it mainly emphasizes detection and notification instead of having a more detailed and accurate rescue mechanism inside the borewell. The studies on the design of grippers, e.g. [29] and [30], are aimed at enhancing the gripping efficiency and flexibility. Although these designs can increase handling ability, their use in borewell rescue needs to be simplified to make practical. Judging by these observations, the majority of the existing systems are either oriented to the intricate robotic designs, IoT-intensive designs with no balanced approach to integrating all the necessary features.

Comprehensively, the literature suggests that effective borewell rescue mechanism must be compact, easily manageable, able to be monitored in real-time and be fitted with accurate sensing to operate safely. However, the suggested solution is the Arduino-based borewell rescue robot that offers a simplistic, inexpensive, and practically feasible answer, featuring a motor-powered gripper, Wi-Fi-based live monitoring (ESP32-CAM), ultrasonic distance sensing, LED lighting, and simple sound detection. Such a moderate approach enhances the efficiency of operation and at the same time simplifies and ensures reliability in the actual emergency rescue situations.

3. PROPOSED SYSTEM

The suggested borewell rescue system will be used to counter the shortcomings experienced in the current manual operated and wired rescue systems. The current work is unlike the previous systems which are mostly based on mechanical switching and minimal sensing, but have combined the wireless webpage-based control, real-time video streaming and multi-sensor feedback to a small embedded platform. Decision making is improved in case of rescue with the introduction of an accurate distance reading with the HC-SR04 ultrasonic sensor and sound detector with LM393 sound sensor module. With the addition of Arduino Uno microcontroller, L293D motor driver IC, 12V DC geared motor, 2-finger gripper mechanism, and ESP32-CAM Wi-Fi module, the system will have better control accuracy, remote operation, and safety of operation than the traditional rescue system.

The architecture of the system is embedded centralized control. Its core central unit, the Arduino Uno is which coordinates the actions of the motors, sensor processing, and communication. The vertical deployment and lifting system is powered by a 12V DC geared motor that has a high torque and the regulated speed to use in winch operations in deep borewells. The motor is connected with L293D dual H-bridge motor driver, which provides the possibility of controlling the motor uphill and downhill. A two finger mechanical hand is activated to firmly grasp the child when retrieving it. The ESP32-CAM provides live video feedback of the Wi-Fi connection, and a high-intensity flash LED makes the ESP32-CAM visible in the dark borewell conditions to be monitored.

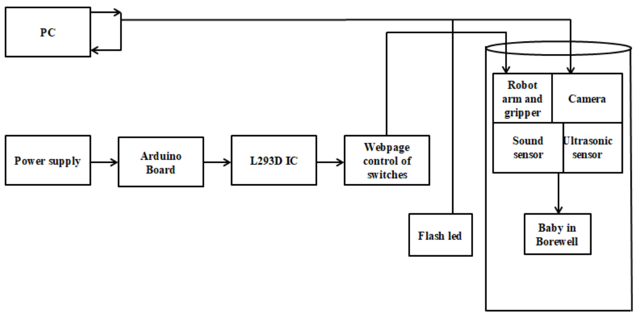

Fig.1. Block Diagram

The regulated power supply activates the Arduino Uno and peripheral modules as shown in the block diagram Fig.1. Arduino controls the L293D motor driver which controls both the winch motor and the gripper actuation mechanism. The ESP32-CAM Wi-Fi board is linked to a Wi-Fi network and has a webpage-based control console, which can be opened with the IP address of the module by means of a browser. This control interface is an HTML based interface that allows the operator to have access to the following commands: Winch Up, Winch Down, Gripper Open, Gripper Close, and Flash ON/OFF.

The ultrasonic sensor HC-SR04 that is able to measure distances of about 2cm to 400cm (4 meters) with a high accuracy is mounted near the gripper to detect the distance between the child and the robotic arm. This allows accurate pre-gripping positioning. Also, there is the sound sensor module (LM393) which can also record sound levels of the intensity inside the borewell which indicates the responsiveness of the child. The monitoring webpage indicates sensor readings in the form of the measured distance and status of sound detection, which enables the rescue operator to monitor in real time.

