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Real-Time Multi-Modal Landslide Early Warning System via IoT- Based Deterministic Threshold Monitoring

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ABSTRACT: Landslides represent a catastrophic geohazard in mountainous and hilly regions, frequently triggered by complex interactions between soil saturation, seismic instability, and intense precipitation. Despite their destructive potential, traditional geodetic monitoring techniques are often reactive, expensive, and lack the high-frequency temporal resolution necessary for effective community-level early warning. This research proposes the design and implementation of an integrated, multi-modal early warning system (EWS) utilizing a distributed three-node IoT sensor network orchestrated by the dual-core ESP32 microcontroller. The perception layer comprises a suite of high-precision sensors, including the MPU6050 6-axis inertial measurement unit for detecting rotational slope shifts, the SW-420 for high-sensitivity vibration interrupt triggers, and capacitive soil moisture probes for non-drift saturation monitoring. To enhance predictive accuracy, the system incorporates a custom-calibrated DIY tipping bucket rain gauge that provides precise quantitative precipitation data in mm/hr, facilitating the transition from binary detection to professional-grade intensity-duration thresholding.The processing layer utilizes a deterministic weighted risk index algorithm—calculating a composite score based on soil moisture (40%), rainfall intensity (40%), and ground vibration (20%)—to distinguish genuine geological precursors from environmental noise. System reliability was ensured through a 72-hour baseline calibration phase and validated via controlled laboratory simulations involving physical slope tilting and volumetric soil saturation. Experimental results demonstrate a near-instantaneous cloud synchronization latency of less than 500 ms using the Firebase Realtime Database and a local alert response time of under 3 seconds for siren activation and high-priority push notifications via Firebase Cloud Messaging (FCM). By bridging the technical gap between raw geological sensing and multi-platform warning dissemination, the proposed system offers a scalable, low-cost, and high-visibility solution for proactive disaster preparedness in resource-constrained hilly regions.

KEYWORDS: Landslide Early Warning System (LEWS), ESP32, Internet of Things (IoT), MPU6050, Deterministic Thresholds, Soil Moisture Saturation, DIY Tipping Bucket, Disaster Mitigation.

I. INTRODUCTION

Landslides are among the most destructive natural geohazards, resulting in catastrophic loss of life and the decimation of critical infrastructure. In 2024 alone, fatal landslides in regions such as Afghanistan and Papua New Guinea claimed thousands of victims, while annual damages in mountainous regions like the Indian Himalayas now exceed USD 20 billion. Traditional slope monitoring relies on manual field inspections and periodic geodetic surveys using high-cost instrumentation. However, these methods are often insufficient for modern disaster risk reduction because they lack the high-frequency temporal resolution required to capture the rapid onset of shallow landslides. Consequently, there is an exigent need for a low-cost, continuous IoT monitoring solution capable of providing instantaneous alerting at the community level.

The emergence of the Internet of Things (IoT) paradigm offers a transformative framework for addressing these geological monitoring gaps. Recent research identifies soil moisture saturation, ground vibration, and slope tilt as the most reliable precursors for predicting imminent slope failure. By leveraging high-speed microcontrollers to process these parameters at the network "edge," early warning systems (EWS) can identify hazardous conditions and trigger local

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alerts in less than 3 seconds, significantly improving evacuation lead times.

This research proposes the design and implementation of a real-time, multi-modal landslide early warning system (LEWS) orchestrated by a distributed three-node IoT network using the dual-core ESP32 NodeMCU. The perception layer comprises a high-precision MPU6050 6-axis inertial measurement unit (IMU) for slope shift detection, an SW-420 vibration sensor for seismic interrupt triggers, and capacitive soil moisture probes to monitor groundwater infiltration. A core technical innovation of the prototype is the implementation of a custom-calibrated DIY tipping bucket rain gauge, which provides precise quantitative precipitation data in mm/hr rather than simple binary detection.

To ensure robust data management and high availability, the system utilizes a modern cloud-native architecture. A server- side application hosted on **Render** manages data ingestion, persisting sensor packets to a **Supabase** PostgreSQL database. By leveraging Supabase's real-time features, changes are instantly broadcast to a responsive web dashboard deployed on **Vercel**. This integrated pipeline ensures a database synchronization latency of below 500ms, providing authorities and residents with a real-time command center for disaster preparedness. The primary objectives of this study are to evaluate the reliability of deterministic threshold-based alerting in simulated hazard environments and to demonstrate a scalable, low-cost architecture for proactive disaster mitigation.

EXISTING THEORIES AND PREVIOUS WORK

Recent literature emphasizes the shift from manual surveys to integrated IoT paradigms. Geotechnical research identifies real-time soil moisture and slope tilt as the most reliable precursors for predicting slope failure.

