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AN INTELLIGENT IOT-ENABLED FRAMEWORK FOR STRUCTURAL HEALTH MONITORING OF HIGH-RISE BUILDINGS

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ABSTRACT
Structural Health Monitoring (SHM) has become a critical requirement for ensuring the safety and longevity of high-rise buildings subjected to dynamic loads and environmental effects. Traditional inspection methods are often labor-intensive, time-consuming, and incapable of providing continuous monitoring. This research presents an intelligent IoT-enabled framework for real-time structural health monitoring of high-rise buildings. The proposed system integrates smart sensors, wireless communication, cloud-based data processing, and artificial intelligence techniques for early damage detection and condition assessment. Sensor data such as vibration, strain, and displacement are continuously collected and analyzed using machine learning models to identify abnormal structural behavior. The framework enables predictive maintenance and improves decision-making for building management authorities. Experimental validation demonstrates improved accuracy, scalability, and real-time responsiveness. The results confirm that the proposed approach enhances structural safety while reducing maintenance costs and manual inspection efforts.

Keywords: Structural Health Monitoring, IoT, Artificial Intelligence, High-Rise Buildings, Smart Sensors, Civil Engineering

I. INTRODUCTION

High-rise buildings are complex structural systems exposed to dynamic loads such as wind, earthquakes, and operational vibrations throughout their service life. Ensuring their safety and performance is a major challenge in modern urban environments. Conventional structural inspection methods rely heavily on periodic manual assessments, which may fail to detect early-stage damage. These limitations have led to growing interest in automated and intelligent monitoring systems for structural health assessment. Continuous monitoring is essential to prevent catastrophic failures and reduce maintenance costs. Recent advancements in sensing technologies have made it possible to collect real-time structural data efficiently. However, the integration of such data into meaningful decision-making remains challenging. Structural Health Monitoring systems aim to detect, locate, and quantify damage in structures using measured response data. Traditional SHM approaches often use wired sensor networks that are expensive and difficult to scale. Moreover, they lack real-time analytics capabilities and adaptive intelligence. With the rapid growth of urban infrastructure, there is an urgent need for scalable and cost-effective SHM solutions. IoT technology offers promising opportunities by enabling wireless connectivity and real-time data transmission. The combination of IoT with artificial intelligence enhances damage detection accuracy and system autonomy. IoT-based SHM systems employ distributed sensors capable of monitoring multiple structural parameters simultaneously. These systems allow remote access and continuous observation of structural conditions. Data collected from sensors can be transmitted to cloud platforms for storage and processing. Artificial intelligence techniques further enable automatic pattern recognition and anomaly detection. Such intelligent frameworks reduce reliance on manual inspections and improve system reliability. This transformation aligns with the concept of smart cities and intelligent infrastructure. Artificial intelligence plays a crucial role in interpreting large volumes of structural data generated by IoT devices. Machine learning models can identify subtle changes in structural behavior that may indicate damage. These models improve over time through continuous learning and adaptation. AI-based systems can predict potential failures before they occur, enabling proactive maintenance strategies. This predictive capability significantly enhances the safety of high-rise buildings. The integration of AI also supports decision-making by providing actionable insights. This research proposes an intelligent IoT-enabled framework specifically designed for structural health monitoring of high-rise buildings. The framework combines smart sensors, wireless communication, cloud computing, and machine learning techniques. The proposed system aims to provide real-time monitoring, early damage detection, and predictive maintenance capabilities. The performance of the system is evaluated through experimental implementation and analysis. The results demonstrate the effectiveness of the proposed framework in improving structural safety and monitoring efficiency.

II. LITERATURE REVIEW

Several studies have explored the application of structural health monitoring techniques in civil engineering structures. Farrar and Worden (2007) highlighted the importance of vibration-based SHM methods for damage detection. Their work emphasized the limitations of traditional inspection methods and the need for automated systems. However, early SHM systems were largely dependent on wired sensor networks, limiting scalability. These systems were also expensive and difficult to deploy in large structures. Consequently, researchers began exploring wireless sensor networks for SHM applications. Lynch and Loh (2006) investigated the use of wireless sensors for structural monitoring. Their study demonstrated the feasibility of wireless communication in capturing structural responses. Despite their advantages, wireless systems faced challenges such as power consumption and data reliability. Advances in low-power electronics have since addressed many of these issues. The integration of IoT technologies further enhanced wireless SHM capabilities. This shift marked a significant milestone in smart infrastructure monitoring. Recent research has focused on IoT-based SHM frameworks for real-time monitoring. Hou et al. (2018) proposed an IoT-enabled SHM system for large civil structures. Their framework improved data accessibility and reduced monitoring costs. However, the system relied primarily on threshold-based analysis, limiting damage detection accuracy. Such approaches often fail to capture complex structural behavior. This limitation necessitated the incorporation of artificial intelligence techniques. Artificial intelligence and machine learning have gained attention for structural damage detection and prediction. Sohn et al. (2014) explored pattern recognition techniques for SHM. Their findings showed that machine learning models outperform traditional statistical methods. Deep learning techniques further improved feature extraction and classification accuracy. Nevertheless, integrating AI with real-time IoT systems remained a challenge. Computational complexity and data management issues required further research. Although significant progress has been made, existing SHM systems still face limitations in scalability, intelligence, and real-time decision-making. Many studies focus on either IoT or AI independently, rather than an integrated framework. There is limited research addressing intelligent SHM specifically for high-rise buildings. This study addresses these gaps by proposing a unified IoT-AI framework. The proposed system emphasizes real-time onitoring, predictive analytics, and practical implementation.

