Experimental Design: Creating An Early-Earthquake Detection System For Third-World Countries Using Machine Learning.

Nikhil Patil

Mahib Rahman

Eliab Melaku

October 25, 2025

Rationale

Earthquakes are one of the most destructive types of natural phenomena. They cause a massive loss of lives and leave large amounts of damage. This is especially the case in third world countries with inadequate technology that lack the advanced detecting mechanisms which first world countries possess. A big problem is that modern detection methods/systems are reliant on ultra-expensive, power intensive networks mapped out over a large area. As one can assume, this makes it very complicated for Third World countries to get the detection technology they need. Our project's goal is to design an affordable and energy efficient early earthquake detection device with the use of piezoelectric transducers (efficient and low-cost sensors suitable for low-power nodes), machine learning (EQ Transformer), and wake-on wireless radio communication (WOR). Earthquakes make quick, low-amplitude waves called Primary waves, or P-waves. This is then followed in quick succession by a large, damaging wave called the secondary wave, or S-wave. Detecting the P-waves in a swift and orderly fashion can save many lives and save a lot of infrastructure in the process. However, the bad part about this is that the batteries must be replaced. That is where the wireless sensor communication network, WOR, comes in as it provides an energy efficient and low-cost option for communication in third world countries where rechargeable batteries may not be in abundance. All in all, the main reason for our project is earthquakes in Third World countries and their inability to detect them early on causing catastrophic damage and we plan to make an early detector which is affordable, and energy efficient. This research is important scientifically due to the fact that it combines aspects of many scientific fields such as electrical and mechanical engineering, a broad knowledge of seismology, and an understanding of machine learning. Societally, this provides third world countries with cheap/affordable, energy-efficient, and early responsive detection in which helps society for the better.

Question

How can a piezoelectric sensor network integrated with machine learning classification from an EQTransformer and wake-on-radio wireless communication detect and transmit early earthquake warnings efficiently and with minimal energy consumption?

Hypothesis

Null Hypothesis: The integration of piezoelectric sensors with a wake-on-radio network and machine learning classifier does not significantly improve detection accuracy or reduce power consumption compared to traditional continuous-monitoring systems of third-world countries that are no capable of funding an advanced detection system.

Alternative Hypothesis: The integration of piezoelectric sensors with a wake-on-radio network and machine learning classifier will significantly improve detection accuracy or reduce power consumption compared to traditional continuous-monitoring systems of third-world countries that are no capable of funding an advanced detection system.

Materials/Research Methods

The system will be built by using piezoelectric transducer materials and microcontroller-based components to detect earthquakes like vibrations. The primary material used is a Zirconate Titanate (PZT) piezoelectric disc. Which converts mechanical strain into readable electrical voltage. The disk is attached to an aluminum base plate via an epoxy adhesive which is mechanically coupled to a 20cm (about 7.87 in) steel rod that is staked into the ground for improved vibration transfer. The ADXL345 accelerometer module will be used as a reference to calibrate the system. Wires will be soldered onto the PZT disk and connected to an OPA2132 analog conditioning circuit component. This amplifies the PZT's voltage, making it readable to the microcontroller. The ESP32 development board will be used as the microcontroller due to its complex processing abilities. This component acts as the brain containing an input-output system which acts as an interface used to control electronic devices and collect data. Data collected would be stored on a 16GB microSD card. Twin LoRa SX1276 radio would be added to the system as it would enable the usage of Wake-On-Radio (WOR). This allowed communication between the 2 sensor nodes, allowing them to be in deep sleep until vibration was detected and triggered a system to wake up. The power source for this prototype design will be a rechargeable Li-ion lithium battery. An isolated ~3.3V buck converter will be used to distribute regulated power through components.

For vibration testing, a drawer-slide shake table is attached to a direct current motor. Using a motor will allow for controlled 1-20hz vibrations (being that the range for an earthquake is ~.5-20hz). Additionally, A Raspberry Pi model 4 will act as a gateway into implementing machine learning. Data collected from PZT disk that is sent through the microcontroller and stored in microSD card will be taken to the Pi which formats the data, so it is legible to EQTransformer model.

During each trial which lasts 30 seconds, the PZT disk voltage is collected through the microcontroller while the shake table produces controlled vibrations. This is then sent to a radio and triggers a WOR signal, subsequently waking up the other node and logging the time of activation. This allows the measurement of the efficiency of the system and how well it avoids background noise. After each trial, the data is sent to the Raspberry Pi, where the EQT machine learning program is used to analyze the vibration recordings. The EQT marks vibration events versus noise and produces a confidence score. This is compared with the controlled shake table's known times and the WOR logs to evaluate overall detection accuracy, and background-noise rejection.

