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An Integrated Natural Disaster Detection Framework for Enhancing Coastal Safety

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ABSTRACT

This paper proposes an integrated natural disaster detection framework designed to enhance coastal safety by leveraging Internet of Things (IoT) technologies. The system integrates NodeMCU ESP32S microcontrollers, ultrasonic sensors for water level measurement, and MPU6050 sensors for seismic activity monitoring. Powered by solar and battery systems, the framework ensures resilience in remote environments. Real-time alerts are disseminated through visual indicators, Telegram, and a dedicated mobile application. The design emphasizes bridging the communication gap, ensuring timely and accessible warnings for coastal populations. Comparative analysis with existing systems highlights the advantages of the proposed architecture in terms of coverage, cost-effectiveness, and reliability. The framework also supports future integration of advanced AI/ML algorithms to improve accuracy and predictive capabilities. Overall, the system provides a robust and scalable approach to disaster preparedness, response, and risk reduction.

Keywords: Coastal safety, Disaster detection, Early warning system, IoT, Resilience

1. INTRODUCTION

Natural hazards, including floods, storms, and landslides, pose a significant and increasing threat to societies globally. Between 2000 and 2019, 7,348 disaster events occurred worldwide, resulting in 1.23 million fatalities and an estimated US$2.97 trillion in economic losses [1]. Coastal communities are particularly susceptible to the devastating impacts of tsunamis and earthquakes [2]. Tsunamis, generated by large and sudden oceanic displacements, can manifest as incredibly destructive waves, sometimes exceeding 100 feet in height, capable of inundating areas over a mile inland and causing widespread destruction to infrastructure and significant loss of life [3].

Early warning system (EWS) are indispensable tools for effective risk management and disaster preparedness, playing a crucial role in saving lives and minimizing the potential adverse impacts of natural disasters [4]. An effective EWS is characterized by its ability to accurately detect emerging threats, a robust civil communication system for timely public dissemination of warnings, and comprehensive pre-event education and preparedness initiatives within the community [2]. Such systems empower individuals, communities, and organizations to undertake appropriate pre-emptive measures, thereby significantly reducing the overall impact of a disaster [4]. Despite their importance, traditional EWS face several inherent limitations. These include the sparse geographical distribution of sensors, high operational costs, delays in information dissemination, buoys loss and others [5].

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In contrast, the Internet of Things (IoT) offers transformative capabilities for enhancing public safety, disaster response and emergency management. By leveraging interconnected devices and real-time data streams, IoT systems can provide continuous monitoring of environmental parameters, such as seismic activity, river water levels, and soil moisture [6]. When these measurements reach predefined critical thresholds, the system can automatically trigger alerts, facilitating timely evacuations and proactive response measures [6].

There is a pressing need for advanced systems that can provide timely and accurate information to enable proactive responses to natural disasters [7]. Many current IoT frameworks, however, struggle with issues related to scalability, real-time data processing, and efficient data handling, which can compromise their effectiveness during large-scale disaster scenarios [8]. Furthermore, integrating these advanced technologies with existing legacy disaster management infrastructures poses significant technical and logistical challenges [8]. To address these multifaceted issues, a comprehensive, integrated framework is essential for robust and effective multi-hazard coastal detection [1].

This project proposes a comprehensive Natural Disaster Detection System specifically designed to enhance coastal safety by leveraging Internet of Things (IoT) technologies. The system integrates real-time monitoring of seismic activity and water levels, utilizing NodeMCU ESP32S microcontrollers powered by resilient solar and battery systems for deployment in remote coastal environments. It employs ultrasonic sensors for water level measurements and MPU6050 sensors for motion and seismic detection. Upon detecting critical conditions, the system triggers immediate alerts through multiple channels, including visual indicators, and Telegram notifications. The aim is to significantly improve early warning capabilities, mitigate risks, and facilitate swift response measures to safeguard coastal populations from natural disasters.

2. RELATED WORK

The application of IoT in disaster management is a rapidly expanding field, encompassing flood monitoring, earthquake detection, and broader environmental change surveillance [6]. Typically, these systems comprise various sensors for data collection, microcontrollers for local processing, and diverse communication networks for data transmission [9]. Noteworthy examples include IoT-based flood detection systems utilizing ultrasonic sensors and rain gauges for water level monitoring [9], and earthquake detection systems that leverage accelerometers to identify seismic activity [10].

