Implementation of an ESP-32 Based Embedded System for Earthquake Detection Using an MPU-6050 Sensor

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***Abstract* – Indonesia is one of the countries with a high risk of earthquakes due to its geographical location near active tectonic plate boundaries. The rapid delivery of earthquake information is important to support early response and disaster mitigation. This study aims to implement an ESP-32 based embedded system for earthquake detection using the MPU-6050 sensor, with real-time monitoring and early warning through a web dashboard and Telegram Bot. The MPU-6050 sensor is used to measure acceleration along the X, Y, and Z axes, while the ESP-32 processes the sensor data and determines the vibration condition based on total acceleration thresholds. The system was evaluated through vibration simulation, comparison of MPU-6050 measurements with the Phyphox reference application, and repeated measurements to analyze the accuracy and consistency of sensor readings. The results show that the system can classify vibration conditions into normal, earthquake alert, and earthquake conditions based on total acceleration values. The earthquake alert condition is defined as $10.5 \text{ m/s}^2 < At \leq 12.0 \text{ m/s}^2$, while earthquake conditions occur when $At > 12.0 \text{ m/s}^2$. Comparison with the reference application resulted in a mean measurement error of 6.67%, corresponding to an accuracy of 93.33%. Repeated measurements produced an average total acceleration of 10.17 m/s^2 with a standard deviation of 0.0256 m/s^2, indicating consistent sensor readings under normal conditions. The system also successfully transmits detected earthquake information to the web dashboard and Telegram Bot, supporting real-time monitoring and early warning.**

Keywords: ESP-32, MPU-6050, Internet of Things, Earthquake Detection, Earthquake Early Warning System

I. INTRODUCTION

Indonesia is located in an active tectonic region and is exposed to significant earthquake hazards. Earthquakes can occur suddenly and cause casualties, infrastructure damage, and disruption of public activities. Therefore, rapid earthquake information is an important component of disaster mitigation. Earthquake Early Warning Systems (EEWS) are designed to detect ground motion and provide warnings within a short time before the arrival of stronger shaking. However, conventional seismic monitoring infrastructure can require relatively high costs and extensive deployment. Low-cost Micro-Electromechanical Systems (MEMS) accelerometers have consequently become an important alternative for developing affordable and distributed earthquake monitoring systems [1],[2]. A systematic review reported that low-cost MEMS-based EEWSs have the potential to increase sensor density and support earthquake warning applications, particularly in developing regions [1]. Recent studies have also demonstrated the use of low-cost MEMS accelerometers for collecting three-axis seismic acceleration data during actual earthquake events [2], [3].

The application of IoT technology further provides an opportunity to connect low-cost sensors with real-time data processing and communication platforms. IoT-based seismic systems can acquire acceleration data, process the measurements locally, and transmit warning information to users through communication networks [4],[5]. In Indonesia, the implementation of an EEW system in western Java demonstrated the capability of real-time accelerograph data to identify earthquake events and provide rapid information regarding earthquake parameters [3]. This result emphasizes the importance of rapid data acquisition and communication in earthquake warning applications. Other studies have investigated IoT-based monitoring architectures and demonstrated that low-cost connected sensor nodes can be used to support real-time environmental and structural monitoring [6], [7].

Several studies have specifically examined accelerometer-based earthquake detection. Sianturi et al. developed an earthquake early warning system using an MPU-6050 accelerometer, Arduino Uno, and NodeMCU ESP-8266, demonstrating the feasibility of MPU-6050 for detecting earthquake-related vibrations[8]. Duggal et al. developed an IoT-based earthquake detection system using MPU6050 and combined accelerometer and gyroscope information with machine-learning techniques for vibration classification [4]. Their approach demonstrates the potential of MPU-6050 for earthquake-related vibration analysis, although the system emphasizes structural analysis and machine-learning-based classification. Other research has also investigated ADXL335 and other accelerometers for earthquake detection and early warning, demonstrating that low-cost acceleration sensors can provide an alternative to conventional seismic instrumentation [9].

The use of ESP-32 has further expanded the development of compact earthquake monitoring systems because the microcontroller provides processing capability and built-in wireless connectivity. Wikantama et al. developed SIGEMPA, an ESP-32-based IoT earthquake early warning system that uses Telegram to disseminate earthquake warnings in real time [10]. The study demonstrated that ESP-32 and Telegram can be integrated to provide accessible warning information to users. Other researchers have combined MPU-6050 and ESP-32 with IoT platforms such as Blynk for real-time earthquake monitoring [11], while Dwiputra and Nazry developed an MPU-6050 and ESP32-based system with real-time monitoring through a mobile application [12] . These studies demonstrate the feasibility of combining low-cost sensors, ESP-32, and IoT communication for earthquake monitoring.

