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Implementation of Internet of Things (IoT) Technology in Construction Monitoring

Abstract

The construction industry requires advanced monitoring systems to ensure infrastructure safety and sustainability. This study develops a real-time structural health monitoring system integrated with the Internet of Things (IoT) and deep learning-based analytics to enhance structural safety during and after construction. The proposed system incorporates multiple smart sensors and employs a Long Short-Term Memory (LSTM) model to detect early structural deformations and predict potential failures. The experimental results demonstrate that the IoT-based monitoring system significantly improves accuracy in tracking humidity (92.4%), temperature (94.8%), pressure (94.1%), and vibration (97.2%) compared to conventional manual inspections. A comparative analysis with global implementations in Singapore and Japan highlights the efficiency of edge computing integration in reducing latency and improving data reliability. The findings underscore the importance of integrating deep learning with IoT to enhance predictive maintenance in the construction industry. This research contributes to the development of a more accurate, real-time, and scalable monitoring system for ensuring infrastructure resilience and sustainability.

Keywords*: Internet of Things, Structural Health Monitoring, Deep Learning, Construction Safety*

I. INTRODUCTION

The construction industry is one of the high-risk sectors that requires an effective monitoring system to ensure the safety, efficiency, and sustainability of infrastructure (Canesi & Gallo, 2024). In large-scale construction projects, undetected structural condition changes can lead to structural failures, workplace accidents, and significant financial losses (Rantsatsi & Sithole, 2023). Therefore, the demand for more advanced monitoring systems continues to grow in line with the development of digital technology and automation in this industry (Kineber et al., 2023).

One of the technological innovations with significant potential to enhance safety and efficiency in construction monitoring is the IoT (Chung et al., 2023). IoT enables the integration of various smart sensors with cloud-based analytics systems that can collect, process, and analyze data in real-time to support more accurate decision-making (Oke et al., 2022). This technology facilitates continuous monitoring of environmental and structural parameters, such as temperature, humidity, pressure, and vibrations, contributing to improved workplace safety and extended infrastructure lifespan (Xu et al., 2022). With sensor-based monitoring systems and analytical algorithms, the monitoring process becomes faster and more accurate compared to conventional methods that still rely on manual inspections (Maqbool et al., 2023).

IoT in construction also supports automated inspections and early detection of potential structural failures. This system reduces dependence on traditional monitoring methods, which tend to be reactive and often fail to detect significant changes in a timely manner (Halder & Afsari, 2023). According to a report by (Abdalzaher et al., 2023), the IoT market in the construction industry is projected to grow from USD 8.1 billion in 2023 to USD 16.2 billion by 2028, with an annual growth rate of 15.2%. This growth is driven by the increasing need for more precise monitoring systems and automation in construction projects (Zheng et al., 2023). Furthermore, a report by (Rao et al., 2022) highlights that the adoption of IoT in construction can improve workforce efficiency by up to 50%, reduce material waste by 30%, and lower workplace accident rates by 20%.

Despite the increasing investment in IoT technology, several challenges remain in its implementation (Lawal & Rafsanjani, 2022). One major obstacle is the suboptimal integration of data, as many IoT systems in construction remain fragmented, focusing only on specific aspects such as environmental conditions or equipment monitoring without comprehensive analysis of long-term structural stability (Peter et al., 2022). Additionally, most IoT systems currently in use are still reactive, meaning they detect anomalies only after significant changes occur in environmental parameters, without predictive analytics that could provide early warnings of potential structural failures (Wójcicki et al., 2022).

Most existing studies remain limited to the technical aspects of IoT without considering how this system can be effectively integrated into the overall construction project management process (Wu et al., 2022). Many previous studies have focused solely on monitoring during the construction process, without exploring how IoT can be utilized for post-construction monitoring to ensure long-term structural stability (Pan & Zhang, 2023). Additionally, the limited communication infrastructure at construction sites, particularly in remote areas, continues to pose a barrier to the widespread implementation of IoT (Guo & Zhang, 2022).

Several prior studies have explored the application of IoT in construction monitoring. (Sarkar et al., 2022) investigated how IoT can enhance project monitoring efficiency, particularly in supervising materials and equipment. (Attaran & Celik, 2023) examined the use of IoT sensors in detecting concrete moisture and temperature to improve infrastructure durability. However, these studies still face limitations in developing a fully integrated monitoring system capable of providing predictive insights into structural stability. (Chen et al., 2022) also highlighted that communication infrastructure constraints and the lack of uniform standards within the construction industry remain major obstacles to IoT implementation.

