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ELUDE: Enhanced Landslide Understanding and Detection Engine Using IoT and Machine Learning

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***Abstract*—Landslides remain a persistent and deadly threat in regions with high rainfall and unstable terrain. To address the challenge of early detection in such areas, this paper presents ELUDE (Enhanced Landslide Understanding and Detection Engine), a low-cost, Wi-Fi-enabled landslide prediction and alert system. The system is built on the ESP32 Wroom microcontroller, supported by dual analog-to-digital converters for seamless integration of multiple analog sensors. These include modules for rainfall intensity, temperature and humidity, and ground vibration, which provide a comprehensive overview of environmental conditions. Collected data is transmitted wirelessly to a remote server for real-time analysis using a machine learning-based anomaly detection model. The proposed system emphasizes modularity, affordability, and ease of deployment in remote or inaccessible terrains. Key contributions include: (1) a unified hardware-software architecture for continuous monitoring, (2) real-time data acquisition and transmission using lightweight IoT protocols, and (3) predictive alert generation based on terrain behaviour patterns. Field-level testing demonstrates the system's accuracy and responsiveness, highlighting its potential for integration into regional disaster preparedness frameworks.**

***Index Terms*—ESP32 Wroom, Analog-to-Digital Converter, Machine Learning, Sensor Network, Vibration Sensor, Rainfall Detection, Wi-Fi Communication.**

1. INTRODUCTION

Landslides are destructive natural disasters that frequently occur in hilly and high-rainfall regions, leading to severe damage to life, infrastructure, and the environment. The unpredictability and sudden nature of such events make early detection systems critically important. To address this issue, we propose ELUDE: Advanced Landslide Prediction and Early Warning System, a real-time, sensor-integrated platform designed to monitor environmental factors and provide proactive alerts. The term "elude" means to escape or avoid danger, which aligns with the system's core objective—to help communities and authorities avoid the consequences of an impending landslide by enabling early action.

Technically, ELUDE utilizes multiple environmental sensors—including a rain sensor, DHT11 temperature-humidity sensor, and vibration sensor—interfaced with an ESP32 Wroom microcontroller. Two analog-to-digital converters are used to ensure precise analog signal processing. Data is continuously captured and transmitted via Wi-Fi to a server, where a machine learning model analyzes the readings to detect early signs of landslide-prone conditions. The results are visualized on a real-time web dashboard, which includes environmental parameter graphs and an alert system (e.g., "Landslide Detected" or "No Landslide"). This compact, cost-effective system emphasizes reliability, scalability, and ease of deployment, aiming to provide a practical solution for disaster prevention in vulnerable regions.

2. ARCHITECTURE

We designed the ELUDE system with a modular, real-time architecture tailored for deployment in landslide-prone regions. Our process begins with the collection of environmental parameters vibration, rainfall, temperature, and humidity using analog sensors. These sensor outputs are first digitized through an Analog-to-Digital Converter (ADC), enabling precise input to our core processing unit.

We used an ESP32 microcontroller as the heart of our system for its low-power consumption and reliable network connectivity. It handles data transmission while being powered by a 3.3V to 5V regulated supply. Once digitized, sensor data is stored in a structured format containing historical logs and alert triggers, which helps in evaluating long-term terrain behaviour.

Our data then moves into the processing and analysis layer, where we implemented custom thresholding, early warning logic, and basic decision-making algorithms to detect anomalies. When potential landslide conditions are identified, the system communicates with our User Interface (UI)—which we configured to visualize incoming data and allow real-time parameter adjustments. Finally, when conditions are met, we trigger alerts via the Early Warning System, notifying authorities or locals about possible threats.

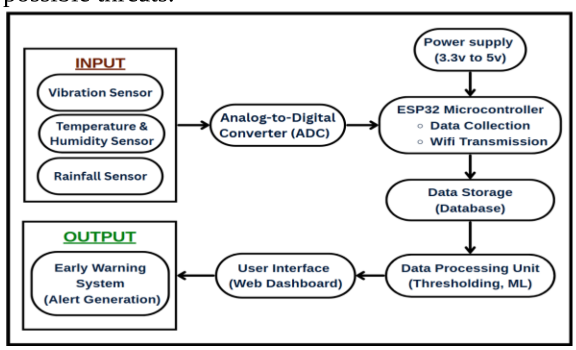

Figure 2.1: Block Diagram

3. METHODOLOGY

The proposed system, ELUDE, is designed to predict landslides in real-time using a combination of environmental sensors, cloud integration, and machine learning. The hardware setup includes a DHT11 sensor for temperature and humidity, a vibration sensor, and a rain sensor, all interfaced through the ESP32 Wroom microcontroller. These sensors collect real-time data from the environment and transmit it to a Firebase Real-Time Database, which acts as a cloud backend for persistent storage and remote access.

On the server side, a Flask-based web application fetches the data from Firebase using a dedicated interface and continuously monitors the values of the environmental parameters. A Decision Tree Classifier, trained on historical landslide data using key features such as temperature, humidity, vibration, and rainfall intensity, is employed to predict the likelihood of a landslide. The machine learning model is trained using the scikit-learn library, and its prediction is used to determine whether a landslide condition exists. When such a condition is detected, the system triggers an alarm sound through the dashboard interface to notify nearby users and relevant authorities, providing early warning and improving disaster responsiveness.

