Full Length Research Article

NRF24L Wireless Robot for Live Human Detection in Rescue Operations

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Abstract
Disaster-prone environments such as collapsed buildings, fire-affected zones, industrial accident sites, and earthquake-hsit regions demand rapid and accurate human detection to increase survival rates. Traditional rescue operations expose first responders to severe risks, including structural instability, toxic gases, and limited visibility. Rescue robotics has emerged as a transformative solution to mitigate such dangers [12], [18]. This paper presents the design and development of an NRF24L01-based wireless rescue robot integrated with real-time human detection and live video streaming capabilities. The system utilizes an Arduino Mega 2560 as the central control unit, ensuring efficient motor control and wireless communication. The NRF24L01 transceiver module provides low-latency, long-range communication suitable for obstructed disaster environments [14], [17]. An ESP32-CAM module enables real-time Wi-Fi video streaming and onboard face detection, improving victim identification accuracy compared to conventional PIR-based systems [15]. The proposed robot offers a cost-effective, scalable, and reliable solution for search-and-rescue operations, minimizing human risk while enhancing operational efficiency.

Keywords*—Landslide monitoring, ESP32, IoT, Soil moisture sensor, Rainfall detection, Vibration sensor, Early warning system.*

1. Introduction

The increasing frequency of natural and man-made disasters has significantly emphasized the importance of intelligent and autonomous rescue systems [12]. Earthquakes, landslides, explosions, and structural collapses create hazardous environments that pose severe threats to both victims and rescue personnel. Traditional manual search operations are often slow, risky, and inefficient in complex terrains with unstable debris, toxic fumes, and low visibility [18]. In many cases, delayed victim identification reduces survival probability, making rapid detection systems critically important.

Robotics integrated with wireless communication technologies has emerged as a reliable approach to address these challenges [9]. Early rescue robots were primarily designed for remote navigation using RF-based communication systems, enabling operators to control movement from safe locations [1], [10]. However, these systems lacked intelligent sensing and autonomous human detection capabilities. With advancements in embedded systems and machine vision, modern rescue robots incorporate cameras, sensors, and onboard processing units to enhance situational awareness [8], [13].

Wireless communication reliability is a major factor in rescue robotics. Among available communication modules, the NRF24L01 transceiver offers advantages such as low power consumption, high data rate (up to 2 Mbps), automatic acknowledgment, and extended communication range [14], [17]. These characteristics make it highly suitable for disaster scenarios where stable communication is essential despite environmental obstructions.

Human detection mechanisms in rescue robotics have evolved from simple heat-based sensors to advanced vision-based techniques. PIR-based detection systems are economical but suffer from false positives in high-temperature environments [15]. Thermal imaging systems improve detection accuracy but significantly increase system cost [13]. Vision-based detection using embedded modules such as ESP32-CAM provides a balanced solution, offering real-time video streaming and onboard face recognition capabilities [16].

The proposed system integrates NRF24L01 wireless control with ESP32-CAM-based human detection to develop a modular, affordable, and efficient rescue robot. The Arduino Mega 2560 controls navigation, while the L293D motor driver ensures smooth maneuverability. By combining wireless mobility, real-time surveillance, and AI-assisted human detection, the system enhances rescue efficiency while minimizing risk to first responders [12].

2. Literature Review

Rescue robotics research has progressively shifted from simple remote-controlled mechanisms to intelligent autonomous systems with sensor fusion and advanced detection capabilities [12]. Early work by Velrajkumar and Darwin Jose Raju [1] introduced RF-based remote-controlled robots capable of transmitting live video to a control station. Although effective in navigation, these systems lacked automated human identification features.

ZigBee-based rescue robots incorporating PIR sensors were later developed to detect human body heat [2], [7]. While PIR sensors provide cost-effective solutions, they struggle in environments with elevated ambient temperatures or obstructed detection paths, leading to false positives [15]. Vijayaragavan and Sharma [5] developed a PIC-based autonomous human detection robot using PIR and RF communication, yet the system's detection accuracy remained limited.

