International Journal of
DATA SCIENCE AND IOT MANAGEMENT SYSTEM
ISSN: 3068-272X www.ijdim.com Original Research Paper

AI ENABLED A STRUCTURAL HEALTH MONITORING USING LOW POWER COST IOT SENSOR

[1]Dharavath Jagan, [2]B Sandeep Kumar
[1]Assistant Professor,Dept of ECE, Christhu Jyothi Institute Of Technology And Science
Jangaon, Telangana
Email:Jagan410d@gmail.com

[2]Assistant Professor,Dept of ECE, Christhu Jyothi Institute Of Technology And Science
Jangaon, Telangana
Email: sandeep56646@gmail.com

ABSTRACT

Structural safety is a critical concern for infrastructure such as bridges, buildings, dams, and industrial facilities, where undetected deterioration can lead to catastrophic failures. Traditional inspection methods are time-consuming, labor-intensive, and prone to human error, creating a need for intelligent and continuous monitoring solutions. This research proposes an AI-enabled Structural Health Monitoring (SHM) system based on low-power, cost-efficient IoT sensors capable of real-time measurement and predictive analytics. The system integrates vibration, strain, temperature, and displacement sensors with an edge-processing IoT architecture, transmitting data securely to a cloud-based platform. Machine learning algorithms analyse sensor readings to identify early abnormalities, quantify damage severity, and predict future structural failures. Energy-efficient communication protocols and optimized data compression techniques extend the battery life of sensor nodes, making the system scalable and economically feasible for long-term deployment. The experimental results demonstrate that the proposed model enhances damage detection accuracy, reduces maintenance costs, and supports proactive decision-making for infrastructure management. Overall, the AI-enabled low-power SHM framework establishes a robust and intelligent solution for smart infrastructure resilience and public safety.

Keywords: Structural Health Monitoring, Artificial Intelligence, IoT Sensors, Low Power Consumption, Predictive Analytics, Smart Infrastructure, Real-Time Monitoring, Damage Detection, Cloud Computing, Edge Processing.

Received: 05-05-2025 Accepted: 07-06-2025 Published: 15-06-2025

I.INTRODUCTION

1. Background and Motivation:

Infrastructure plays a foundational role in economic development and public safety, yet many civil structures—such as bridges, flyovers, buildings, and dams—are aging and exposed to environmental stress, heavy loads, material degradation, and unexpected events. Conventional structural inspection techniques depend heavily on manual surveys and periodic maintenance schedules, which often fail to detect hidden or early-stage damage. As a result, structural issues remain unnoticed until they escalate into catastrophic failures, leading to property loss, fatalities, and high rehabilitation expenses. Recent advancements in the Internet of Things (IoT) and Artificial Intelligence (AI) have created a transformative opportunity to monitor infrastructure health intelligently and continuously. IoT sensors allow real-time measurement of vibration, strain, temperature, and displacement, while AI-based predictive models can automatically detect anomalies, assess damage severity, and predict future deterioration trends. However, large-scale deployment of SHM systems faces major challenges, including high installation costs, power consumption, and communication overhead. To address these limitations, low-power and cost-efficient IoT sensors combined with AI analytics provide a sustainable solution for long-term monitoring of structural performance.

2. Problem Definition:

Structural deterioration in critical infrastructure often remains undetected due to the limitations of traditional inspection methods, which are costly, infrequent, labor-intensive, and incapable of providing continuous real-time monitoring. Existing SHM solutions that utilize advanced sensors are effective but are not widely adopted due to their high power consumption, expensive hardware, and large data processing requirements. Consequently, early-stage damage, abnormal vibration patterns, and material fatigue frequently go unnoticed until they lead to severe failures. Therefore, there is a need for an intelligent, low-power, and cost-efficient monitoring system that can continuously collect and analyze sensor data using AI techniques to accurately detect structural abnormalities and predict potential failures in a timely manner.

3. Objective and Scope:

The primary objective of this research is to develop an AI-enabled Structural Health Monitoring (SHM) system using low-power, cost-efficient IoT sensors that can continuously track structural integrity, detect early signs of damage, and provide predictive insights for timely maintenance. The system aims to integrate multi-sensor data acquisition with intelligent AI algorithms to classify structural conditions, estimate damage severity, and forecast potential failures while ensuring energy-efficient communication and long-term deploy ability.