2.1 Analysis of Sensor Technologies

2.1.1 Ultrasonic Sensors

The HC-SR04 ultrasonic sensor is a widely adopted, cost-effective device for distance measurement. It operates by emitting ultrasonic waves at a frequency of 40 kHz and calculating the distance to an object based on the time it takes for the echo to return [11]. The fundamental principle is Distance = (Speed of Sound × Time) / 2 [11]. Its technical specifications typically include a measuring range of 2 cm to 400 cm with an accuracy of ±3 mm, operating at 5V DC with a 15mA working current and a 15-degree measuring angle [11]. Its simplicity makes it easy to interface with microcontrollers [11]. A significant challenge for ultrasonic sensors is their susceptibility to environmental factors. Changes in temperature, humidity, and air composition can alter the speed of sound, thereby affecting the accuracy of water level readings [12].

2.1.2 MPU6050 Sensors

The MPU6050 is a popular low-cost choice for earthquake detection and general vibration analysis due to its ability to detect subtle vibrations and changes in orientation [10]. It can detect low-frequency vibrations characteristic of P-waves, which are primary seismic shock waves [10]. While highly versatile, the accuracy of the MPU6050 can be influenced by factors such as calibration, specific environmental conditions, and the context of its application [10]. Critically, low-cost Micro-Electro-Mechanical Systems (MEMS) technology sensors like the MPU6050 can produce noisy signals, particularly in urban environments, necessitating robust data processing mechanisms to minimize false alarms [10].

The MPU6050 is a versatile 6-axis motion tracking device that integrates a 3-axis gyroscope and a 3-axis accelerometer, along with a Digital Motion Processor (DMP) [13]. It utilizes MEMS technology to sense motion and orientation. The accelerometer measures linear acceleration based on the piezoelectric effect, while the gyroscope measures angular rotation based on the Coriolis effect [14]. The sensor features integrated 16-bit Analog-to-Digital Converters (ADCs) for high accuracy and communicates via the I2C protocol [13]. Its configurable ranges include ±2g to ±16g for acceleration and ±250 to ±2000 °/s for angular velocity [14].

2.2 Communication Protocols for Data Transmission

IoT devices rely on various networking techniques to facilitate data transmission [15]. For localized connectivity, Wi-Fi and Bluetooth are commonly employed [16]. However, for applications requiring long-range and low-power communication, such as collecting data from thousands of sensors in remote or hard-to-reach areas, Low Power Wide Area Network (LoRaWAN) stands out as a highly suitable protocol [15]. LoRaWAN offers an expansive operational range (up to 15 km in rural settings), minimal power consumption (enabling devices to operate for years on a single battery), cost-effectiveness, and high scalability [17]. It is specifically noted for its applicability in coastal environment monitoring [18].

Message Queuing Telemetry Transport (MQTT) is a lightweight messaging protocol well-suited for constrained devices and low-bandwidth, high-latency, or unreliable networks. It is frequently used with microcontrollers like the ESP32 for efficient data transfer to IoT servers [19]. Cellular networks (e.g., GSM, 3G, 4G, 5G) also serve as vital communication channels, particularly for "last-mile" alerts and in scenarios where other wireless options are limited [9].

The choice of communication protocol is not merely a technical detail but a critical determinant of the system's practical viability and resilience in remote coastal environments. If the system were to primarily rely on Wi-Fi for sensor data transmission, its operational range would be severely restricted to areas with existing Wi-Fi infrastructure. For true remote functionality, a long-range, low-power protocol like LoRaWAN becomes a necessity for backhauling sensor data where conventional Wi-Fi or cellular networks are impractical or unavailable [15]. This selection ensures that the system can effectively collect and transmit data from geographically dispersed and isolated coastal monitoring points, which are often beyond the reach of standard Wi-Fi networks. This design consideration is fundamental to achieving the intended operational scope and reliability of the framework.