Following the powering of the system, the process of the working order can be followed according to the flowchart presented in Fig.2 which includes the initialisation of all the modules connected to the Arduino such as the L293D driver, ultrasonic sensor, sound sensor, ESP32-CAM, flash LED, and motor system. The unit is then lowered in the borewell using the webpage controlled winch technique into the robotic unit. The operator is able to view the live video being displayed on the HTML console webpage.

In case there is no sight of the child then the deployment proceeds. After the child is identified by the camera feed, the HC-SR04 ultrasonic sensor produces the distance between the gripper and the child as a means of safe orientation. The sound sensor LM393 detects the responsiveness of the child. With the help of the webpage interface, the operator is able to place the arm carefully using the fingers and brings the two-finger gripper to action. The action on the grips is watched on the video feed in real time. The winch action is also performed by the activation of the winch mechanism using the webpage to bring the child out of the borewell safely to complete the rescue mission.

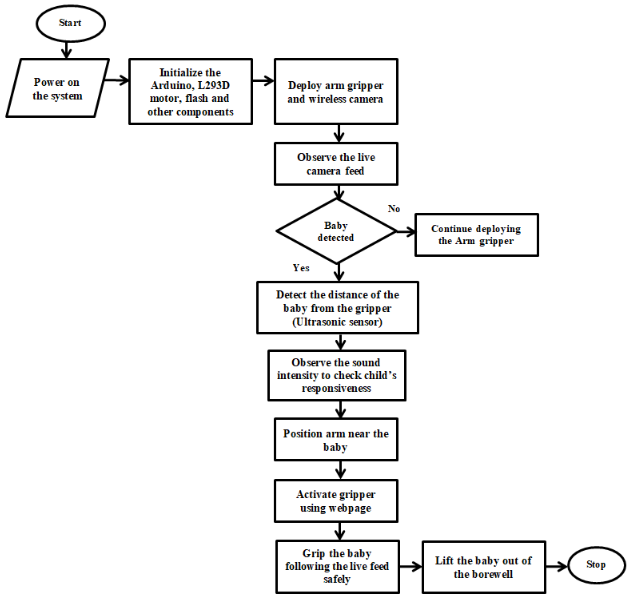

Fig.2. Flowchart

The control console is implemented based on HTML within the IP address of ESP32-CAM over Wi-Fi. Being integrated into the same network, the operator may enter the IP address in a browser to open the Rescue Robot Console. The webpage displays:

- The ESP32-CAM live camera feed.
- Winch control buttons (UP / DOWN)
- Gripper control buttons (OPEN / CLOSE)
- Flash control (ON / OFF)
- Ultrasonic distance and sound detector sensor status display.

This Web-based architecture does not require specific physical control panels, and allows remote control, which is flexible, using a laptop or mobile equipment. Real-time monitoring, wireless communication, and embedded motor control contribute greatly to preciseness of rescue, lessening of manual control and the general security of the borewell rescue operations.

4. RESULTS AND DISCUSSION

The prototype of the borewell rescue robot was tested in order to check the functionality of the mechanical structure, wireless communication, sensor integration and remote control interface. These tests aimed at checking the ability of the system to cope with the main activities that would need to be fulfilled in an instance of a borewell rescue, in terms of monitoring, positioning, gripping and controlled lifting. The results of the experiment prove that the combination of built-in control, wireless monitoring, and sensing modules considerably enhances precision and safety of the rescue.

The initial experiment as in Fig.3 and Fig.4 was the experiment with the mechanical deployment mechanism of the rescue unit. That robotic framework was lowered and raised with the help of a motor-controlled system that was intended to mimic the vertical movement within a borewell. The prototype was structurally stable during suspension and controlled using the control interface. The minimal size of the controller, sensors, camera module and robotic gripper fulfilled the fact that the system is deployable in small borewell spaces. The mechanical gripper system with the two fingers proved to be responsive to the control commands and showed that it is able to reach out to an object and hold it with security, meaning that it can hold the trapped child.