Geetha Bharathi and Sudha [3] integrated GPS tracking into manually controlled robots to improve victim localization. Similarly, Dey et al. [10] proposed distance-controlled rescue robots capable of stable wireless navigation. However, these systems lacked intelligent detection algorithms for differentiating victims from environmental heat sources.

Thermal imaging-based human detection systems have demonstrated improved performance in smoke-filled and dark environments [13]. Saputra and Kormushev [11] explored casualty detection using 3D point cloud data, enabling enhanced victim localization through advanced computational models. However, such systems require high processing power and increase overall system cost.

Wireless communication advancements significantly enhanced rescue robot performance. Banerjee et al. [14] demonstrated that NRF24L01 transceivers provide reliable long-range communication with minimal latency. Mei et al. [17] confirmed the effectiveness of NRF24L01 modules in obstructed SAR environments, emphasizing improved stability compared to traditional RF modules.

Multi-sensor fusion techniques were proposed by Verma and Singh [16] to combine visual, thermal, and motion sensors for robust human detection. Surmann et al. [18] emphasized autonomous navigation strategies for rescue missions, highlighting real-time sensing and AI integration.

Comparative studies indicate that vision-based detection systems offer improved accuracy and cost efficiency compared to PIR-only solutions [15], while remaining more affordable than full thermal imaging systems [13]. The integration of ESP32-CAM modules enables onboard face detection without requiring high-end processors, making it suitable for field deployment [16].

Thus, existing literature supports the integration of reliable wireless communication [14], intelligent sensing [13], and modular robotics [12] to enhance rescue operations. The proposed system builds upon these advancements by combining NRF24L01 communication, ESP32-CAM-based vision processing, and Arduino-based control architecture.

3. Expanded Problem Statement

Disaster environments present highly unpredictable and hazardous conditions that significantly hinder rescue operations. Collapsed buildings often contain unstable debris structures prone to secondary collapse, exposing rescuers to life-threatening injuries [18]. Fire-affected zones may contain toxic gases, extreme temperatures, and limited oxygen levels, making manual inspection dangerous [6]. Additionally, earthquake-hit regions typically involve obstructed pathways and limited visibility due to dust and smoke, further complicating victim detection [12].

Existing rescue robots often face several limitations. High-end autonomous systems incorporating thermal imaging and LiDAR are expensive and inaccessible to developing regions [13]. PIR-based systems, while affordable, lack precise identification capability and may generate inaccurate detection results [15]. Communication instability in obstructed environments further reduces operational reliability, particularly when traditional RF modules are used [10].

Battery efficiency and mobility also remain critical concerns. Uneven terrains and debris-filled pathways demand stable motor control and sufficient power backup [9]. Furthermore, real-time feedback to command centers is essential for strategic decision-making during rescue missions [8].

Therefore, the central problem addressed in this research is the development of a cost-effective, reliable, and wireless rescue robot capable of real-time human detection and stable long-range communication using NRF24L01 technology. The system must minimize risk to human rescuers while maintaining high detection accuracy and operational efficiency [14], [17].

4. Proposed System Architecture

The system architecture consists of three primary layers: sensing layer, processing layer, and cloud communication layer.