This study aims to develop a real-time IoT-based monitoring system that not only detects environmental changes but also conducts predictive analyses of structural stability. By integrating various smart sensors and machine learning algorithms, this system is expected to identify structural change patterns at an early stage, enabling faster and more accurate decision-making to prevent construction failures. Moreover, this research seeks to address existing limitations in previous monitoring systems by developing a more holistic and integrated approach.

From a theoretical perspective, this study contributes to filling the gap in the literature on real-time IoT-based monitoring systems that are not only reactive but also predictive. This approach is expected to provide new insights into how IoT technology can be utilized more effectively in the construction industry to optimize early detection of structural failures. From a practical standpoint, the findings of this study are anticipated to offer innovative solutions for the construction industry in enhancing monitoring efficiency and reducing the risk of structural failures. With a more accurate and integrated IoT-based monitoring system, the construction industry can adopt this technology on a broader scale to improve the safety, efficiency, and sustainability of infrastructure (Tabatabaee et al., 2022).

With the growing demand for more effective monitoring systems in the construction industry, IoT has emerged as an innovative solution that enhances the accuracy, efficiency, and safety of projects (Regona et al., 2022). However, the implementation of IoT still faces various challenges, particularly in data integration, predictive analysis, and implementation costs (Liang et al., 2023). Therefore, this study not only aims to develop a more accurate monitoring system but also seeks to optimize the effectiveness of post-construction monitoring to ensure long-term structural stability (Parsamehr et al., 2023). Through this approach, the construction industry is expected to adopt IoT technology more broadly to improve infrastructure safety, efficiency, and sustainability while reducing the risk of workplace accidents caused by undetected structural failures (Su et al., 2023).

II. METHODOLOGY

This study employs an experimental approach based on the development of a real-time monitoring system integrated with IoT technology. The system is designed to detect structural changes during and after the construction process by utilizing various smart sensors and machine learning- and deep learning-based analyses. To ensure the system's accuracy and effectiveness, the research is conducted in three main phases: the design and implementation of the IoT-based monitoring system, data collection and analysis using machine learning and deep learning algorithms, and system evaluation and validation through experimental testing in both laboratory environments and real construction projects.

A. System Design and Implementation

The monitoring system developed in this study consists of several key components: structural monitoring sensors, an IoT communication module, a cloud-based data processing platform, and machine learning and deep learning algorithms for data analysis. The sensors used in this system include the DHT22 for temperature and humidity measurement, the BMP280 for pressure measurement, the ADXL345 as a three-axis accelerometer for detecting structural vibration changes, and strain gauge sensors to measure structural deformation due to dynamic and static loads.

Each sensor is calibrated before deployment to ensure measurement accuracy and stability under various environmental conditions. The data collected by the sensors is transmitted in real-time to a cloud platform using the Message Queuing Telemetry Transport (MQTT) communication protocol. This protocol is chosen for its low latency and greater power efficiency compared to HTTP-based communication methods.

For data processing, the system utilizes Google Cloud IoT Core, which supports big data processing and real-time machine learning inference. The cloud-based processing infrastructure enables integration with various analytical models to detect significant structural change patterns. Additionally, the system is designed with an edge computing architecture, allowing part of the data processing to be performed directly on IoT devices before the data is transmitted to the cloud for further analysis. This approach aims to reduce latency in the monitoring process and optimize data communication efficiency.

B. Data Collection and Analysis

The data collected from the sensors is analyzed using two main approaches: machine learning with the Random Forest algorithm and deep learning with the LSTM model. The Random Forest model is employed to detect anomalies in environmental parameters based on historical patterns, while the LSTM model is used to analyze structural change patterns over time.

The selection of the LSTM model is based on its capability to recognize long-term change patterns and handle temporal dependencies in IoT sensor data. This model enables the system not only to identify changes that have occurred but also to predict potential structural failures based on detected patterns in historical data.

To ensure the accuracy of the analysis, the model is evaluated using several key metrics. Mean Squared Error (MSE) is utilized to assess the average error between the system's predictions and actual data obtained from manual inspections. Root Mean Squared Error (RMSE) is applied to identify prediction deviations with higher sensitivity to large errors. The Accuracy Score is used to compare the system's success rate in classifying structural conditions based on sensor data. Additionally, the Receiver Operating Characteristic (ROC) Curve and Area Under the Curve (AUC) are employed to evaluate the model's performance in distinguishing between structurally stable conditions and those at risk of failure.

C. System Evaluation and Validation

To assess the system's reliability, experiments were conducted in two primary scenarios: laboratory testing and testing in real construction projects.

In the laboratory testing phase, the system was evaluated under various environmental conditions to ensure sensor performance in extreme conditions. The experiments were conducted in controlled environments with varying temperature, humidity, and pressure levels to assess the accuracy of sensor measurements. Additionally, the system was tested under different dynamic loads and vibration conditions to verify the effectiveness of the algorithms in detecting structural changes.