2.3 Comparative Analysis of Existing IoT Disaster Detection Systems

A comparative analysis of existing IoT disaster detection systems is presented in Table 1, providing contextual understanding of the proposed framework. This table summarizes key characteristics, highlighting the diverse approaches and common challenges in the field.

Table 1 Comparative analysis of existing IoT disaster detection systems

System Name	Disaster Type(s) Monitored	Key Sensors Used	Communication Methods	Features	Limitations
Indian Tsunami EWS (ITEWS) [2]	Tsunami, Seismic	Seismic network, Tsunami buoy network, Tide levels	Civil communication system (dissemination)	24/7 manned/automated center, pre-run scenario models, SIL4/SIL3 reliability	High cost of buoys, fragility/loss of buoys, time delay in info dissemination, limited coverage
Japan's EWS (2011 Tohoku) [5]	Earthquake, Tsunami	Seismographs	Public broadcast (TV, radio), phone	EEW system, tsunami database simulations	Underestimation of magnitude/height, communication failures, lack of offshore gauges, lack of urgency in announcements
LoRaWAN for Disaster Monitoring [20]	General Disaster Monitoring	Various IoT devices	LoRaWAN	Long range, low power, high scalability	Vulnerabilities, performance degradation under high load
IoT-Based Landslide Early Warning [21]	Landslide	Soil moisture sensors	Wi-Fi (NodeMCU 8266)	Energy neutrality, autonomous optimization	Energy variability, scalability, operational sustainability in harsh environments
Earthquake Monitoring [22]	Earthquake	Satellite-derived data		Monitoring predefined regions, spatial/temporal data mining	Difficulty in predicting exact timing, region-specific

This comparative analysis highlights several key gaps that the proposed integrated framework aims to address. Existing systems often suffer from limitations in coverage, particularly in remote or unequipped areas, due to high costs and infrastructure fragility. There are also persistent challenges in ensuring timely and accurate information dissemination, especially when traditional communication channels fail during a disaster. The proposed framework seeks to overcome these limitations by integrating cost-effective, resilient hardware with multi-channel communication strategies and human-centered warning dissemination.

3. SYSTEM ARCHITECTURE AND DESIGN

Figure 1 shows the block diagram of Natural Disaster Detection System for Coastal Safety. The system has several crucial parts for both inputs and outputs. An ultrasonic sensor is used to measure sea level changes for inputs by determining the level of sea after the earthquake. By measuring acceleration and gyroscopic movements, a motion sensor can detect seismic activity, thereby identifying potential earthquakes. Additionally, a water level sensor is used to gauge the water level in particular locations to avoid flooding. These sensors provide crucial real-time data that are necessary for timely disaster detection. For power supply, the system has a 5V solar panel and a 3.7 V ion battery as shown in Figure 2, making it continue to function even in remote coastal areas without a reliable power supply. The solar panel charges the battery, giving the system a reliable source of energy. An LED, an OLED display, a buzzer, and a telebot for notifications are the output components. The telebot sends user notifications via the LED, the OLED display provides detailed information about the detected events, and the buzzer sends audible warnings. All these things ensure that alerts are communicated quickly and effectively.