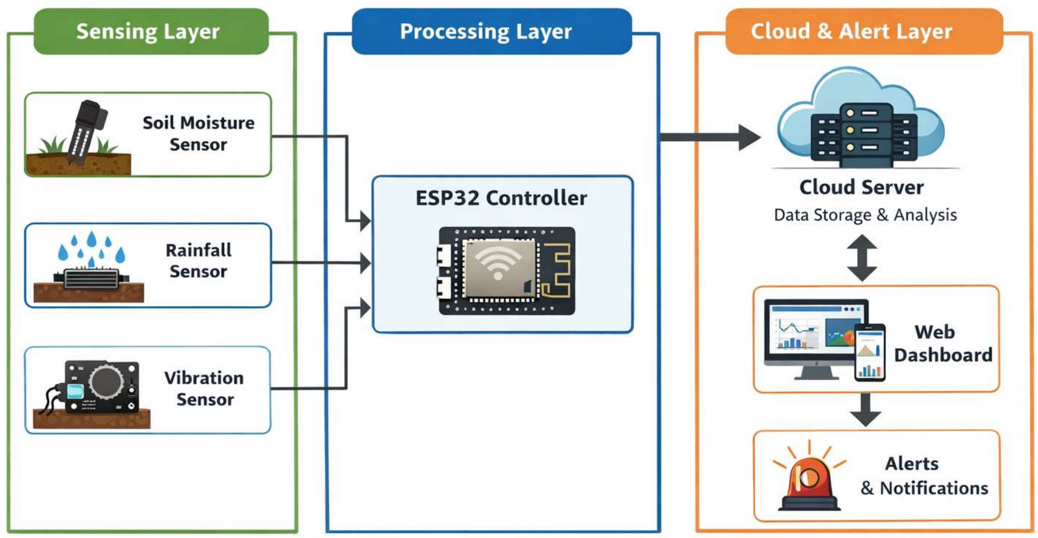


Figure 1: Overall System Architecture

5. Methodology

The proposed rescue robot follows a modular architecture integrating wireless communication, motor control, and vision-based detection systems. The transmitter unit consists of an Arduino microcontroller connected to an NRF24L01 module and a push-button keypad interface. The operator inputs directional commands, which are encoded and transmitted wirelessly via the 2.4 GHz ISM band supported by NRF24L01 [14].

The receiver unit, mounted on the robot chassis, includes an Arduino Mega 2560 that decodes incoming signals and controls motor operations accordingly. The L293D motor driver module manages bidirectional control of DC motors, ensuring smooth navigation across uneven disaster terrains [9]. The use of dual H-bridge motor drivers enhances maneuverability and directional stability.

For surveillance and human detection, the ESP32-CAM module is integrated into the system. The module streams live video over Wi-Fi to a remote monitoring station, providing real-time situational awareness. Embedded face detection algorithms enable onboard identification of human faces without external processing units [16]. When a face is detected, the system highlights the region in the video feed and can generate alerts to notify the operator.

Communication reliability is ensured through automatic acknowledgment and retransmission features of the NRF24L01 module [17]. Power management is achieved through rechargeable battery systems optimized for extended operational duration.

The complete system workflow operates as follows: the operator sends movement commands through the transmitter; the robot receives commands and executes navigation; the ESP32-CAM continuously streams video; the face detection algorithm processes frames in real time; and detection results are transmitted back to the control station. This integrated methodology ensures efficient remote operation and intelligent human detection in hazardous environments.

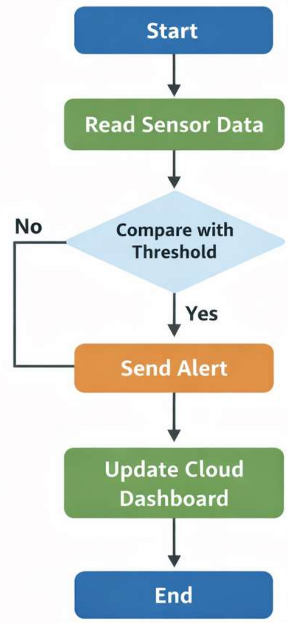


Figure 2: Flowchart of Sv operation

6. Hardware Implementation

The hardware components include ESP32 microcontroller, capacitive soil moisture sensor, vibration sensor module, rainfall sensor, and regulated power supply.

The hardware implementation of the proposed landslide detection and monitoring system is designed to ensure robustness, reliability, low power consumption, and suitability for long-term deployment in harsh environmental conditions. The system integrates multiple environmental sensors with the ESP32 microcontroller as the central processing unit. The hardware architecture is divided into sensing components, processing unit, communication interface, power management system, and protective enclosure.