The scope of the work includes the design and deployment of a distributed IoT sensor network for capturing key structural parameters such as vibration, strain, temperature, and displacement.

- Deployment of low-power, cost-efficient IoT sensors for continuous structural condition monitoring.
- Acquisition of critical parameters such as vibration, strain, displacement, and temperature from infrastructure.
- Integration of edge and cloud computing for efficient data processing and analytics.
- Application of AI/ML techniques for anomaly detection, damage classification, and failure prediction.
- Real-time alerting and visualization of structural health status through a centralized dashboard.
- Scalable framework applicable to various infrastructures such as bridges, buildings, dams, and industrial structures.
- Focus on reducing energy consumption and data transmission overhead for long-term system deployment.
- Consideration of environmental and operational uncertainties to enhance system robustness and reliability.

II.RELATED WORK

Structural Health Monitoring (SHM) has evolved significantly from traditional visual inspections and wired instrumentation to intelligent, sensor-driven and AI-enabled frameworks. Early SHM systems relied mainly on wired accelerometers and strain gauges, which, although accurate, were expensive, power-hungry and difficult to deploy on large-scale structures. Wireless Sensor Networks (WSNs) were introduced to overcome wiring constraints; Harms et al. designed and tested a low-power WSN based on SmartBrick nodes for bridge monitoring, demonstrating the feasibility of distributed sensing but highlighting challenges in energy management and data handling [1]. Subsequent works on smart and sustainable WSNs for SHM emphasized that next-generation nodes must be low-cost, low-power, self-organized and capable of local processing to reduce communication overhead [2]. Abdulkarem et al. provided a comprehensive review of wireless sensor networks for SHM and reported that power consumption, network reliability and long-term durability remain major bottlenecks for real deployments [3].

With the rapid growth of IoT, researchers began integrating cloud platforms and internet connectivity into SHM systems. IoT-based bridge and building monitoring solutions using load, vibration, temperature and humidity sensors have shown that continuous online monitoring and remote diagnostics are possible, but they also increase data volume and require robust architectures for storage and analytics [4][5]. Recent studies on IoT-driven SHM for bridges report low-cost, wireless, and user-friendly designs that classify health conditions using deflection, vibration and environmental parameters, sometimes enhanced with fuzzy logic or rule-based decision modules for risk evaluation [6]. Parallelly, reviews on the use of IoT for SHM in civil infrastructure highlight that sensor miniaturization, low-power electronics and pervasive connectivity enable dense instrumentation, yet energy efficiency and secure communication are crucial for long-term deployment [7].

Artificial Intelligence and machine learning have become central to modern SHM. Deep learning-based approaches using vibration signals, modal parameters and finite element–generated data have been used for detecting single and multiple damages with high accuracy, employing 1D CNNs, LSTMs and other architectures for feature learning from raw time series [8][9]. Recent reviews on AI in SHM summarize how machine learning and deep learning models outperform traditional statistical methods in pattern recognition, anomaly detection and damage localization, and note emerging trends like vision-based SHM and multimodal fusion of vibration and image data [10][11]. Deep learning-based SHM surveys further point out the need for edge computing and lightweight models to bring inference closer to the sensor and reduce dependence on high-bandwidth cloud links [12]. Edge-SHM frameworks have demonstrated that low-power microcontrollers equipped with MEMS accelerometers can extract frequency- and time-domain features at the edge and only transmit compact indicators, significantly extending battery life while maintaining diagnostic performance [13]. Very recent AI-based SHM and IoT platform studies propose integrating ML models with cloud dashboards and secure communication protocols, but they often use relatively power-intensive hardware or focus more on analytics than on energy-aware sensing [14][15].

From this literature, it is evident that although AI and IoT have considerably advanced SHM capabilities, there is still a gap in combining energy-efficient, low-cost IoT sensor nodes with AI-driven analytics in a tightly integrated architecture optimized for long-term deployment. This motivates the present work to design an AI-enabled SHM framework that specifically targets low-power operation, reduced data transmission, and cost-effective sensing, while still achieving accurate damage detection and predictive maintenance for diverse civil structures.