Recent research has also focused on improving the reliability and response of low-cost EEWS architectures. Node-level detection and alert generation have been investigated as an approach for reducing warning-generation time and improving system responsiveness [5]. Other studies have explored low-cost MEMS networks, seismic signal processing, and magnitude estimation to improve the capability of earthquake early warning systems [13], [14]. Research on MEMS-based seismic systems has also demonstrated the use of frequency-domain characteristics and acceleration measurements to support earthquake detection and warning [15]. In addition, IoT-based structural monitoring research indicates that distributed sensors and real-time communication can support continuous monitoring and rapid information delivery [16].

Although these studies demonstrate substantial progress, differences remain in sensor configuration, detection algorithms, communication platforms, and monitoring interfaces. Previous research has focused on MPU-6050 based earthquake detection [8], machine-learning classification [4], ESP32 and Telegram warning [10], Blynk-based monitoring [11], and mobile application monitoring [12]. However, there remains an opportunity to develop a simple integrated local-scale system that combines three-axis MPU-6050 acceleration measurement, threshold-based vibration classification, Web Dashboard monitoring, and Telegram notification within a single ESP-32 based platform. The proposed approach emphasizes a practical architecture that does not require complex machine-learning processing or a dedicated cloud infrastructure.

Therefore, this study implements an ESP32-based embedded system for earthquake vibration detection using an MPU-6050 sensor. The proposed system integrates three-axis acceleration measurement, total acceleration calculation, threshold-based classification, a Web Dashboard for real-time monitoring, and Telegram Bot for warning notification. The vibration conditions are classified into normal, alert, and earthquake states according to predetermined acceleration thresholds. The system is evaluated through repeated acceleration measurements and manual vibration simulations using light and strong vibrations. The main contribution of this study is the integration of sensing, local processing, condition classification, web monitoring, and Telegram-based warning in a single low-cost IoT platform intended for local-scale earthquake vibration monitoring and early warning.

II. METHOD

A. Research Stages

The research was conducted through several stages, including literature review, system requirements analysis, hardware and software design, system implementation, vibration simulation, and system testing. The MPU-6050 sensor was integrated with the ESP32 to measure acceleration on the X, Y, and Z axes. The acquired data were processed to calculate total acceleration and classify vibration conditions based on predetermined thresholds. The system was then evaluated through sensor measurements, web dashboard monitoring, and Telegram notifications. The collected data were analyzed using mean, measurement error, and standard deviation. The research stages are illustrated in Figure 1.

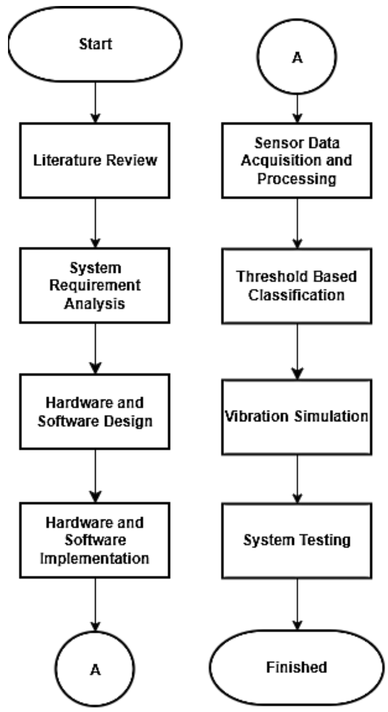

Figure 1. Research Stages

B. System Architecture and Hardware Design

The system architecture consists of the MPU-6050 sensor, ESP-32 microcontroller, LCD I2C, buzzer, Wi-Fi communication, database server, web dashboard, and Telegram Bot. The MPU-6050 measures acceleration on the X, Y, and Z axes and sends the measurement data to the ESP32 for processing. The ESP-32 calculates the total acceleration and determines the vibration condition based on the predetermined thresholds. The processed data are displayed locally on the LCD and transmitted through a Wi-Fi connection to the database for visualization on the web dashboard. When the detected acceleration meets the specified alert or earthquake condition, the system activates the warning indicators and sends a notification through the Telegram Bot. The overall system architecture is illustrated in Figure 2.