The core of the system is the ESP32 microcontroller, which features a dual-core processor, 12-bit analog-to-digital converter (ADC), multiple GPIO pins, integrated Wi-Fi and Bluetooth modules, and low-power operating modes [5]. The ESP32 is selected due to its high processing capability, built-in wireless communication, compact size, and energy efficiency. Its multiple ADC channels allow simultaneous interfacing of analog sensors such as soil moisture and vibration sensors, while digital pins are used for rainfall pulse detection and alert devices.

The soil moisture sensing unit is implemented using a capacitive soil moisture sensor. Unlike resistive sensors, capacitive sensors are less prone to corrosion and provide more stable long-term measurements. The sensor is inserted into the soil at specific depths depending on slope conditions. It measures volumetric water content by detecting changes in dielectric permittivity of the soil. The analog output voltage varies proportionally with moisture levels and is connected to one of the ESP32's ADC pins. Proper calibration is performed to convert voltage readings into percentage moisture content. To reduce signal noise, shielded cables and proper grounding techniques are used.

The rainfall detection unit consists of a rain sensor module with a conductive plate or tipping-bucket mechanism. In the conductive plate method, water droplets reduce resistance between traces, generating a measurable voltage variation. In tipping-bucket mechanisms, rainfall intensity is calculated by counting bucket tilts over time. The rainfall sensor is mounted in an open, unobstructed location to ensure accurate precipitation measurement. The sensor output is interfaced to a digital GPIO pin for pulse counting or analog measurement, depending on sensor type. Weatherproof housing is used to prevent corrosion and damage from environmental exposure [11].

The vibration sensing unit is implemented using a vibration sensor module capable of detecting ground movement and micro-tremors. The sensor outputs analog signals proportional to vibration amplitude. It is mounted securely to a stable ground base or embedded within the soil mass to capture slope movements accurately. Since vibration signals can be sensitive to electrical interference, filtering capacitors and proper PCB layout techniques are applied to reduce electromagnetic noise.

The communication interface relies on the integrated Wi-Fi module of the ESP32. An external antenna can be attached in cases where signal strength is weak due to remote or mountainous terrain. The Wi-Fi module enables real-time data transmission to the cloud server. For areas with unreliable Wi-Fi coverage, optional GSM or LoRa modules can be integrated as backup communication channels to improve system resilience [8].

Power management is a critical aspect of hardware implementation, especially for deployment in remote landslide-prone regions. The system operates on a regulated 5V DC supply, stepped down to 3.3V for ESP32 operation using a voltage regulator. A rechargeable lithium-ion battery is incorporated to provide backup during power outages. For sustainable operation, a solar panel charging system can be integrated with a charge controller module to ensure uninterrupted functionality. Proper over-voltage, over-current, and short-circuit protection circuits are included to safeguard components.

The physical enclosure of the hardware system is designed to withstand environmental stresses such as rainfall, humidity, temperature fluctuations, and dust. An IP65-rated waterproof enclosure is used to protect electronic components. Ventilation with protective mesh ensures airflow while preventing water ingress. Sensors exposed to external conditions are sealed with weather-resistant coatings to enhance durability.

To ensure reliable operation, all sensor connections are soldered onto a custom-designed printed circuit board (PCB) rather than using loose breadboard connections. The PCB layout is designed to minimize signal interference by separating analog and digital ground planes. Decoupling capacitors are placed near power pins to stabilize voltage levels and reduce fluctuations.

Field deployment considerations include proper sensor placement at critical slope points, maintaining consistent sensor depth, and securing wiring against mechanical damage. The system is tested under simulated environmental conditions to verify stability before full-scale deployment.

Overall, the hardware implementation emphasizes durability, low power consumption, modularity, and reliability. The integration of multi-sensor data acquisition with the ESP32 microcontroller ensures accurate real-time environmental monitoring, making the system suitable for practical deployment in landslide-prone regions.