Studies such as those in IJSREM (2025) have validated low-cost MEMS accelerometers for detecting preliminary instability . Furthermore, Hidayat et al. (2024) established that capacitive moisture sensors provide research-grade accuracy when properly calibrated against standard soil textures . Current research advocates for deterministic thresholding to provide transparent alert frameworks for initial prototype-level hazard detection.

METHODS

The proposed methodology follows a structured four-layer IoT model: Perception, Transport, Processing, and Application.

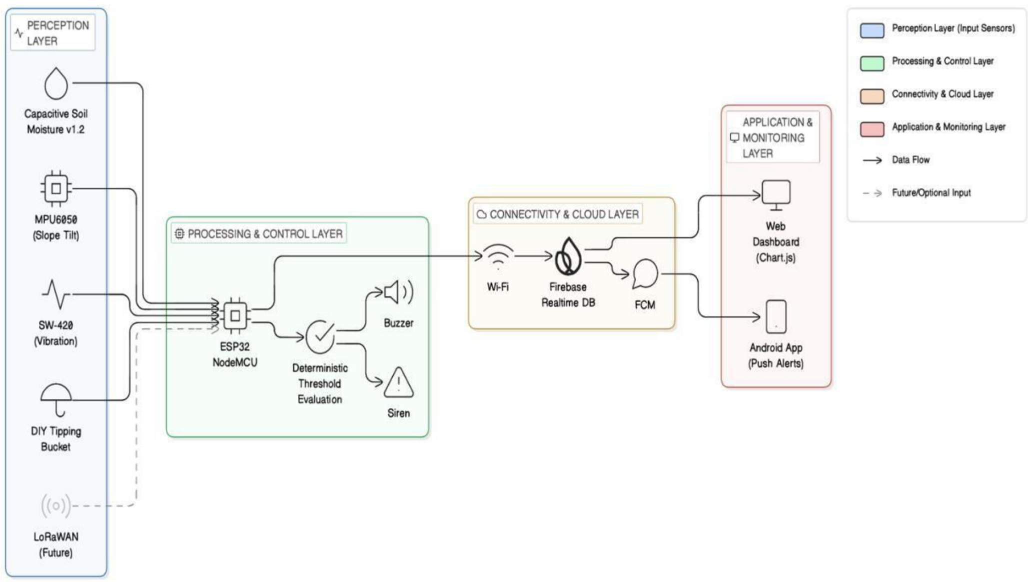

Fig 1Block Diagram

1.1 Research Model and Instruments

The "Perception Layer" consists of 3 autonomous nodes. The hardware configuration includes:

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- **Node Core:** ESP32 NodeMCU (Dual-Core 240MHz).
- **Sensors:** MPU6050 (6-axis IMU), SW-420 (Vibration), and Capacitive Moisture v1.2.
- **DIY Tipping Bucket:** A custom mechanical gauge with a magnetic reed switch providing quantitative mm/hr data.
- **Power:** 18650 LiFePO4 battery (3.2V) providing stable voltage without regulator losses.

1.2 Applied Research Methods

To ensure reliability, the system employs a **Weighted Risk Index (WRI)** calculated as follows: OverallRisk=(0.4×Moisture%)+(0.4×RainfallIntensity%)+(0.2×VibrationTrigger)

Alerts are categorized into three levels: **SAFE** (<25%), **VIGILANCE** (50–75%), and **CRITICAL** (>75% or Tilt >20∘).