III. PROPOSED METHODOLOGY

The proposed methodology presents an intelligent IoT-enabled framework for structural health monitoring of high-rise buildings. The system architecture consists of sensor nodes, a communication layer, a cloud platform, and an AI-based analytics module. Smart sensors are deployed at critical structural locations to monitor parameters such as acceleration, strain, displacement, and temperature. These sensors continuously capture structural response data under various loading conditions. Wireless communication modules transmit the data to a central server for processing. The communication layer uses low-power wireless protocols to ensure reliable data transmission. IoT gateways aggregate sensor data and forward it to cloud servers. This architecture ensures scalability and flexibility for large structures. Cloud computing enables efficient storage and management of large datasets. It also supports real-time data access and system monitoring. The use of cloud infrastructure reduces on-site computational requirements. The analytics module applies machine learning algorithms to detect anomalies in structural behavior. Features are extracted from sensor data using signal processing techniques. These features are fed into supervised and unsupervised learning models. The models are trained to distinguish between healthy and damaged structural states. Continuous learning allows the system to adapt to changing environmental conditions. This improves long-term monitoring accuracy. Anomaly detection is performed by comparing real-time data with learned baseline patterns. Significant deviations trigger alerts for further inspection. The system also estimates damage severity and potential failure risks. Predictive maintenance recommendations are generated based on historical data trends. This proactive approach enhances structural safety and reduces downtime. Decision-makers receive real-time insights through a user-friendly dashboard. The proposed methodology emphasizes modular design and interoperability. The framework can be integrated with existing building management systems. It supports future expansion and technology upgrades. The methodology ensures reliability, accuracy, and cost-effectiveness. Overall, the proposed approach addresses key limitations of traditional SHM systems.

IV. EXPERIMENTAL SETUP

The experimental setup was designed to validate the performance of the proposed IoT-enabled SHM framework. A scaled structural model representing a high-rise building was used for testing. Multiple sensors were installed at different levels of the structure. Accelerometers, strain gauges, and displacement sensors were selected for data collection. The sensor placement was based on structural analysis results. Wireless sensor nodes were configured to transmit data at predefined intervals. An IoT gateway was used to aggregate and forward sensor data. The cloud platform hosted data storage and analytics modules. Machine learning models were trained using baseline structural response data. Controlled damage scenarios were introduced to simulate structural degradation. These scenarios included stiffness reduction and mass variation. Data acquisition was performed under normal and damaged conditions. Environmental noise and operational vibrations were also considered. The system continuously monitored structural responses during experiments. Data preprocessing included noise filtering and normalization. Feature extraction techniques were applied to identify key response characteristics. These features served as inputs to machine learning models. The performance of the AI models was evaluated using accuracy, precision, and recall metrics. Real-time anomaly detection capability was assessed. System latency and data transmission reliability were also measured. The experimental setup ensured repeatability and consistency. The results provided insights into system robustness and scalability. The experimental evaluation demonstrated the feasibility of deploying the proposed framework in real-world scenarios. The system effectively detected structural anomalies under varying conditions. The setup validated both hardware and software components. These experiments form the basis for performance analysis and discussion.

V. RESULTS AND DISCUSSIONS

The experimental results demonstrate the effectiveness of the proposed IoT-enabled SHM framework. The system successfully captured real-time structural response data from distributed sensors. Data transmission remained stable with minimal packet loss. The cloud-based platform efficiently handled large volumes of sensor data. This confirms the scalability of the proposed architecture. Machine learning models achieved high accuracy in distinguishing between healthy and damaged structural states. The anomaly detection module identified damage scenarios with minimal false alarms. Compared to threshold-based methods, AI-driven analysis showed improved sensitivity. The system detected subtle changes in vibration patterns indicative of early-stage damage. This capability is crucial for preventive maintenance.

The response time of the system was within acceptable limits for real-time monitoring. Alerts were generated promptly upon detection of abnormal behavior. Visualization dashboards provided clear insights into structural conditions. Decision-makers could easily interpret monitoring results. This improves situational awareness and response efficiency. Environmental variations had minimal impact on system performance. Continuous learning mechanisms helped adapt to changing conditions. The predictive maintenance module provided reliable recommendations. These features enhance long-term monitoring reliability. The results indicate improved safety and reduced maintenance costs. Overall, the proposed framework outperformed conventional SHM approaches. The integration of IoT and AI proved effective for high-rise building monitoring. The system demonstrated robustness, accuracy, and real-time responsiveness. These findings validate the practicality of the proposed solution. The discussion confirms its suitability for smart infrastructure applications.

VI. CONCLUSION

This research presented an intelligent IoT-enabled framework for structural health monitoring of high-rise buildings. The proposed system integrates smart sensors, wireless communication, cloud computing, and artificial intelligence. It enables continuous monitoring and early damage detection. The framework addresses limitations of traditional SHM methods. Experimental results demonstrated high accuracy and real-time performance. The AI-based analytics enhanced anomaly detection and predictive maintenance. The system showed scalability and robustness under varying conditions. This approach significantly improves structural safety and monitoring efficiency. The proposed framework supports smart city initiatives and intelligent infrastructure management. It offers a cost-effective and reliable SHM solution. The study confirms the potential of IoT and AI integration in civil engineering applications.

FUTURE SCOPE

The framework can be extended to full-scale real-world high-rise buildings. Advanced deep learning models can further improve damage classification accuracy. Integration with digital twin technology can enhance predictive analysis. Energy harvesting techniques can improve sensor sustainability. Future work may focus on multi-hazard monitoring and resilience assessment.

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