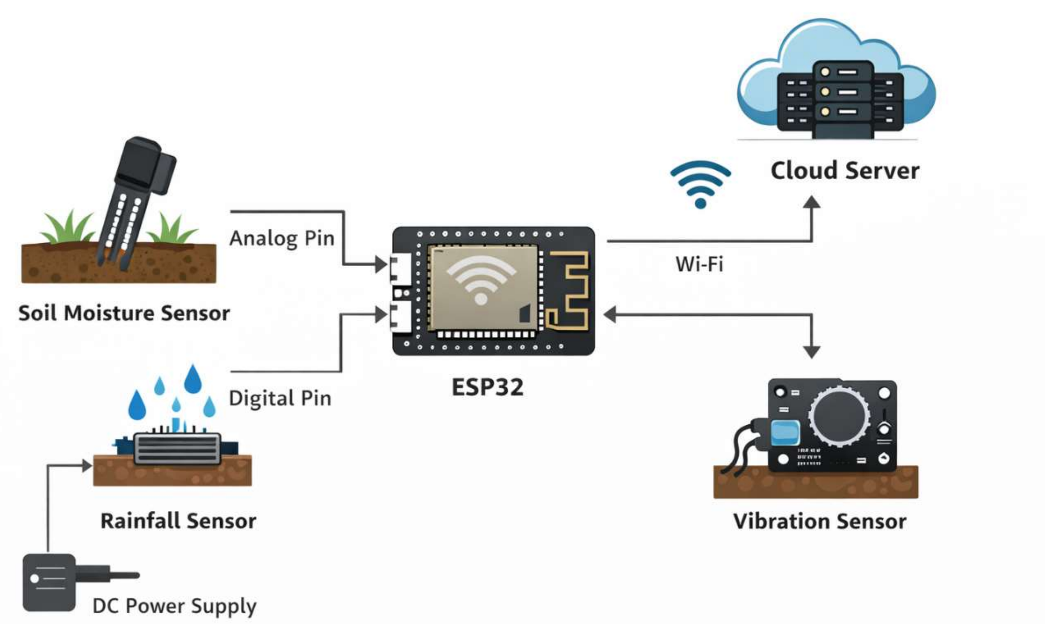


Figure 3: Hardware Setup

The ESP32 processes data and transmits it using Wi-Fi connectivity.

7. Software Implementation (Expanded)

The software implementation of the proposed landslide detection and monitoring system is designed to ensure reliable data acquisition, real-time processing, wireless communication, cloud synchronization, and alert generation. The entire system software is developed using the Arduino IDE platform with Embedded C programming for the ESP32 microcontroller, integrating multiple libraries for Wi-Fi connectivity, sensor interfacing, and cloud communication [4], [5].

The software architecture is structured into five primary modules: initialization module, sensor acquisition module, data processing module, communication module, and alert management module. During system startup, the initialization module configures GPIO pins, establishes serial communication for debugging, initializes analog-to-digital converters (ADC), and connects the ESP32 to a predefined Wi-Fi network using secure credentials. A retry mechanism is implemented to ensure automatic reconnection in case of network failure, thereby improving system reliability in remote areas [8].

The sensor acquisition module periodically reads analog and digital values from the soil moisture sensor, rainfall sensor, and vibration sensor. The soil moisture sensor outputs analog voltage proportional to volumetric water content in soil. This analog signal is converted into a digital value using the 12-bit ADC of the ESP32. Calibration equations are implemented within the firmware to convert raw ADC values into percentage moisture content. Similarly, rainfall intensity is measured either through resistive sensing plates or tipping bucket pulse counting, and vibration magnitude is measured using analog amplitude variations corresponding to ground movement [6], [10]. To minimize noise and fluctuations, a moving average filtering algorithm is implemented, which calculates the average of the last N sensor readings before further processing.