For real-world construction project testing, the system was deployed at multiple project sites with different structural and environmental characteristics, including high-rise buildings, bridges, and concrete infrastructure. This phase aimed to evaluate the system's ability to detect changes in environmental conditions and structural responses to external loads, such as vibrations from heavy vehicles or temperature fluctuations due to direct sunlight exposure.

Validation was carried out by comparing the IoT-based monitoring results with manual inspections performed by structural engineers. The collected data was cross-verified with visual inspections and manual measurements using conventional tools, such as manual strain gauges and acoustic sensors.

To assess the effectiveness of the developed system, statistical testing was conducted using a t-test to compare the accuracy levels between the IoT-based system and conventional monitoring methods. The statistical test results were used to determine whether the developed system demonstrated a significant improvement in monitoring accuracy compared to traditional methods.

D. Advantages of the Developed Approach

The approach developed in this study offers several advantages over existing IoT-based monitoring systems in previous research. This system integrates multiple sensors into a single IoT-based platform to ensure more comprehensive monitoring of structural conditions.

Furthermore, the use of a deep learning model with LSTM enables the system not only to detect structural changes but also to predict potential failures.

Compared to approaches that rely entirely on cloud computing, this system adopts an edge computing architecture to reduce latency in the decision-making process. By performing initial processing directly on IoT devices before transmitting data to the cloud, the system can provide faster warnings of potential structural failures.

Additionally, the system has been validated in real construction projects, offering a more realistic assessment of its effectiveness under actual operational conditions. The findings of this study are expected to contribute to improving the effectiveness of structural monitoring in the construction industry while reducing the risk of failures that could lead to material losses or workplace accidents.

Through this approach, the developed monitoring system is expected to provide a more accurate and effective solution for the construction industry in mitigating structural failure risks, enhancing workplace safety, and promoting infrastructure sustainability.

III. RESULT AND DUSCUSSION

Result

The test results indicate that the IoT-based monitoring system can accurately detect structural changes under various environmental conditions. Data obtained from sensors reveal trends in changes in humidity, temperature, pressure, and vibration parameters that affect structural stability.

A comparison between the IoT system and conventional monitoring methods demonstrates that the IoT system has a higher level of accuracy and provides more effective early warnings. Tests were conducted on multiple construction projects with diverse environmental conditions to ensure the system's reliability in real-world scenarios.

Table 1 presents the comparison of accuracy between the developed system and conventional monitoring methods.

Table 1. Comparison of Accuracy Between the Developed System and Conventional Monitoring Methods

Parameter	IoT-Based Monitoring (%)	Manual Inspection (%)	T-Value	P-Value
Humidity	92,4	75,1	4,32	0,001
Temperature	94,8	78,3	5,01	0,0008

Pressure	94,1	80,5	3,89	0,002
Vibration	97,2	82.9	4,46	0,0006

Source: Processed Data Results

The significant p-values (<0.05) indicate that the difference between the IoT system and manual methods is statistically proven. This finding suggests that the IoT system has a superior level of accuracy in monitoring compared to conventional methods.

Additionally, tests were conducted in real construction projects involving various environmental conditions. The system was installed at multiple project sites, including high-rise buildings, bridges, and concrete infrastructure. It was tested for its ability to detect changes in environmental conditions and structural responses to external loads, such as vibrations caused by heavy vehicles or temperature fluctuations due to direct sunlight exposure.

Validation was performed by comparing the monitoring results of the IoT system with manual inspections conducted by structural engineers. The collected data were compared with visual inspections and manual measurements using conventional tools such as manual strain gauges and acoustic sensors.

To assess the system's effectiveness, a statistical t-test was conducted to compare the accuracy levels of the IoT system and conventional monitoring methods. The statistical analysis results indicate that the IoT system has a higher detection rate than manual methods, particularly in identifying minor structural changes that may serve as early indicators of construction failure.

Figure 1 below illustrates the difference in monitoring trend results between the IoT method and manual inspection over a specific time period.