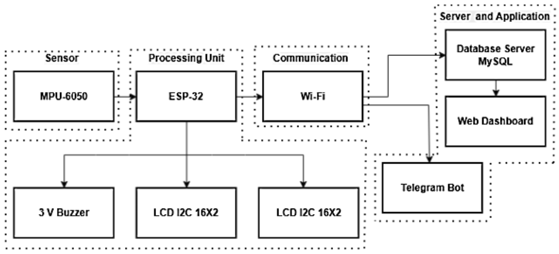

Figure 2. System Architecture

After determining the System Architecture, the next step was designing the interconnection components. The design is show in Figure 3.

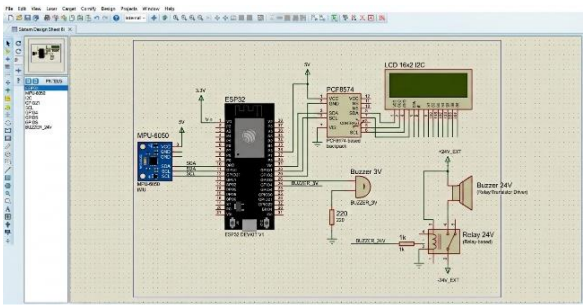

Figure 3. Wiring Diagram of Interconnected Components

The following is the acrylic case design used for the placement of all hardware components in the system, as shown in Figure 4.

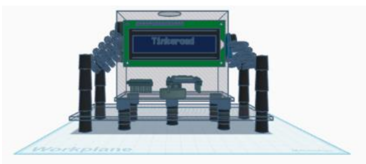

Figure 4. Acrylic Case Box Design

The acrylic case design was developed to protect the components, improve system organization, and maintain stable system operation, making the device more compact and suitable for real-time applications.

C. Software Design on the System

The software design of this earthquake detection system was carried out to ensure that all system components operate in an integrated manner, starting from the sensor data acquistion process, real-time Telegram notifications, and information visualization on the web dashboard. The following are the software design stages shown in Figure 5.

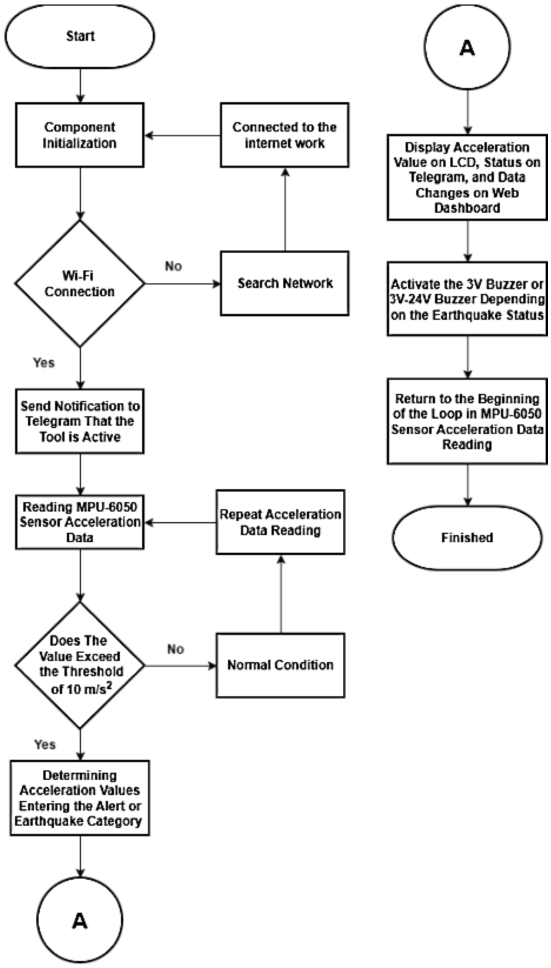

Figure 5. Software Design Stages

The software system was developed using the arduino IDE programming enviroment. The program was designed to continuously acquire acceleration data from the MPU-6050 sensor and calculate the total acceleration data from three axes. The software implementation consisted of several operational stages, including:

a. Sensor data acquistion
b. Acceleration data processing
c. Threshold-based condition classification
d. Real-time data transmission
e. Web dashboard updating
f. Telegram notification delivery

The ESP-32 continuously transmitted sensor data to the database server through wireless internet communication. The monitoring data were then visualized through the web dashboard interface.