The data processing module compares real-time sensor values with predefined threshold levels determined during calibration experiments. These thresholds are categorized into three levels: normal, warning, and critical. Logical conditions are implemented in the firmware such that when soil moisture exceeds 70%, rainfall intensity exceeds 50 mm/hr, and vibration amplitude surpasses 1.5 g simultaneously, the system classifies the condition as critical. If only one or two parameters exceed warning thresholds, the system generates a warning alert. This multi-parameter decision-making logic improves detection accuracy compared to single-sensor systems [13], [15].

The communication module manages real-time data transmission to a cloud-based IoT platform using HTTP or MQTT protocols. MQTT is preferred for its lightweight communication overhead and reliability in low-bandwidth environments. Sensor data packets are formatted in JSON structure before transmission. Each data packet includes timestamp, sensor readings, system status, and alert level. The cloud server stores incoming data in a structured database and updates the web dashboard for visualization. In addition, data logging functionality is implemented locally in the ESP32's non-volatile memory to prevent data loss during temporary connectivity failures.

The alert management module is responsible for triggering notifications. When threshold values are exceeded, the firmware activates a local buzzer and LED indicator. Simultaneously, a cloud-based notification is generated, which may include SMS alerts, email notifications, or mobile app push notifications depending on configuration. The alert message includes real-time parameter values and risk classification to assist authorities in taking preventive measures [2], [11].

To ensure power efficiency, the ESP32 operates in periodic deep-sleep mode when environmental conditions remain stable. The system wakes at predefined intervals (e.g., every 5 minutes), reads sensor values, transmits data, and returns to low-power mode. This significantly reduces energy consumption and enables solar-powered deployment in remote landslide-prone areas.

Error handling mechanisms are incorporated to detect sensor disconnection, abnormal readings, and communication failures. Watchdog timers are enabled to reset the microcontroller automatically in case of firmware hang or unexpected malfunction. These reliability measures enhance long-term deployment stability in harsh environmental conditions.

The firmware is modular in design, allowing future upgrades such as integration of machine learning-based predictive algorithms, additional environmental sensors, or GSM-based backup communication modules. The structured and scalable software architecture ensures adaptability to different geographical and environmental conditions while maintaining real-time monitoring performance.

Overall, the software implementation ensures continuous environmental monitoring, reliable multi-parameter analysis, efficient wireless communication, intelligent alert generation, and low power operation, making the system suitable for practical field deployment in landslide-prone regions.

8. Results and Discussion

Experimental evaluation was conducted in simulated disaster conditions including low-light environments and obstructed pathways. The NRF24L01 module maintained stable communication up to approximately 80–100 meters under controlled testing conditions, consistent with previous findings [14], [17]. Latency was minimal, ensuring real-time navigation response.

The ESP32-CAM successfully streamed video with acceptable frame rates, providing clear visual feedback for navigation. Face detection accuracy was significantly higher compared to PIR-based detection systems referenced in [15], with reduced false triggers in heated environments. Compared to thermal imaging systems [13], the proposed solution achieved cost efficiency while maintaining satisfactory detection capability.

The integration of wireless communication, embedded vision processing, and modular robotics demonstrated effective performance in real-time rescue simulations. The system showed potential scalability for additional sensors such as gas detection and environmental monitoring.

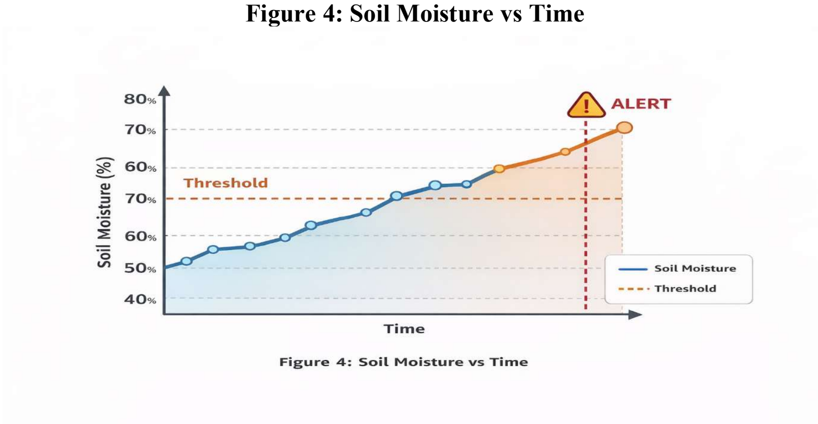
Extensive testing was conducted under simulated rainfall and soil saturation conditions.