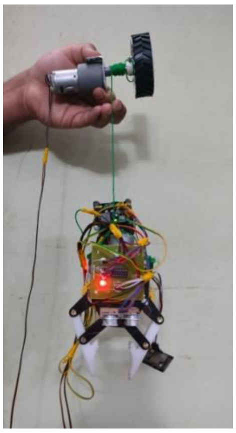

Fig.3. Hardware Setup

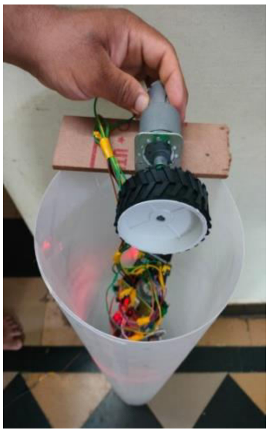

Fig.4. Setup lowered in borewell

The second section addressed the network communication and connectivity with the system. The Wi-Fi module, which was based on ESP32, was able to connect to the local wireless hot spot and it received a unique IP address as indicated in Fig.5. With this IP address typed in a web browser, the operator could have accessed the control webpage, which was based on HTML. This finding confirms the idea that the system is able to service wireless remote operation without necessarily having physical control panels as well as wired communication. The network interface enabled the rescue operator to transmit commands and real-time monitoring of the system parameters, which enhanced the safety and comfort of the operation.

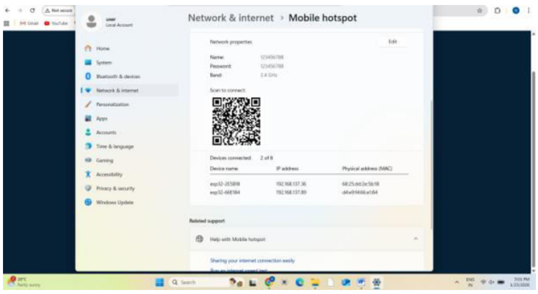

Fig.5 Wi-Fi Hotspot IP Configuration for Web Monitoring

The HTML-based rescue robot control console was made as shown in Fig.6 that is the central control interface. The console has the control buttons of the winch (move up and down), operations of the gripper (open and close) and the flash LED. The live video stream is also shown in the interface that is taken by ESP32-CAM module. There are several ways in which the operator can monitor the interior of the borewell in a visual manner by this interface and can command the robotic arm precisely towards the victim in a comfortable manner. The control web page allows easy user functioning and removes the constraints of the manual push-button systems.

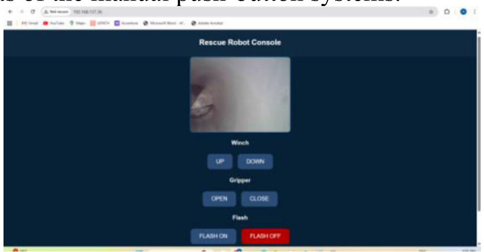

Fig.6. HTML-Based Control Panel for Borewell Rescue Robot

The outcome of the experiment proved that the flash LED illumination system was effective. Borewells are normally very dark places in which there is very little visibility. Once the flash LED was turned on with the help of the control console the camera feed was much clearer. The better lighting enabled the operator to have a better idea about the position of objects within the borewell and to position the robotic gripper in the right place. The latter is a critical attribute especially when using gripping to ensure that the child trapped is not hurt.

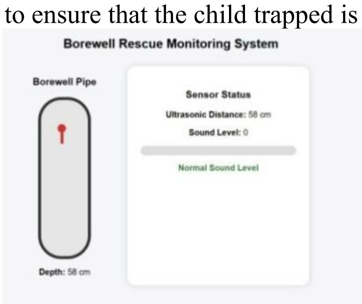

Fig.7. Ultrasonic Distance and Sound Monitoring Output

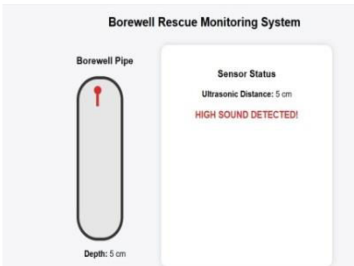

Fig.8. Ultrasonic Distance Measurement with High Sound Detection

As the second outcome was the real time sensor monitoring in the case of the ultrasonic and sound sensors as seen in Fig.7. The sensor was the HC-SR04 ultrasonic sensor that was utilized to test the distance between the robotic arm and the object within the borewell. The sensor readings are represented in the monitoring webpage and they assist the operator to know the precise positioning of the gripper. Also, sound sensor module based on LM393 was able to record changes in the sound levels within the borewell. In high sound levels where it was found as in Fig.8, the system was able to tell that there was an activity or responsiveness. The distance measurement and sound detection give good situational information that will help the operator in the rescue operation.