Data Analysis

The data we collect and analyze will be used to answer the research questions and hypotheses. Our objective is to use this data to evaluate the performance of the piezoelectric transducer network that is integrated with our machine learning classifier. We would then compare the results of our detection system with the performance of traditional continuous-monitoring systems, more specifically those that are in third-world countries that are not able to afford advanced seismic detection.

The first step in analysis involves data collection from the Zirconate Titanate (PZT) piezoelectric sensing network. This network converts vibration to a proportional voltage whenever there is seismic activity. The OPA2132 circuit amplifies the voltage signal, making it readable data for the ESP32 microcontroller. Alongside it, the ADXL345 accelerometer calibrates the system, meaning it sets out a reference measurement for when its output is experiencing 0 external vibrations. All the sensor data is transferred from the ESP32 sensor node to the Raspberry Pi 4 wirelessly, via LoRa communication.

Once the data is stored into the Raspberry Pi 4, it processes the digital data and classifies parameters such as the root mean square amplitude, signal energy, zero-crossing rate, and the dominant frequency for each event. These features will then be organized into labeled datasets and evaluated as “false alarm”, “potential seismic activity", and "other environmental disturbances”. Then, model performance is measured using accuracy, precision, recall, and F1-score metrics. Additionally, the responsiveness of the system will be evaluated by measuring the detection-to-alert latency and communication delay of the two LoRa-connected sensor nodes.

To analyze the energy efficiency of this system, ESP32's ability to measure current drawn will allow the system to log the amount of voltage and current drawn to calculate energy usage per event. From there, we will compare the statistical values of energy consumption between our wake-on-radio functionality to that of the continuous monitoring mode.

Lastly, all data is collected and summarized with graphs and statistics. Differences in energy consumption and alert latency between the two modes will be illustrated with bar graphs. Additionally, confusion matrices are utilized to evaluate classification performance. From these analyzations, an evaluation will be made on the system as a whole. More specifically, we will determine if our early earthquake detection prototype design is an energy efficient system and capable of providing early earthquake warnings for developing regions of the world that lack such technology and funds to create their own.

Risk and Safety

A serious risk in our project is working with electrical circuitry. The way we stay safe is by only using low-voltage systems, and we will avoid coming in contact with exposed circuits. Another risk can be thermal radiation from batteries. We must avoid overheating the batteries by charging them to an appropriate area. Lastly, the testing area must be neat and safe. Tasks that can ensure safety can be wearing safety glasses for the eyes and maintaining a reasonable distance from the site of testing.

Bibliography

Hung, S. L., Ding, J. T., & Lu, Y. C. (2018). Developing an energy-efficient and low-delay wake-up wireless sensor network-based structural health monitoring system using on-site earthquake early warning system and wake-on radio. *Journal of Civil Structural Health Monitoring*, *9*(1), 103–115. https://doi.org/10.1007/s13349-018-0315-2

Jaffe, H., & Berlincourt, D. A. (1965). Piezoelectric transducer materials. *Proceedings of the IEEE*, *53*(10), 1372–1386. https://doi.org/10.1109/proc.1965.4253

Lalithavani, K., Arasan, G., Premsundar, S., Venkatasubash, V., & Vijayaraj, R. (2025). AI-Powered based real time earthquake early warning system using deep learning. *Journal of Engineering Research and Reports, 27*(5), 433–442. https://doi.org/10.9734/jerr/2025/v27i51516

Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y., & Beroza, G. C. (2020). Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-17591-w

Sheehan, J., Zhai, Q., Chuang, L. Y., Officer, T., Wang, Y., Zhu, L., & Peng, Z. (2025). Applying EQTransformer to laboratory earthquakes: detecting and picking acoustic emissions with machine learning. *Earth Planets and Space*, *77*(1). https://earth-planets-space.springeropen.com/articles/10.1186/s40623-025-02237-2

Tan, M. L., Becker, J. S., Stock, K., Prasanna, R., Brown, A., Kenney, C., … Chen, Y. (2022). Earthquake early warning systems based on low-cost ground motion sensors: A systematic literature review. *Frontiers in Sensors*, 7. https://doi.org/10.3389/fsens.2022.1020202

Wu, R., Selvadurai, P. A., Chen, C., & Moradian, O. (2021). Revisiting Piezoelectric Sensor Calibration Methods Using Elastodynamic Body Waves. *Journal of Nondestructive Evaluation*, *40*(3). https://doi.org/10.1007/s10921-021-00799-1