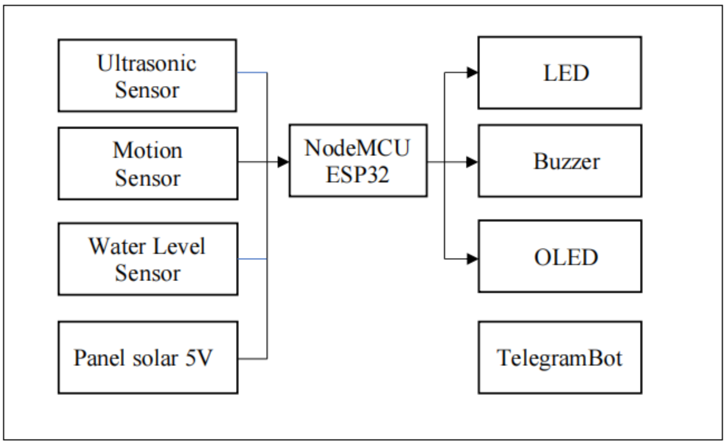

Figure 1 Block diagram of Natural Disaster Detection System for Coastal Safety

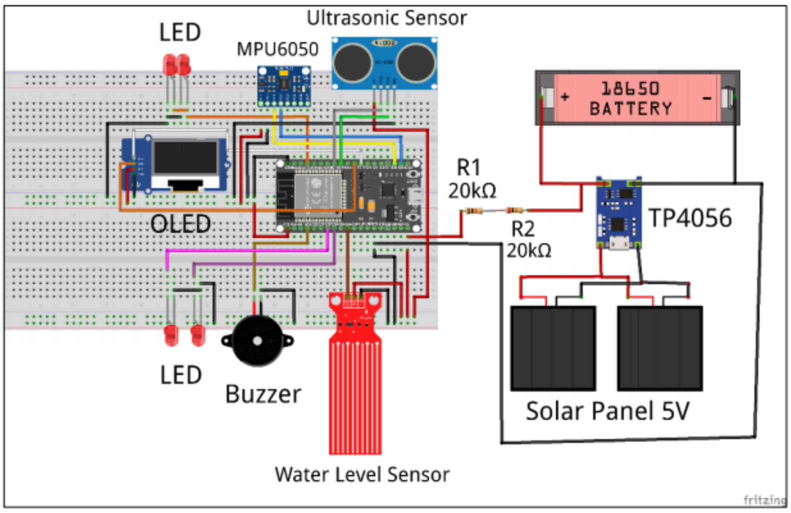

Figure 2 The Circuit Diagram

3.1 Design Flow and Process

Figure 3 shows the general flowchart of the proposed system. A 3.7V ion battery and a solar system power the NodeMCU ESP32S effectively. In remote coastal environments, this setup ensures uninterrupted operation and resilience. A water level sensor that activates at 2 meters and indicates potential flooding, as well as an ultrasonic sensor for monitoring sea levels, an MPU6050 for detecting motions exceeding 1000 m/s2 for indicating earthquakes. An LED and buzzer activate, giving immediate visual and audible alerts, when threshold breaches are discovered. Real-time sensor data is displayed on an OLED screen simultaneously, improving situational awareness and facilitating quick decision-making. When any sensor triggers an alert, the system's intended purpose is to send Telegram notifications, enabling swift responses and mitigation efforts in times of crisis. This comprehensive approach makes use of renewable energy sources to reduce grid power dependence and robust disaster detection and management capabilities along coastal regions.

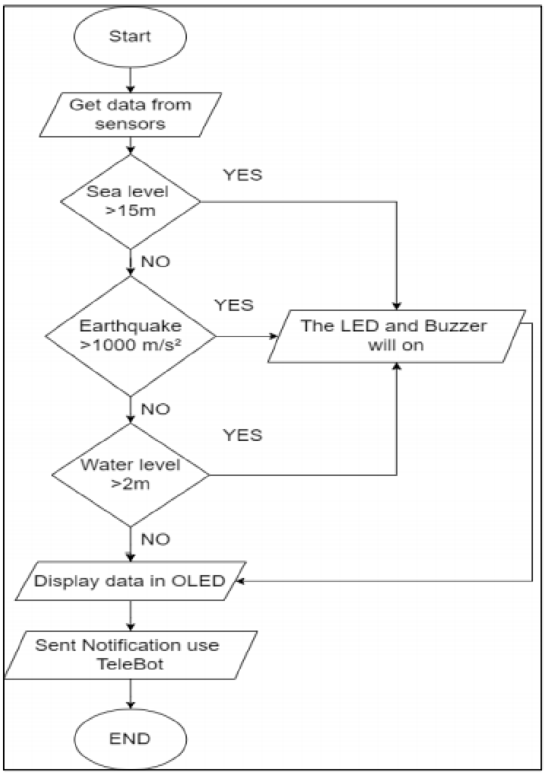

Figure 3 The general flowchart

Table 2 The voltage levels outputted by the MPU6050

Range of reading	Notification on Telegram
0v - 1v	-
1.1v - 2v	Alert Earthquake detected!
2v - 3.3v	Major Earthquake detected!