All in all, the experimental outcomes prove that the suggested system manages to combine the mechanical actuation, wireless monitoring, sensor feedback, and remote webpage control into a single rescue platform. The system portrays a good communication, motor control as well as environmental monitoring. In comparison to classic rescue techniques, which are based on manual estimates and restricted visibility, the created prototype is much more accurate, the reaction time is reduced, and the operations are safer.

Table.1. Comparison of proposed work with the existing work

Ref	Dia. (cm)	Delay (s)	Pos. Res. (cm)	Dist. Sensor	Sound Sensor	Control
[1]	25–30	3.0	0	—	—	Manual
[2]	20–25	2.5	0	—	—	Mobile
[5]	18–22	2.2	3–5	IR	—	Manual
Prop	12–15	1.2	1–2	US	Yes	Webpage

The abbreviations in Table.1. are:
Dia. - Diameter,
Pos. Res. - Positioning Resolution,
Dist. - Distance Sensor,
IR - Infrared,
US - Ultrasonic

The Table.1. compares the compactness, response delay, positioning resolution, sensing capability, sound detection, and control interface of various borewell rescue systems mentioned in [1], [2], and [5]. From the table, it can be concluded that the compactness of the system in [1], [2], and [5] is high, which is a drawback since these systems cannot operate in a narrow borewell due to their larger diameter. The positioning resolution of these systems is zero since they do not have a distance-sensing capability. The system in [5] has used an infrared sensor, which offers a certain level of positioning capability, although its accuracy is limited.

The proposed system offers a number of advantages, such as a small diameter, which makes it suitable for operating in a narrow borewell, a small response delay, a high positioning resolution with the help of an ultrasonic sensor, sound detection, and a webpage-based control interface, which offers flexibility in operating the system in real-time, unlike the control interface in [1], [2], and [5].

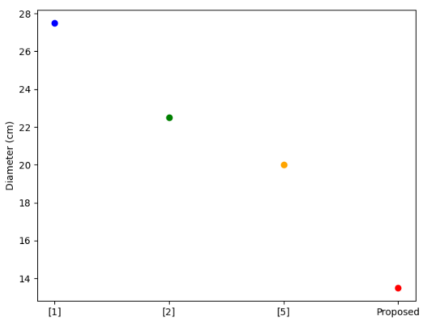

Fig.9. Diameter-based compactness comparison of existing systems and proposed system

The graph from Fig.9 represents the variation in system diameter, which represents compactness. It can be observed that system [1] and system [2] have larger diameters, which are less suitable for a narrow borewell environment. The system in [5] has a reduced diameter, while the proposed system has the smallest diameter.

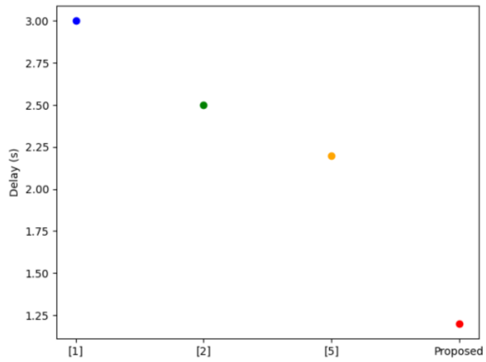

Fig.10. Response delay comparison of existing systems and proposed system

The graph from Fig.10. represents the variation in system response delays for different systems. It can be observed that system [1] has the highest delay, while system [2] and system [5] have a moderate level of delay with improved control mechanisms. The proposed system has the least delay, indicating faster system response.

