EXPERIMENTAL STUDY OF IOT SENSOR PERFORMANCE FOR BUILDING MOVEMENT MONITORING

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Abstract *— Real-time monitoring of building movement is essential to mitigate structural damage risks, particularly in earthquake-prone regions. The application of Internet of Things (IoT) technology enables continuous and efficient measurement of structural deformation and inclination through the integration of smart sensors and cloud-based systems. The primary objective of this study is to evaluate the performance of a MEMS-based IoT sensor system in detecting displacement and angular changes in building structures. An experimental laboratory test was conducted by comparing the readings of accelerometer, gyroscope, and inclinometer sensors with standard measuring instruments. Results indicate an average measurement error of 1.58%, a response time of 2.34 seconds, and data transmission reliability of 97.8%, demonstrating high accuracy and stability. The integration of sensors, an ESP32 microcontroller, and a cloud computing platform shows strong potential for implementation as an effective IoT-based Structural Health Monitoring (SHM) system, supporting the development of resilient and sustainable smart infrastructure.*

Keywords*:* IoT, MEMS sensor, building movement, Structural Health Monitoring, smart infrastructure

I. INTRODUCTION

Monitoring the movement of buildings is one of the important aspects in maintaining the safety and sustainability of infrastructure structures, especially in areas prone to earthquakes, subsidence, or changes in structural loads. Small movements that occur repeatedly can cause permanent deformation and lead to a decrease in structural strength and the risk of building failure. In general, structural movements are triggered by natural factors such as earthquakes and land subsidence, as well as technical factors such as dynamic loads and changes in the temperature of construction materials [1]. Therefore, continuous and real-time structural monitoring is an urgent need in modern building safety systems.

As technology has evolved, the Internet of Things (IoT) has become an innovative approach to structural monitoring systems due to its ability to integrate intelligent sensors with wireless networks that can transmit data directly to digital platforms [2]. IoT-based systems enable remote monitoring of critical parameters such as vibration, tilt, and shift of building structures efficiently, accurately, and affordably [3]. Conventional building movement monitoring systems are still dominated by manual methods such as the use of total stations, waterpasses, and analog inclinometers, which, while accurate, have limitations in high installation costs, the need for experts, and the inability to provide data in real-time. This condition causes delays in the early detection of potential structural damage, thus risking the safety of building users.

To overcome these obstacles, an adaptive, wireless, and automated monitoring system is needed, with low operational costs but still has high accuracy. The use of MEMS (Micro-Electro-Mechanical Systems) sensors such as accelerometers, gyroscopes, and inclinometers in IoT networks is a promising alternative solution. These sensors have advantages in small size, low power consumption, and the ability to measure three-dimensional movement [4]. With IoT integration, data from sensors can be sent directly to cloud-based servers for real-time analysis, graphical visualization, and automated early warning systems, so that the process of detecting structural anomalies can be carried out faster and more accurately [5].

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Research on structural health monitoring (SHM) has grown rapidly in the last two decades as the need for safe, efficient, and sustainable infrastructure increases. The initial approach used in SHM was based on conventional methods such as measurements using total stations, waterpasses, and manual tilt meters[6]. Despite its high accuracy, the system is limited in range, requires specialized experts, and is not capable of providing data in real-time. This condition causes delays in the early detection of structural damage, especially in buildings in disaster-prone areas. The development of sensor technology then presents a more compact, energy-efficient, and economical MEMS-based sensing system [7]. MEMS sensors such as accelerometers, gyroscopes, and inclinometers began to be applied in the monitoring of deformation and vibration of structures [4]. Preliminary studies show that the combination of the three sensors is able to provide a three-dimensional representation of the movement of the structure with fairly high precision. However, the use of this sensor in the early stages is still stand-alone, not yet integrated with wireless data transmission systems or cloud-based analysis.

Entering the 2018–2024 period, the concept of IoT has become a new paradigm in the SHM system. IoT enables the integration of sensors with wireless communication networks and cloud computing, enabling real-time collection and analysis of structural movement data [3], [8]. The system can monitor various parameters such as acceleration, rotation, and tilt of the structure, as well as display data through a web-based visualization dashboard. Recent research trends even show the integration between IoT and Artificial Intelligence (AI) for predictive analysis and automatic anomaly detection [9], [10].