D.Vibration Simulation and Testing Procedure

The vibration simulation was conducted to evaluate the response of the MPU-6050 sensor and the ability of the system to classify vibration conditions. During the test, the prototype was placed horizontally on the ground using a flat ordinary wooden board as the test base. The vibration was applied manually by hand with two different intensities, namely light and strong vibrations. Light vibrations were applied to simulate the alert condition, while strong vibrations were applied to simulate the earthquake condition. During each test, the acceleration values on the X, Y, and Z axes were recorded by the ESP32 and processed to calculate the total acceleration. The test duration was 2 minutes and 30 seconds. The obtained acceleration values and system responses were recorded for further analysis and evaluation of the detection and warning functions.

Table 1. System Testing Procedure

Test Type	Tested Parameters	Test Steps	Initial Conditions	Expected Results
Power Supply	ESP-32 input Voltage	Connecting the adapter to the system	Active system	The system is active without interruption
MPU-6050 Sensor	X.Y. and Z Acceleration Values	Giving Vibration to the tool	The system is active under normal conditions	The sensor reads the data correctly
Threshold	Total acceleration value	Provides gradual vibrations to the tool	Active system	Classification according to threeshold
LCD 16X2 I2C	Data and status display	Observe the LCD display	Active system	Data and status are clearly readable
Buzzer 3V	Earthquake alert alarm sound	Provide moderate vibration to the tool	Normal status	When the earthquake alarm alert status is active
Buzzer 3V-24V	Alarm sounds during an earthquake	Gives strong vibration to the tool	Alert status	When an earthquake occurs, the earthquake alarm is activated
Wi-Fi connection	Network connection status	Connecting ESP-32 ti Wi-Fi	Active system	Wi-Fi connected
Telegram notifications	Warning message	Simulating an earthquake	Wi-Fi connected	Status notifications during earthquake simulations are received in real-time
Web dashboard	Real-time Data	Acces the web dashboard	Active system	Real-time stored data

E.Threshold Classification and System Testing

The vibration condition was classified based on the total acceleration obtained from the MPU-6050 sensor. The total acceleration was calculated from the acceleration values on the X, Y, and Z axes and compared with the predetermined threshold values. The classification consisted of three conditions: normal, alert, and earthquake. A total acceleration of $At < 10.5$ m/s^2 was classfied as normal, $10.5 < At \leq 12.0$ m/s^2 as alert, and $At > 12.0$ m/s^2 as earthquake. The classification and system response are presented in Table 2.

Table 2. Threshold Classification

Total Acceleration Range (m/s^2)	Category	System Status
$At \leq 10.5$	No vibration	Normal
$10.5 < At \leq 12.00$	Light vibration	Earthquake alert
$At > 12.00$	Strong vibration	Earthquake

Data analysis was performed to evaluate the measurement results obtained from the MPU-6050. The analysis included the calculation of the mean, measurement error, accuracy, and standard deviation. The mean was used to determine the average measurement value, while measurement error and accuracy were used to evaluate the difference between the sensor measurement and the reference value. Standard deviation was used to determine the consistency of the measurement results. The equations used for the data analysis are presented below.

Measurement Error:

$$Error = \frac{\sum x\,measured - x\,reference}{\text{x reference}} \times 100\% \quad (1)$$

Accuracy:

$$Accuracy = 100\% - Error \quad (2)$$

Standard Deviation:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}} \quad (3)$$

III. RESULTS AND DISCUSSION

The data collection process for this earthquake detection devices was carried out after the hardware and software development had been completed. The data collection was conducted on 27th April, 2026. The assembled and fully integrated earthquake detection device is shown in Figure 6 as follows:

Figure 6. Earthquake Detection Device

The following data were obtained during the simulation testing of the earthquake detection system:

Table 3. Simulation Testing On The System

Testing time	Ax (m/s^2)	Ay (m/s^2)	Az (m/s^2)	Total acceleration
2026-04-27 08.31:01	-3.4	-0.68	9.63	10.24
2026-04-27 08.31:03	-3.48	-0.72	9.62	10.26
2026-04-27 08.31:06	-3.46	-0.7	9.65	10.27
2026-04-27 08.31:09	-3.39	-0.7	9.62	10.22
2026-04-27 08.31:18	-7	-0.38	16.75	18.16
2026-04-27 08.31:21	-3.51	-0.72	9.61	10.25
2026-04-27 08.31:24	-3.42	-0.73	9.59	10.21
2026-04-27 08.31:27	-3.51	-0.66	9.66	10.3
2026-04-27 08.31:30	2.85	0.62	4.96	5.76
2026-04-27 08.31:39	-15.76	-12.75	16.21	25.95
2026-04-27 08.31:42	-3.49	-0.7	9.55	10.19
2026-04-27 08.31:45	-3.49	-0.71	9.49	10.14
2026-04-27 08.31:47	-3.47	-0.76	9.52	10.16
2026-04-27 08.31:50	-3.43	-0.75	9.56	10.18
2026-04-27 08.31:55	-3.48	-0.69	9.55	10.19
2026-04-27 08.31:58	-3.52	-0.71	9.55	10.21
2026-04-27 08.32:01	-3.29	-0.94	8.72	9.37
2026-04-27 08.32:09	-4.17	-0.83	12.1	12.82
2026-04-27 08.32:12	-3.51	-0.68	9.57	10.22
2026-04-27 08.32:15	-3.46	-0.74	9.58	10.21
2026-04-27 08.32:18	-3.51	-0.7	9.55	10.2
2026-04-27 08.32:30	-2.43	0.14	15.09	15.29
2026-04-27 08.32:32	-3.54	-0.7	9.46	10.13
2026-04-27 08.32:35	-3.55	-0.65	9.74	10.39
2026-04-27 08.32:38	-3.51	-0.66	9.72	10.36
2026-04-27 08.32:42	-3.5	-0.72	9.58	10.23
2026-04-27 08.32:44	-3.5	-0.76	9.58	10.23
2026-04-27 08.32:47	-3.6	-0.71	9.6	10.28
2026-04-27 08.32:50	-3.54	-0.66	9.56	10.21
2026-04-27 08.32:53	-3.51	-0.71	9.62	10.26
2026-04-27 08.33:06	-2.52	-1.95	14.74	15.08

2026-04-27 08.33:08	-3.42	-0.67	9.58	10.2
2026-04-27 08.33:17	-4.73	0.19	11.15	12.12
2026-04-27 08.33:23	-3.53	-0.73	9.57	10.23
2026-04-27 08.33:28	-3.23	-0.39	10.38	10.88
2026-04-27 08.33:31	-3.47	-0.71	9.52	10.16

Based on 36 simulation trials, the MPU-6050 sensor registered varying acceleration responses: alert condition (10.5 $m/s^2 < At \leq 12.00$ m/s^2) and earthquake condition ($At \leq 12.00$ m/s^2). The test results graph for this experiment is shown in Figure 7.

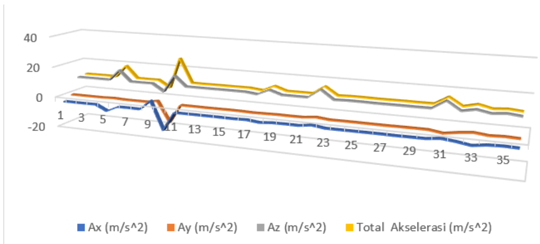

Figure 7. Graph Of The Device Testing Results

The acceleration values from the device testing are saved to a MySQL database, allowing real-time monitoring of the data during the experiment.

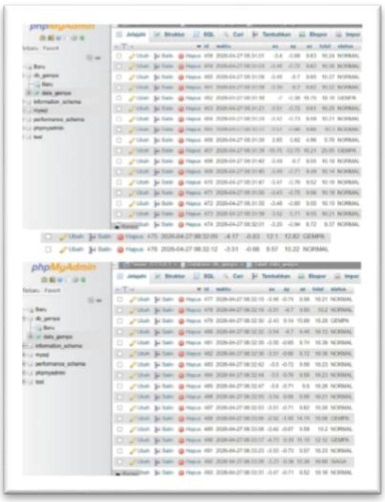

Figure 8. Database View Saved in MySQL

When the system is activated, any detected vibrations corresponding to alert or earthquake conditions are trasnmitted in real time to the local website and sent via telegram notifications, The web dashboard and telegram notification displays from the acceleration test are shown in figure 9 and figure 10, respectively.

Figure 9. Web Dashboard Display

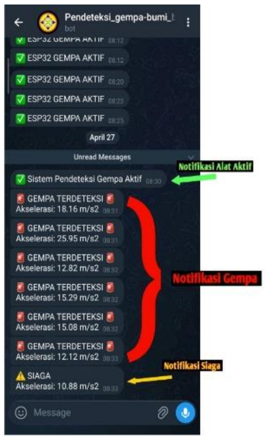

Figure 10. Telegram Notification Display

After testing was completed, a comparision was conducted the reference measuring tool (Phypox Application on a Smarthphone) and the MPU-6050 sensor to calculate the sensor error rate.