The earthquake's severity is categorized based Table 2, which varies from 0V to 3.3V depending on the intensity of the detected motion. By mapping these voltage levels to predefined categories, the system can classify the earthquake's intensity, providing detailed information in the Telegram alert. For instance, minor tremors might correspond to lower voltage readings (0V to 1V), moderate tremors to mid-range readings (1.1V to 2V), and severe tremors to higher readings (more than 2) as shown in Table 2. To implement the Telegram notification feature, the ESP32 is programmed to send messages via the Telegram API. When the MPU6050 detects motion exceeding the threshold, the microcontroller not only triggers the local alerts but also constructs a message detailing the earthquake's intensity based on the voltage reading. This message is then sent to the predefined Telegram bot, which disseminates the information to all subscribed users. This integrated notification system significantly enhances the functionality and utility of the earthquake detection project. By leveraging the ubiquitous presence of smartphones and the widespread use of messaging apps like Telegram, the system ensures that critical information reaches users promptly, enabling timely responses and potentially mitigating the impact of seismic events.

3.2 Design Implementation

The project to detect earthquakes using the MPU6050 Inertial Measurement Unit (IMU) focuses on monitoring ground movements via its integrated accelerometer and gyroscope. The MPU6050 continuously gathers acceleration and rotational motion data as shown in Figure 4, which is processed by a microcontroller (ESP32) to identify significant tremors. When movements exceeding a predefined more than 1000 m/s^2, indicating potential seismic activity, are detected by the MPU6050, the system triggers an alert by illuminating an LED and sounding a buzzer.

The process begins by initializing the MPU6050 and configuring it to start recording motion data. The microcontroller continuously reads this data, paying particular attention to the accelerometer values to identify sudden changes in acceleration that could signal an earthquake. By setting a specific threshold 1000 m/s^2 for acceleration, the system can distinguish between normal vibrations and significant seismic events. When the sensor data surpasses this threshold, the microcontroller activates the LED and buzzer, providing visual and auditory alerts to indicate potential danger.

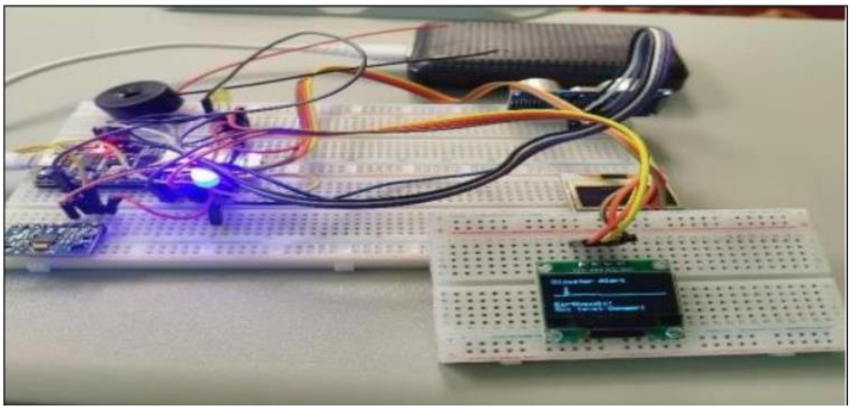

Figure 4 The earthquake detection circuit

Figure 5 shows a sequence of notifications on a Telegram chat, which is part of the detection system. This system is intended to alert users to significant natural disasters, such as earthquakes. In this instance, the notifications report the detection of a major earthquake with messages like "Alert Earthquake detected!" and "Major Earthquake detected!" sent at different times. This indicates that the system automatically detects and notifies users of natural disasters without requiring manual commands. Overall, this system is essential for providing timely alerts to enhance coastal safety, allowing residents and authorities to take prompt action to mitigate the impact of natural disasters. The use of real-time notifications via a widely used platform like Telegram improves accessibility and the immediate dissemination of critical information.

Figure 5 The Telegram bot notification on earthquake detection

Flood detection with a Water Level Sensor entails continually monitoring the water level in each location, such as a river, reservoir, or flood-prone zone. The Water Level Sensor, also known as a float switch or ultrasonic sensor, is strategically situated to properly monitor water depth. This sensor sends real-time data to a microcontroller (ESP32), which analyses the readings to determine whether the water level exceeds predefined safety limits.