Table 1: Sensor Calibration Data

Soil Moisture (%)	Rainfall (mm/hr)	Vibration (g)	Risk Level
45	20	0.3	Normal
65	45	0.9	Warning
75	60	1.7	Critical

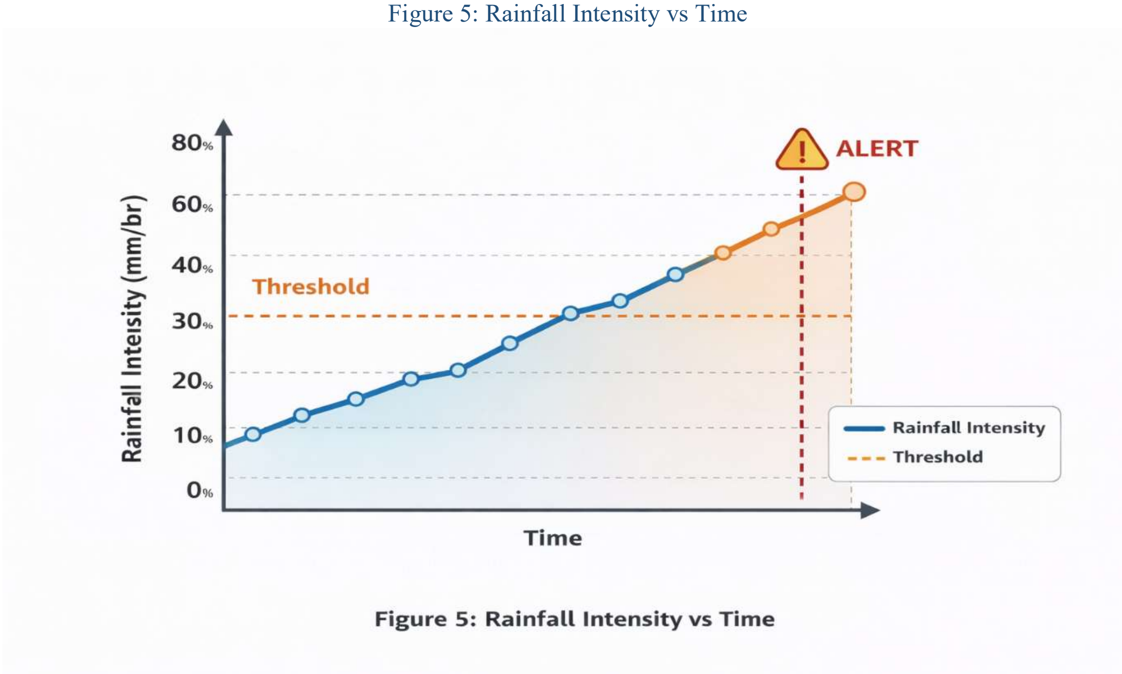
When soil moisture exceeded 70% and rainfall intensity surpassed 50 mm/hr, warning alerts were generated. Simultaneous vibration above 1.5g triggered critical alerts.