Table 4. Comparison Of The MPU-6050 Sensor With The Reference Measuring Tool

Trial	Phypox Reference tool (m/s^2)	MPU-6050 (m/s^2)	Error (%)
1.	9.56	10.26	7.32
2.	9.55	10.12	5.97
3.	9.61	10.19	6.03
4.	9.57	10.25	7.11
5.	9.56	10.2	6.69
6.	9.51	10.21	7.36
7.	9.55	10.11	5.86
8.	9.59	10.1	5.32
9.	9.53	10.2	7.03
10.	9.54	10.3	7.97

After calculating the individual error values for the acceleration readings between the MPU-6050 sensor and the reference tool, the mean error percentage was determined using the following formula:

$$Error = \frac{\sum x\,measured - x\,reference}{\text{x reference}} \times 100\%$$

The total accumulated error from the test comparisons was 66.67%. Using the formula above, the calculated mean error was:

$$Error = \frac{66.67\%}{10} = 6.67\%$$

Consequently, the measurement accuracy reached 93.33%.

Following the comparison with the reference measuring tool, retesting was conducted on the devices to determine the mean and standard deviation values. The ratesting results are presented in Table 5.

Table 5. Repeat Testing of Device

Trial	Testing Time	Total Accelaration (m/s^2)
1.	2026-05-04 09:46:52	10.14
2.	2026-05-04 09:46:54	10.2
3.	2026-05-04 09:46:57	10.16
4.	2026-05-04 09:47:00	10.14
5.	2026-05-04 09:47:03	10.19
6.	2026-05-04 09:47:06	10.21
7.	2026-05-04 09:47:09	10.19
8.	2026-05-04 09:47:11	10.19
9.	2026-05-04 09:47:14	10.14
10.	2026-05-04 09:47:17	10.17

In the retesting phase, 10 trials were conducted, yielding a total acceleration value of 101.73 (m/s^2) . The mean acceleration value ($\bar{x}$) was calculated using the following formula:

$$(\bar{x}) = \frac{\sum xi}{\mathrm{N}}$$

$$(\bar{x}) = \frac{101.73}{10} = 10.17$$

The resulting mean value of 10.17 m/s^2 indicates that the system maintained a stable state close to normal conditions throughout the retesting process.

Following the determination of the mean value, the standard deviation of retest acceleration data was calculated using the formula:

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$$

To calculate, the deviation of each individual measurement from the mean $(x_i - \bar{x})$ was determined, with the corresponding results presented in Table 6.

Table 6. Calculation of Standard Deviation

Trial	x_i	$(x_i\text{-}\bar{x})$	$(x_i - \bar{x})^2$
1.	10.14	-0.03	0.0009
2.	10.20	0.03	0.0009
3.	10.16	-0.01	0.0001
4.	10.14	-0.03	0.0009
5.	10.19	0.02	0.0004
6.	10.21	0.04	0.0016
7.	10.19	0.02	0.0004
8.	10.19	0.02	0.0004
9.	10.14	-0.03	0.0009
10.	10.17	0.00	0.0000

Substituting $\sum(x_i - \bar{x})^2 = 0.0066$ and N = 10 into the equation yields:

$$\sigma = \sqrt{\frac{0.0066}{10-1}} = 0.0256 \text{ m/s}^2$$

The resulting low standard deviation of 0.0256 m/s^2 Confirms that the MPU-6050 sensor produces highly stable and consistent readings under normal operating conditions.

IV. CONCLUSION

This study successfully implemented an ESP32-based earthquake vibration detection system using the MPU-6050 sensor, integrated with a Web Dashboard and Telegram Bot. The system can measure three-axis acceleration, classify vibration conditions into normal, alert, and earthquake states based on predetermined thresholds, and provide remote warning information. The 350 measurement tests produced an average total acceleration of 10.17 m/s^2 with a standard deviation of 0.0256 m/s^2, indicating relatively consistent sensor measurements under the tested conditions. These results demonstrate the feasibility of integrating vibration detection, condition classification, web monitoring, and Telegram notification in a low-cost local-scale system.

However, the system has several limitations. The vibration tests were performed manually, so the frequency and acceleration of the applied vibrations were not precisely controlled. In addition, remote monitoring and Telegram notification depend on local Wi-Fi and Internet connectivity, while the system does not have a backup battery or UPS. Consequently, network failure or a power outage caused by an earthquake may interrupt remote warning functions and system operation. Future studies should use a controlled vibration or calibrated shake table, evaluate the system using real or recorded earthquake data, provide alternative communication methods, and integrate a battery, UPS, or solar-powered backup system to improve reliability and ensure continuous operation.

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