Some advanced research expands the application of IoT for the monitoring of bridges, dams, and tall buildings, using different types of sensors such as MEMS accelerometers, strain gauges, fiber optics, GPS, and LVDT (Linear Variable Differential Transformer). The latest study highlights that IoT-based monitoring systems have experienced rapid growth since 2019, with a focus on multi-mode sensing, cloud-based data processing and edge computing, as well as AI analytics that improve monitoring accuracy and efficiency [11]. However, the results of the meta-analysis study by [10] shows that while IoT offers great potential in the integration of SHM systems, implementation challenges are still significant, including communication reliability, sensor calibration, power management, as well as the standard integration of communication between devices [12].

From the course of the study, it can be concluded that most of the previous studies focused on the development of IoT systems and architectures for structural monitoring, but there was little experimental testing of the performance of IoT sensors under real conditions. The majority of studies stop at the hardware validation stage in the laboratory, without conducting direct testing of the accuracy, data transmission stability, and robustness of the system in situations of simulated structural or vibrational loads. This research gap indicates the need for a measurable and systematic experimental study to evaluate the performance of IoT sensors in relevant environments, especially in buildings in earthquake-prone areas such as Indonesia that have complex and varied geotechnical characteristics.

As a state of the art, recent research has begun to focus on the integration of distributed smart sensors, cloud/edge analytics, and machine learning algorithms that are capable of processing data on the movement of structures in an adaptive and sustainable manner [9], [11]. Recent prototypes have demonstrated the use of multi-axis MEMS accelerometers connected to mobile gateways or NB-IoT for long-term vibration monitoring as well as structural modal analysis [3]. However, much of the research is still limited to system evaluation in the context of large-scale testing, rather than to the quantification aspects of sensor accuracy and data transmission reliability in simple prototype units that can be applied practically in the field. Therefore, the novelty of this study lies in a comprehensive experimental study approach to the performance of IoT sensors, including the analysis of measurement accuracy, response time, and stability of wireless data transmission by comparing the results of sensor readings against standard measuring instruments. This approach makes a new contribution in the form of empirical validation of IoT sensor performance in a realistic structural context, which has not been widely studied in previous studies. In addition, the results of this research serve as a scientific basis for the development of more efficient, adaptive, and affordable IoT-based building monitoring systems, while supporting a national roadmap towards intelligent infrastructure monitoring technology and disaster early warning systems.

This study aims to experimentally test the performance of IoT sensors in building movement monitoring systems, with a focus on analyzing the level of accuracy and reliability of sensors against changing structural conditions. The test was conducted to assess the extent to which MEMS-based sensors such as accelerometers, gyroscopes, and inclinometers are able to detect changes in position, tilt, and building vibration precisely and in real-time. Through this experimental approach, it is hoped that a quantitative picture can be obtained regarding the accuracy of sensor reading results compared to standard measuring instruments and the stability of wireless data transmission in IoT-based systems. The results of these tests are not only used to determine the measurement error rate and system response time, but also serve as a scientific basis for measuring the feasibility of implementing IoT sensors in building monitoring systems in real environments. Thus, this research contributes to the development of structural monitoring technology that is efficient, affordable, and can be integrated in future disaster early warning systems, in line with the current research direction in IoT-based structural health monitoring [3], [10], [11].

II. METHODS

This study uses a laboratory experimental approach with a performance test design for an IoT-based sensor system. This approach was chosen because it aims to measure the level of accuracy, stability, and response time of sensors in detecting changes in the position and slope of buildings. The experimental design was carried out by comparing the reading results of IoT sensors with standard measuring instruments, such as digital inclinometers and vibration meters, to obtain error values and reliability of wireless data transmission systems. The design of this research also follows the principle of design validation, which is the testing of prototype tools that have been developed at the previous stage, with the conditions of the test environment that resemble the real situation in the building structure. The test is carried out repeatedly to ensure consistency and stability of results, as per the recommendations of modern SHM research [3], [13].

A. Hardware Configuration

The hardware configuration used in the monitoring system consists of a MPU6050 sensor, which combines an accelerometer and a gyroscope with a measurement range of ±2 g and ±250°/s and a resolution of 16 bits, thus being able to detect changes in acceleration and rotation with precision. The tilt angle measurement is supported by a digital inclinometer with an accuracy of 0.01°, which serves as a comparator in calibration. All sensors are integrated with the ESP32 microcontroller, which has a 240 MHz dual-core processor, 802.11 b/g/n Wi-Fi support, and 520 KB of SRAM internal memory to process and transmit data quickly and stably. The built-in Wi-Fi module is used for real-time data transmission to a cloud-based server, while the system obtains power from a 5V USB supply with a 3.3V internal regulator to ensure a stable energy supply. The measurement data is then visualized through a cloud dashboard, which allows for direct monitoring of the movement of the structure through charts and digital interfaces [14].