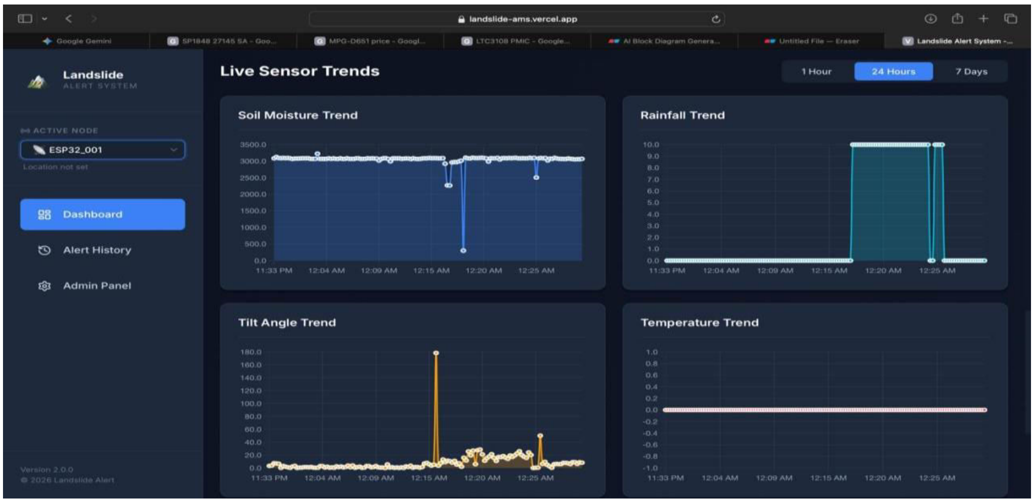

Fig 2Web Dashboard

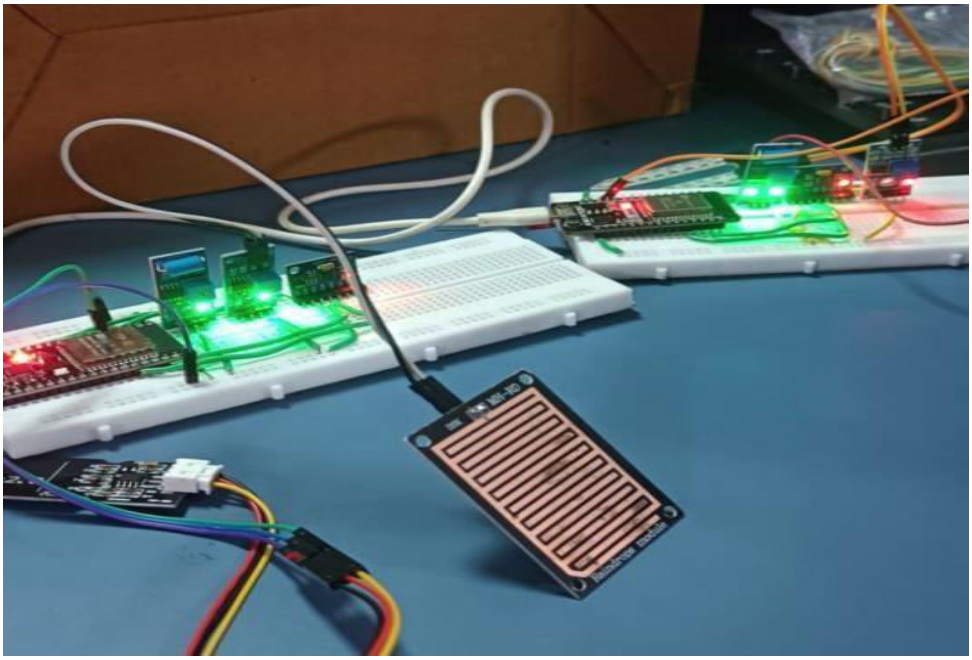

Fig 3 hardware

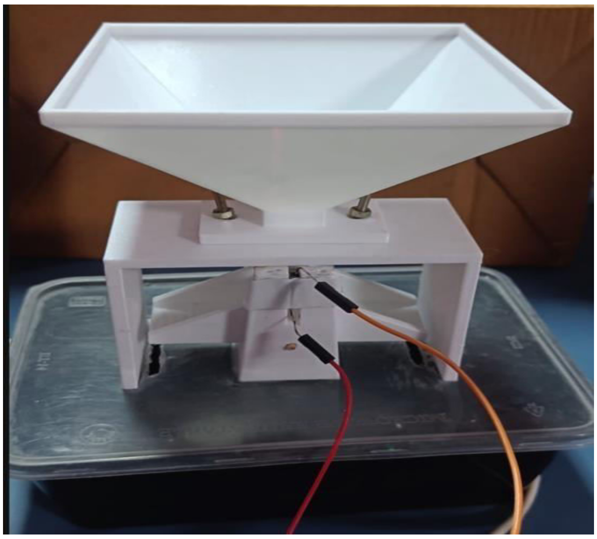

Fig 4 Rain Drop Tipping Bucket (3D printed)

1.3 Experiment and Calibration

Nodes are buried at a depth of 20 cm to ensure stable moisture readings and mechanical grounding. A 72-hour "learning period" was implemented to establish site-specific noise floors, distinguishing between environmental noise and genuine geological instability signals.

II. FINDINGS

Collected Data and Analysis

System testing under simulated soil saturation and physical tilting demonstrated that the MPU6050 successfully captured rotational shifts with 16-bit resolution. The SW-420 successfully acted as a low-power hardware interrupt, waking the ESP32 from Deep Sleep (10μA) upon detecting tremors.

Discussion

Experimental results confirm that the sensor-to-cloud pipeline updates the web dashboard in under 500ms. The use of a weighted risk score significantly reduced the rate of false positives compared to single-parameter systems. Initial technical struggles, such as the WHO_AM_I register mismatch in clone MPU6050 modules (0x70 vs 0x68), were resolved by implementing flexible, address-aware drivers.

III. CONCLUSION

This study successfully integrated a physical IoT monitoring pipeline with a real-time cloud-based alerting framework. The prototype demonstrated technical resilience, overcoming boot-loop issues and power instabilities to deliver highly accurate localized data.

Future Work: Future iterations will focus on transitioning from Wi-Fi to LoRa for extended 15km range in rugged terrain and integrating SP1848-27145 TEG modules for maintenance-free thermal energy harvesting.

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