A. Decision Tree Algorithm

A Decision Tree Classifier is a supervised machine learning algorithm used for classification tasks. It structures the data in a tree-like format where each internal node represents a decision based on input features, and each leaf node represents a classification outcome. The model is simple, interpretable, and effective for small to medium-sized datasets, making it ideal for time-sensitive and critical decision-making systems.

In our project, ELUDE (Enhanced Landslide Understanding and Detection Engine), the Decision Tree Classifier is utilized to determine the risk of a landslide using real-time environmental parameters such as temperature, humidity, ground vibration, and rainfall intensity. These sensor values are collected via an ESP32 module and pushed to a cloud database. The classifier processes this data to predict the occurrence of a landslide. The Decision Tree was selected for its transparency, fast inference, and ability to handle non-linear data boundaries, which are essential in dynamic and potentially hazardous conditions like landslide-prone zones.

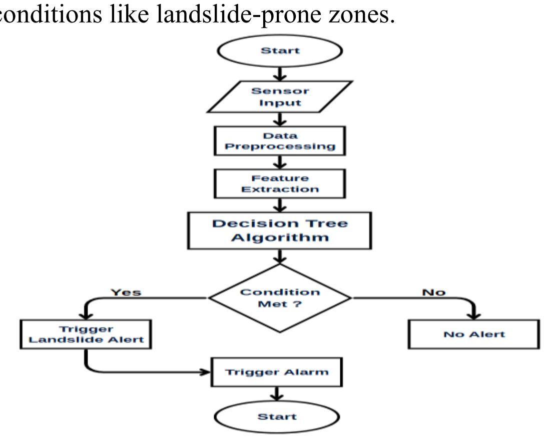

Figure 3.1: Decision Tree Classifier Algorithm

4. IMPLEMENTATION

A. Software

The software system is built using a Flask web application hosted on a local server. It performs the following:

1. Sensor Data Acquisition: The ESP32-WROOM collects real-time readings from rain, vibration, temperature, humidity, and inclination sensors and sends the data to the Flask server over Wi-Fi.
2. Prediction Logic: The server includes a predict () function that analyzes sensor thresholds to determine landslide risk. If risk is detected, an alert status is triggered.
3. User Interface: A web dashboard displays real-time sensor values and system status. The dashboard also shows visual indicators when thresholds are breached.
4. User Authentication: Includes simple login and registration features for restricted access to the dashboard.
5. Alert System: When landslide conditions are detected, an alert message is displayed on the web dashboard, and an alarm (siren) is triggered.

B. Hardware

1. SW-420 Vibration Sensor Module:

- Operating Voltage: 3.3V to 5V, making it compatible with most microcontrollers like Arduino and Raspberry Pi.
- Sensitivity Adjustment: Equipped with a potentiometer (the blue component) to adjust the sensitivity threshold.
- Output Pins: • DO (Digital Out): Provides a high or low signal based on vibration detection. • GND: Ground connection. • VCC: Power supply input (3.3V-5V).
- Indicator LEDs: Usually has an onboard LED to indicate power status and when vibration is detected.

Figure 4.1: SW-420 Vibration Sensor

2. ESP 32 Wroom Module

- Camera: OV2640 2MP image sensor.
- Wi-Fi : 802.11b/g/n/n/ac 2.4GHz Wi-Fi.
- Bluetooth : Bluetooth v4.2 BLE.
- Storage: 4MB SPI Flash.
- Pins: 34 GPIO pins.
- Power Supply: 3.3V DC.

Figure 4.2: ESP32-Wroom Module

3. Rainfall Sensor:

- Type: Analog Rain Sensor.
- Power Supply: 3.3V DC.
- Output: Analog voltage (varies with rainfall intensity).
- Connected To: ESP32 ADC GPIO pin.
- Use: Detects rain level for early warning logic.
- Working: Higher analog value = more rainfall.

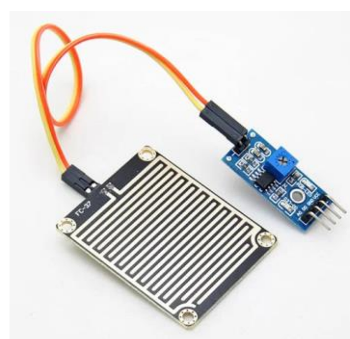

Figure 4.3: Rainfall Sensor

4. DHT11 Temperature and Humidity sensor:

- Type: Digital Temperature & Humidity Sensor.
- Power Supply: 3.3V to 5V DC.
- Output: Digital signal (single-wire protocol).
- Connected To: ESP32 GPIO pin.
- Use: Measures ambient temperature and humidit.
- Accuracy: ±2°C (temp), ±5% RH (humidity).