B. Instrumen Penelitian

The main research instruments consist of two categories, namely test instruments and comparative instruments (standard tools), namely.

1. Test Instruments (IoT System)
    a. Accelerometer and Gyroscope (MPU6050) as the main sensor to detect acceleration and rotation.
    b. Inclinometer for measuring the angle of the slope of a buildingn.
    c. ESP32 as a data processing microcontroller.
    d. Wi-Fi module for data transmission to cloud systems.
    e. Web dashboard to display measurement data in real-time.
2. Standard Instruments
    a. *Digital Inclinometer* (0.01° accuracy)
    b. *Digital Vibration Meter* (accuracy ±0.5%)

Data from both instruments are recorded simultaneously to obtain **the measurement difference (Δ)** used in the calculation of system accuracy and error. All tools have been calibrated prior to testing to guarantee the validity of the experimental results.

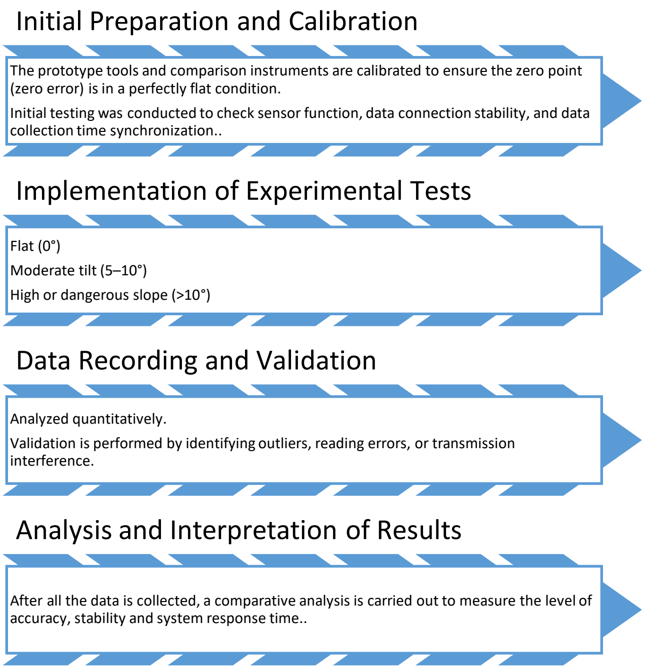

Figure 1. Research Procedure

C. Data Analysis Techniques

Data analysis was carried out in a descriptive quantitative manner with the aim of assessing the accuracy, reliability, and stability of the IoT sensor system. The stages of analysis include:

Sensor Accuracy Analysis

1. The accuracy level is calculated using the relative error formula:

$$Eror\ (\%) = \left|\frac{X/_s - X/_r}{X/_r}\right| = 100\% \qquad (1)$$

which X_s is the result of IoT sensor measurements and X_r is the result of a standard measuring instrument.

2. Reliability Analysis and Response Time

Response time and signal stability data are analyzed by calculating the time difference between the physical input and the digital data display, as well as the level of data loss during transmission.

3. System Stability Analysis

The stability of the system is evaluated through standard deviation (σ) from the results of the sensor reading in one fixed condition. Value σ Small indicates stable and non-volatile sensor.

4. Data Calibration and Validation Methods

The calibration process is carried out using a laboratory-standard digital inclinometer and vibration meter to ensure the accuracy of angle reference and acceleration before data collection. Each test condition is repeated 10 times to obtain an average value and standard deviation that represents the sensor's performance consistently. Data collection was carried out for 180 minutes (3 hours) to assess the stability of the sensor in the medium term and identify potential measurement fluctuations. In addition, cross-validation was carried out by comparing the measurement patterns generated by the IoT system to the reading curve of standard tools, so that trend suitability and relative accuracy could be comprehensively evaluated.

5. Visualization and Interpretation of Results

The results of the analysis are presented in the form of tables and graphs comparing the results of IoT measurements and standard tools to clarify the differences in performance. This analysis is also linked to previous research findings such as [10], [11] to demonstrate the relevance of results to global trends in IoT-based structural monitoring.