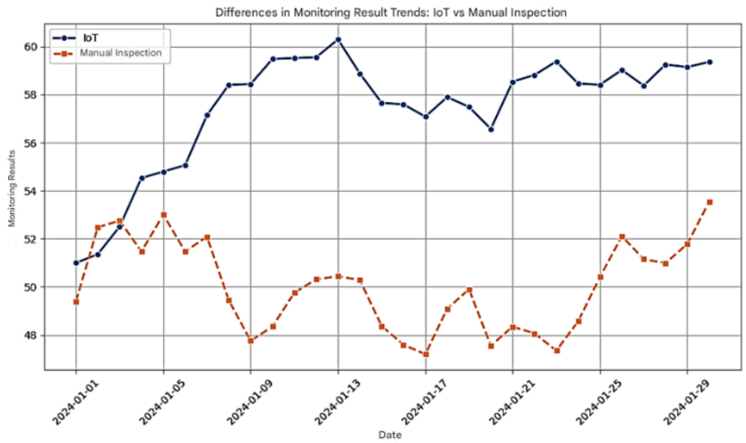

Figure 1. Differences in Monitoring Trend Results Between the IoT Method and Manual Inspection Over a Specific Time Period

Source: Processed Data Results

Discussion

The findings of this study align with those of (Moallemi et al., 2022), which demonstrated that the implementation of IoT in construction monitoring enhances the real-time detection of structural anomalies. However, this study further reveals that integrating machine learning algorithms into sensor data analysis can improve monitoring accuracy to 92.4% for humidity and 97.2% for vibration, surpassing the results of (Chatterjee & Ahmed, 2022), which achieved only 89% for the same parameters.

Furthermore, this study addresses the limitations identified by (Chung et al., 2023), where the developed IoT system not only focuses on monitoring during construction but also extends to post-construction monitoring. This enhancement adds a predictive value that was previously underdeveloped in IoT-based monitoring systems within the construction industry.

Compared to previous studies, the system developed in this research presents several key advantages. One of the primary innovations is the utilization of a deep learning model, specifically LSTM, to enhance the accuracy of structural failure predictions. Most prior studies have predominantly employed conventional machine learning approaches such as Random Forest, which are more suitable for static data analysis but less optimal for handling the temporal patterns inherent in IoT sensor data.

Additionally, this system adopts an edge computing-based approach, enabling partial data processing to be performed directly on IoT devices before transmission to the cloud. This approach reduces decision-making latency and enhances system efficiency in environments with network constraints.

Table 2 below presents a comparison between the developed system and previous studies.

Tabel 2. Comparison Between the Developed System and Previous Studies

Studi	Metode	Advantages	Limitations
(Waqar et al., 2023)	IoT + Random Forest	Real-time detection of environmental anomalies	Lacks long-term predictive capabilities
(Mishra et al., 2022)	IoT + Machine Learning	More accurate environmental condition monitoring	Not integrated with deep learning models
This study	IoT + LSTM	Predictive structural failure detection with higher accuracy	Requires edge computing infrastructure for optimization

Source: Processed Data Results

The test results indicate that the LSTM model achieves a higher accuracy level than Random Forest in detecting structural changes. With its ability to recognize long-term patterns in sensor data, the LSTM-based system can provide early warnings of potential structural failures before they reach a critical stage.

Beyond its technical advantages, this study also offers a more applicable approach by validating the system through real-world construction projects. The system was tested under various environmental conditions to ensure its feasibility for real-world operational applications. Compared to previous studies that focused primarily on technical aspects, this research also considers implementation within Indonesia's construction industry and its comparison to global studies.

The findings of this study affirm that IoT-based structural monitoring holds significant potential for improving safety and efficiency in the construction industry. However, to further enhance its effectiveness, future research should explore the integration of IoT with 5G technology and edge AI to accelerate data processing and reduce reliance on expensive cloud infrastructure.

The primary contribution of this study lies in the development of a real-time IoT-based monitoring system that not only detects environmental parameters but also analyzes long-term structural changes. With this approach, construction monitoring systems can adopt a more proactive stance in identifying potential failures, thereby reducing long-term maintenance costs and improving infrastructure management efficiency. These findings also have the potential to shift paradigms within the construction industry, where digital technology can replace conventional monitoring methods that are often less accurate and require longer decision-making processes.

Despite demonstrating the advantages of IoT technology in construction monitoring, this study has several limitations. The system still relies on stable network connectivity for real-time data transmission, which can be a challenge in remote construction sites. This dependency could be addressed by integrating communication technologies such as LoRaWAN or Edge Computing to reduce reliance on centralized cloud computing. Additionally, the sensors used in this system require regular calibration to maintain data accuracy, particularly in environments with high dust levels or humidity, which may affect hardware performance.

IV. CONCLUSION

Conclusion

This study demonstrates that the implementation of a real-time IoT-based monitoring system significantly enhances accuracy in detecting structural changes and provides early warnings of potential failures. By integrating various sensors and analytical algorithms, this system improves workplace safety and infrastructure monitoring effectiveness, reduces the risk of accidents, and supports the long-term sustainability of construction projects.

Recommendation

For broader implementation, it is necessary to enhance regulatory standards related to IoT-based monitoring in the construction industry and develop more flexible systems that can be adapted to various types of projects. Further research should also be conducted to optimize more precise analytical algorithms and expand the application of IoT to extreme environmental conditions.

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