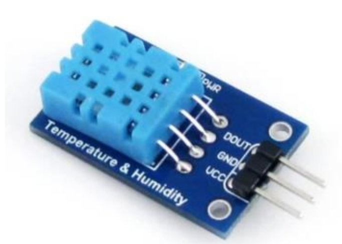

Figure 4.4: DHT11 Temperature and Humidity sensor

5. RESULTS

After successful integration of the hardware and backend system, our ELUDE project was tested under simulated conditions to validate its performance. The ESP32-WROOM module efficiently collected real-time data from multiple sensors including rain, vibration, temperature, humidity, and inclinometer. This sensor data was transmitted to our Flask-based web application, which displayed it on a secure and user-friendly dashboard. The prediction function was tested rigorously and showed correct behaviour by immediately triggering an alarm when any sensor values exceeded the defined safety thresholds. The front-end interface reflected these changes in real time, making it easy to monitor environmental conditions.

During testing, the system demonstrated reliable responsiveness and accuracy. The detection logic consistently identified potential hazards without generating false alarms or overlooking critical changes. Additionally, the login and user authentication system worked smoothly, supporting secure access and role-based control of the dashboard. Overall, ELUDE successfully fulfilled its intended role as a lightweight and responsive early warning system. Its real-time operation, integration simplicity, and strong sensor performance suggest its practical usability in landslide-prone regions.

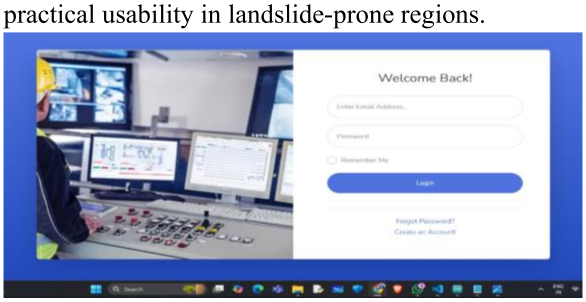

Figure 5.1: Registration & Login Page

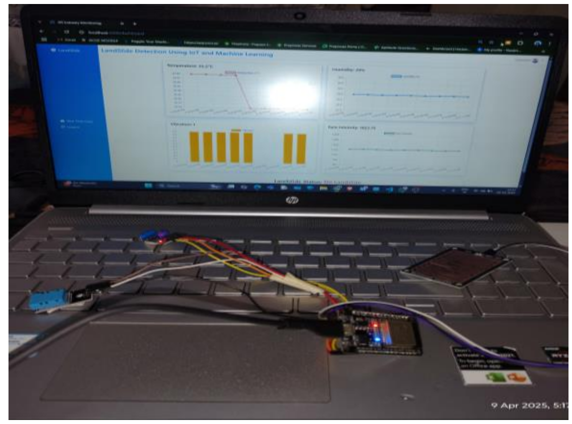

Figure 5.2: Hardware Implementation

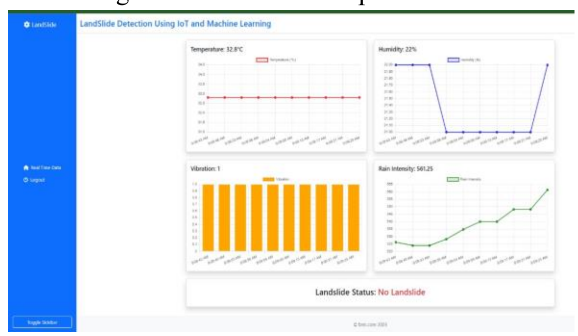

Figure 5.3: Landslide Not Detected - No Alert

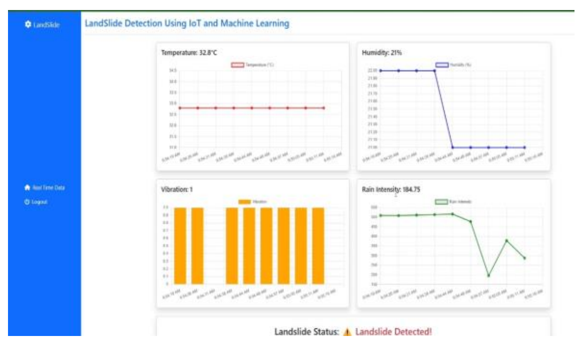

Figure 5.4: Landslide Detected - Alert Generated

6. CONCLUSION

The ELUDE system presents a reliable and cost-effective solution for landslide prediction and early warning in regions susceptible to high rainfall and unstable terrain. By integrating multiple environmental sensors—rain, temperature, humidity, and vibration—interfaced with the ESP32 Wroom microcontroller, the system continuously collects and transmits real-time data. This data is then processed on a remote server using a machine learning-based anomaly detection model to assess the likelihood of landslide events. When hazardous conditions are detected, the system triggers timely alerts through a user-friendly web dashboard, enabling authorities and local communities to take proactive measures.

The field tests conducted demonstrate that the ELUDE system reliably identifies landslide-prone conditions with minimal false alarms. Its modular architecture, combined with the low-cost, easy-to-deploy design, makes it highly suitable for use in remote or hard-to-reach areas. The real-time monitoring and predictive alert capabilities offered by ELUDE significantly enhance disaster preparedness and response, ensuring that communities in landslide-prone regions can take preventative actions to safeguard lives and infrastructure.

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