Figure 6 shows the flood detection circuit. The process starts with the Water Level Sensor, which continuously monitors the water level. Upon detecting water, the sensor signals the ESP32 microcontroller. The microcontroller then activates an LED for a visual alert and shows the current water level on an OLED screen, providing immediate feedback for local monitoring and alerting nearby individuals to potential flooding.

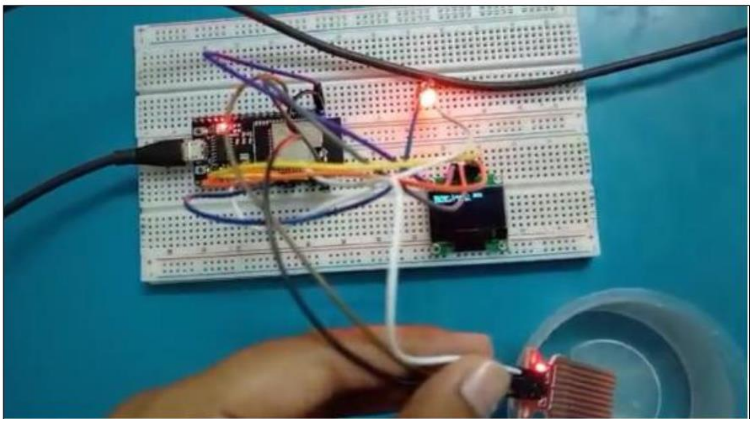

Figure 6 The flood detection circuit

The Telegram notification system in Figure 7 plays a crucial role in disseminating this information rapidly. Once the water sensor detects a high-water level, an urgent message is sent through Telegram, stating, "Emergency! Water level is high: 3536. Please evacuate immediately." This real-time alert mechanism ensures that users are immediately informed of potential flooding, allowing them to take swift action to ensure their safety. By leveraging a widely used platform like Telegram, the system enhances communication efficiency, ensuring that critical alerts reach a broad audience quickly.

Figure 7 The Telegram notification on flood detection

When the water level reaches between 1.5 and 1.9 meters, the ESP32 sends a notification to a Telegram bot, cautioning users about potential flooding. This early warning allows users to take precautionary measures. If the water level exceeds 2 meters, the system issues a more urgent notification, labelling it as a danger alert, prompting immediate actions such as evacuation or deployment of flood defences.

By integrating with Telegram, users receive real-time updates on their smartphones, even when away from the detection site. The microcontroller leverages the Telegram API to send these notifications, ensuring timely and reliable communication. This system enhances safety by providing both local and remote alerts, enabling prompt responses to rising water levels and mitigating the potential impact of flooding.

4. CONCLUSION

This project has detailed a comprehensive content framework for an integrated natural disaster detection system aimed at enhancing coastal safety. The proposed system leverages Internet of Things (IoT) technologies, specifically NodeMCU ESP32S microcontrollers, ultrasonic sensors for water levels, and MPU6050 sensors for seismic activity. Designed for resilience in remote coastal environments, it incorporates solar and battery power systems and disseminates immediate alerts through visual indicators and Telegram notifications. While the current framework focuses on foundational IoT elements and threshold-based detection, the current trend strongly suggests that integrating advanced AI and Machine Learning algorithms would significantly enhance the system's accuracy, reduce false alarms, and improve predictive capabilities, particularly when dealing with noisy data from low-cost sensors. This represents a crucial avenue for future development. Similarly, for truly remote coastal deployments, the adoption of a long-range, low-power communication protocol such as LoRaWAN for sensor data transmission would be essential to extend the system's operational reach beyond conventional Wi-Fi networks.

In conclusion, the proposed integrated natural disaster detection framework represents a significant step towards enhancing coastal safety through intelligent IoT deployment. By addressing the multifaceted challenges of disaster detection, communication, and resilience, this system has the potential to provide more timely and effective warnings, ultimately safeguarding lives and mitigating the impact of natural disasters on vulnerable coastal populations. Future work will focus on the full implementation of advanced data processing algorithms and the optimization of long-range communication for broad-scale deployment.

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