III. RESULTS AND DISCUSSION

The test was carried out at the Civil and Electrical Engineering Laboratory of the National Institute of Technology Yogyakarta with the aim of evaluating the **accuracy, stability, and response time of IoT sensors** in monitoring the movement of building structures. The prototype consists of an accelerometer and gyroscope (MPU6050) sensor, inclinometer, ESP32 microcontroller, as well as a Wi-Fi module that sends data in real-time to a cloud-based dashboard.

Three test conditions were used to simulate the movement of the structure, namely:

1. **Flat conditions (0**°) indicate the stability of the system in a static state.
2. **Moderate tilt (5–10**°) describes mild deformation due to vibration or mild lateral load.
3. **High tilt conditions (>10**°) simulate critical conditions due to ground shifts or strong shocks.

Table 1. Results of IoT Sensor Accuracy Test against Standard Tools

Structural Conditions	Reference Angle (°)	IoT Sensor Angle (°)	Error (%)	Category Stability	Response Time (sec)
Flat (0°)	0	0.04	0.4	Highly Stable	2.1
Medium Tilt (5°)	5	5.12	2.4	Stable	2.4
Medium Tilt (10°)	10	10.18	1.8	Stable	2.3
High Tilt (15°)	15	15.22	1.47	Stable	2.6
Light Vibration (0.12 g)	0.12 g	0.11 g	0.83	Highly Stable	2.3

The average error value of 1.58% indicates that the MEMS sensor is capable of measuring microdeformations with high accuracy, making it suitable for use as a key component in an IoT-based SHM system.

Figure 2. Prototype of IoT Sensor Test System for Building Movement Monitoring

Figure 2 is a prototype of the tool installed on a model of a miniature building with a wooden and light steel structure. A MPU6050 sensor and *inclinometer* are placed at the top of the model to detect tilt angles due to vibration or position adjustment. The ESP32 microcontroller connects to the *Wi-Fi module* to send data to *the cloud server*, while *the dashboard* displays results in tilt and vibration graphs. The test was carried out by gradually changing the slope using *an adjustable platform* to simulate ground movement and lateral load.

A. Accuracy and Stability Analysis

The data shows that IoT sensors have a high level of accuracy across test conditions. The highest error value of 2.4% occurred in the 5° tilt condition, while in the extreme position (>10°) the error actually decreased to 1.47%. This phenomenon suggests that the resolution of the sensor increases at greater inclination angles, as the sensitivity of the MEMS works more optimally at significant acceleration changes. These results are in line with research [4] which indicates that the MEMS sensor has a high linearity range at clear dynamic changes, with an accuracy of up to 98%. In addition, the stability of the system with a standard deviation <0.05° showed that the sensor was able to provide consistent results without significant fluctuations during 3 hours of continuous testing, supporting the conclusion about the importance of data stability as a prerequisite for the integration of the SHM system into the BIM digital model.

To assess the consistency of the sensor's performance over a period of time, a 180-minute reading stability test was performed under static conditions. The test aims to observe the angular value fluctuations generated by MEMS-based IoT sensors and ensure that the device is able to maintain accuracy in medium-term monitoring. Visualization of measurement results shown in Figure 3.

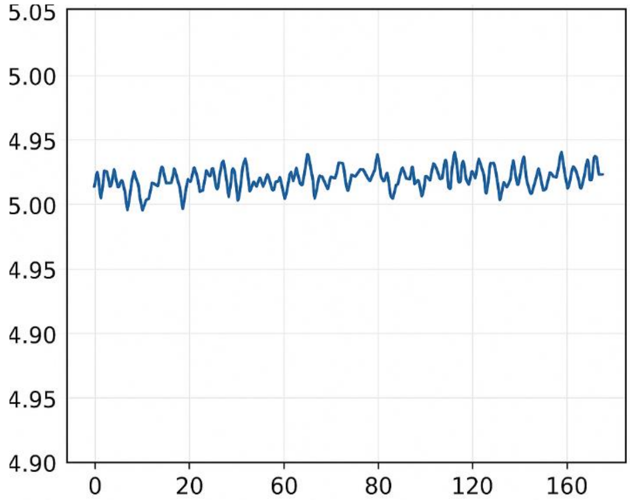

Figure 3. IoT Sensor Reading Stability Graph for 180 Minutes

Figure 3 shows that the angular value generated by the MEMS-based IoT sensor fluctuates very little around the face value, with a standard deviation of less than **0.05**°, which indicates an excellent level of stability during the 180 minutes of testing. This minimal fluctuation pattern reflects the characteristics of stable MEMS sensors in both static and semi-dynamic conditions, where noise remains within the normal range without causing significant deviations.