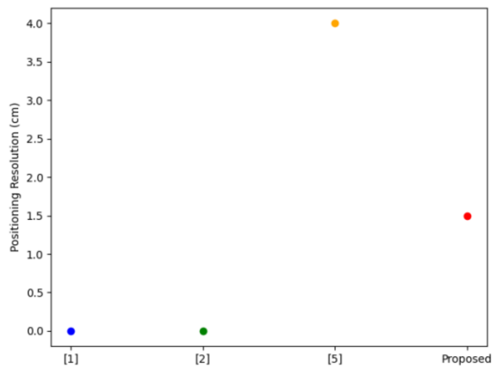

Fig.11. Positioning resolution comparison of existing systems and proposed system

The graph from Fig.11. represents the variation in positioning resolution for different systems. It can be observed that system [1] and system [2] have zero positioning resolution, indicating no distance sensors are used in these systems. The system in [5] has a moderate level of positioning resolution using an infrared sensor, while the proposed system has improved positioning resolution using an ultrasonic sensor.

The graph from Fig.12. represents the variation in sound detection capability for different systems. It can be observed that system [1], system [2], and system [5] do not have sound sensors, while the proposed system has a sound detection capability, which helps in identifying the responsiveness of the victim.

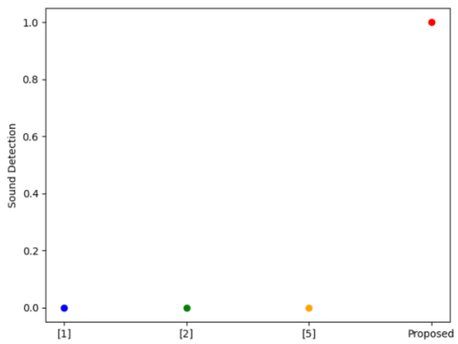

Fig.12. Sound detection comparison of existing systems and proposed system

The graph from Fig.13. represents the variation in control mechanisms for different systems. It can be observed that system [1] has a manual control system, while system [2] and system [5] have improved control mechanisms. The proposed system has enhanced control capability using a webpage interface, indicating faster control mechanisms.

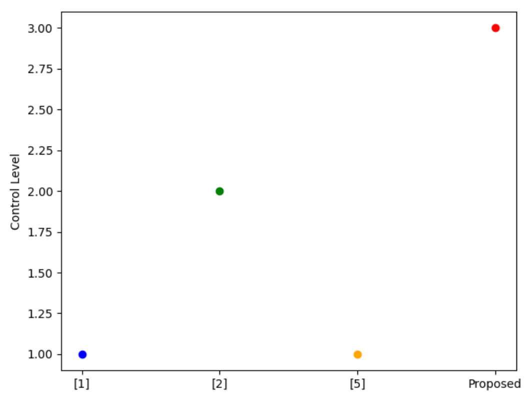

Fig.13. Control comparison of existing systems and proposed system

Graphical analysis helps to highlight the differences in performance between the existing systems [1], [2], [5], and the new system, based on several key factors. It can be observed from the analysis that there is a significant improvement in compactness, response time, and positioning in the proposed system compared to the existing systems, along with some added features like sound detection. At the same time, there is a lack of support in terms of sensing in the existing systems. Therefore, the graphical analysis clearly depicts the effectiveness of the proposed system in terms of practicality.

5. CONCLUSION

This paper was a design and realization of a borewell rescue system using embedded and wireless technologies in the form of a robotic system. The system under consideration combines an Arduino-based control unit, motor-based robotic gripper, ESP32-CAM to provide real-time monitoring, and several sensors, including HC-SR04 ultrasonic sensor and LM393 sound sensor, to aid the accident-free and accurate process of rescuing. The control interface is a webpage which enables the operator to monitor and remotely control the robot via a Wi-Fi network without the operator being required to be close to the borewell. Video feedbacks in real time, better visibility with flash LEDs and measurement of the distance aids in the precise placement of the gripper and minimizes the likelihood of error in the rescue. Experimental findings show that the system is reliable in a simulated borewell setting and it offers superior monitoring, control and safety over the traditional methods of rescue. The proposed solution based on the integration of mechanical design, embedded sensor and wireless communication provides a feasible and cost-effective solution to an emergency rescue situation. All in all, the system has a good chance of enhancing efficiency during rescue operations and raising the probability of saving lives during a borewell accident. The work of the future can be aimed at enhancing the mechanical design in order to have greater adaptability to the sizes of borewells and depths. The system can be further refined to become portable and applicable in real time in the field, thus this can enhance the practical use of the system in the case of an emergency.

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