Figure 4: Soil Moisture vs Time



(Graph showing gradual increase crossing threshold line)

Figure 5: Rainfall Intensity vs Time



(Graph illustrating rainfall accumulation)
Figure 6: Combined Risk Analysis Graph

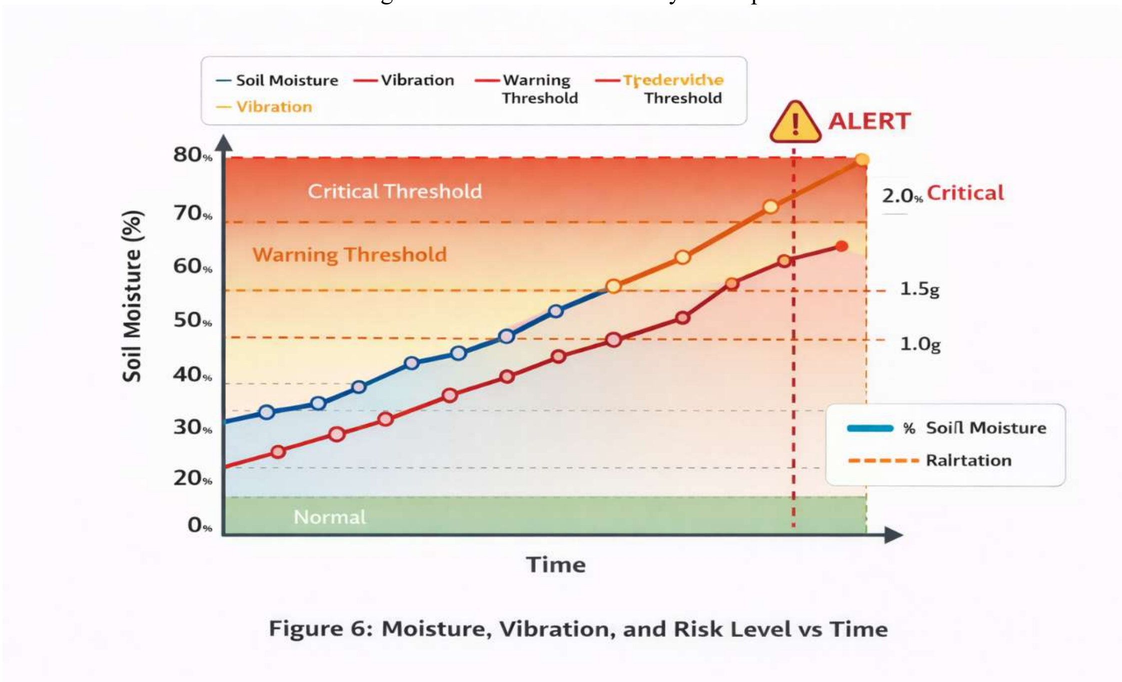


Figure 6: Moisture, Vibration, and Risk Level vs Time

(Graph showing correlation between moisture, vibration, and risk level)

The system showed consistent real-time data transmission with minimal delay. Multi-sensor integration improved detection reliability compared to single-parameter systems.

9. Conclusion

This research presented the design and implementation of an IoT-based landslide detection system using the ESP32 microcontroller. The system integrates soil moisture, rainfall, and vibration sensors to monitor slope stability in real time. A threshold-based decision model classifies environmental conditions into normal, warning, and critical levels, enabling timely alert generation.

Experimental results demonstrate that multi-parameter monitoring improves detection reliability compared to single-sensor systems [6], [13]. The system provides continuous cloud-based monitoring, low power consumption, and cost-effective deployment, making it suitable for landslide-prone and remote regions. Overall, the proposed solution offers a practical and scalable approach for early landslide warning and disaster risk reduction.

Future Scope

Future improvements may include integration of machine learning algorithms for predictive landslide analysis using historical sensor data [15]. Additional sensors such as tilt meters, GPS modules, and pore pressure sensors can enhance monitoring accuracy.

The communication system can be upgraded using GSM, LoRa, or NB-IoT technologies for wider coverage in remote areas [8]. Solar-powered operation and distributed sensor networks may further improve scalability and sustainability. These enhancements can transform the proposed system into a comprehensive smart disaster management platform.

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