B. Analysis of Response Time and Transmission Reliability

An average response time of 2.34 seconds indicates that the system can quickly transfer data from sensors to cloud-based servers. This is faster than the results of the study [8], which reported a response time of about 3 seconds on the first generation IoT-based SHM system.

The reliability of data transmission was recorded at 97.8% without packet loss, which proves that the prototype is capable of working stably with local Wi-Fi networks. Stable data allows the implementation of an early warning system, where alerts can be activated automatically when the slope angle exceeds the danger threshold (>12°). This is relevant to the IoT-based early warning system proposed by [3], where wireless sensors are used to warn of bridge structure deformation in real-time.

The findings of the study indicate that the direction of development of structural health monitoring (SHM) systems is now leading to the comprehensive integration of high-performance IoT sensors, cloud-based data processing and *edge computing*, as well as the use of artificial intelligence (AI/ML) algorithms to build more robust, efficient, and sustainable monitoring mechanisms [9], [11]. This approach enables real-time detection of structural movements while providing early prediction of potential damage through historical pattern analysis and intelligent anomaly detection. In the context of the accuracy test results, the highest error of 2.4% at an angle of 5° occurred because the region is the transition zone of the MEMS sensor linearity, where the acceleration change is so small that the noise floor sensor is more dominant. When the angle is enlarged (>10°), the dynamic signal becomes stronger than the noise, so the error value decreases. This phenomenon is consistent with the findings that MEMS performance reaches optimal under conditions of more significant acceleration changes [4].

Various international studies show that the development of Structural Health Monitoring (SHM) systems is moving towards an integrated approach that combines IoT sensors, cloud/edge computing, and artificial intelligence algorithms to improve damage detection and early prediction capabilities. This approach has proven to be effective, as shown by research on bridges and high-rise buildings [14], which has managed to reduce detection response times by up to 45% through the integration of wireless sensors, machine learning, and multi-layer analytics. Similar findings are also shown by studies applying edge computing [15], as well as research that emphasizes the importance of integrating multi-source MEMS, camera, GPS data into three-dimensional digital twin models [2], thus allowing simulation of structural behavior under various conditions. In addition, the concept of data fusion framework [16] It is also an important reference in improving the accuracy of damage diagnosis through the incorporation of the characteristics of various sensors. All of these developments are in line with the global Smart Infrastructure 2030 agenda and the Sendai Framework, which emphasizes the importance of smart sensors and digital analytics in disaster early warning systems.

On the other hand, the limitations of the study are worth noting, including laboratory tests that do not yet represent field conditions, the use of a single sensor, as well as the reliance on untested Wi-Fi on remote networks such as NB-IoT or LoRaWAN. These limitations open up development opportunities towards a more comprehensive and adaptive IoT-AI-based SHM system. Overall, the results reinforce the importance of integrating sensor technology, cloud computing, and machine learning to create a structure monitoring system that is responsive, predictive, and supports the development of intelligent infrastructure and disaster early warning systems that are aligned with SDG 11 goals.

IV. CONCLUSION

Experimental tests of IoT sensor systems showed that MEMS-based devices had high accuracy with an average measurement error of 1.58% and a response time of 2.34 seconds. The combination of accelerometer, gyroscope, and inclinometer sensors is able to detect movement and tilt of buildings in real-time with good data stability and transmission reliability of up to 97.8%. The integration between sensors, ESP32 microcontrollers, and cloud computing systems has been proven to improve the efficiency of structural monitoring over conventional methods, supporting the implementation of resilient and responsive SHM systems to changes in structural conditions.

The integration opens up opportunities for the development of monitoring systems that not only detect the movement of structures, but also be able to predict potential damage early. Key recommendations include the expansion of full-scale field tests with multi-node systems and the use of remote protocols such as NB-IoT or LoRaWAN, as well as the incorporation of AI models for anomaly detection and predictive analysis. This integrated approach is expected to support the development of smart infrastructure and disaster early warning systems that are in line with Sustainable Development Goal (SDG) 11 towards resilient and sustainable cities and settlements.

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