III.METHODOLOGY

The methodology for the proposed system is designed to enable continuous, intelligent, and energy-efficient monitoring of civil infrastructure using low-power IoT sensor nodes combined with AI-driven analytics. The workflow consists of a sequence of interconnected stages described below:

1. Structural Sensor Deployment

Low-power IoT sensors—including accelerometers, strain gauges, temperature sensors, and displacement sensors—are strategically installed on critical locations of the structure. Sensor placement is optimized using structural modeling to ensure maximum sensitivity to stress concentration zones and vibration modes.

2. Data Acquisition and Local Pre-Processing

Each sensor node collects real-time physical measurements and performs lightweight on-board pre-processing to reduce data volume. Techniques such as noise filtering, FFT-based feature extraction, signal normalization, and threshold-based quantization are implemented to minimize wireless transmission energy while preserving structural behavior information.

3. Edge Computing and Adaptive Power Control

Edge microcontrollers perform intermediate analytics such as event-triggered sampling, anomaly scoring, and data compression. Adaptive duty-cycling and sleep-mode control allow dynamic adjustment of sampling rates based on structural conditions, thereby extending battery life and minimizing resource wastage.

4. Wireless Data Transmission

Pre-processed feature data—not raw continuous time-series—is transmitted to the gateway using low-power communication protocols (LoRa, BLE, ZigBee, NB-IoT). Secure data aggregation at the gateway further removes redundant measurements and forwards information to the cloud server.

5. Cloud-Based Data Storage and AI Analytics

The cloud platform stores historical and live sensor data and performs deep learning–based analytics for accurate structural assessment. Models such as 1D CNN, LSTM, SVM, Random Forest, or hybrid deep learning models detect abnormalities in vibration/strain patterns, classify damage severity, estimate performance degradation, and predict future failure trends through time-series forecasting.

6. Decision Intelligence and Alert Generation

The results from trained AI models are converted into actionable insights. When the system identifies early signs of structural damage or unusual vibration characteristics, automated alerts are sent to engineers and maintenance authorities through email/SMS/web dashboard. Predictive maintenance reports provide damage localization and severity scoring.

7. Visualization Dashboard and Reporting

- A centralized interactive dashboard displays:
- Real-time sensor values
- Damage severity index and risk score
- Structural trend analysis via graphs and heat maps
- Historical conditions and maintenance history
- Reports and decision support analytics allow quick interpretation for maintenance scheduling and safety evaluation.

8. System Optimization and Feedback Loop

Continuous performance monitoring is used to refine sensor thresholds, retrain AI models with newly collected data, and dynamically adjust data sampling rates based on environmental and structural behavior. This iterative feedback loop ensures system accuracy, longevity, and adaptability in real-world deployment.

IV. RESEARCH GAP

Although significant advancements have been made in Structural Health Monitoring (SHM) through IoT-based sensing and AI-driven analytics, several limitations continue to hinder practical large-scale deployment in real infrastructure. Many existing systems rely on high-cost sensor hardware and power-intensive communication modules, making long-term usage economically unfeasible. Furthermore, most AI-enabled SHM frameworks depend heavily on cloud computation and continuous raw data transmission, which increases latency, bandwidth consumption, and energy usage—significantly reducing sensor battery life. Several studies also focus on detecting damage only after it becomes severe rather than emphasizing early prediction of deterioration trends using real-time temporal data. In addition, previous works are often tailored to specific structures and lack adaptability and scalability across different infrastructure types. Security and reliability concerns related to wireless data transfer are also rarely addressed. Thus, there is a clear research gap in developing a low-cost, low-power, and scalable SHM solution that seamlessly integrates edge processing, energy-efficient IoT sensing, and AI-based anomaly prediction to ensure continuous monitoring, real-time fault detection, and long-term structural safety.

V. DISCUSSION

The integration of AI with low-power IoT-based sensing provides a promising shift from manual and periodic inspections to real-time intelligent infrastructure monitoring. The proposed system shows that structural vibration, strain, temperature, and displacement can be continuously monitored using low-power sensor nodes without increasing operational cost or energy consumption. Unlike traditional SHM systems that depend on high-end hardware or power-intensive communication, this approach uses edge-level processing to extract meaningful features locally and transmits only essential information to the cloud. This greatly reduces bandwidth usage and extends battery lifetime, which has been one of the primary barriers to scalable SHM deployment.

AI-based learning models further strengthen the framework by converting multi-sensor data patterns into actionable knowledge. By leveraging damage classification, anomaly detection, and failure prediction, the system supports proactive maintenance instead of late-stage structural repair. A user-friendly dashboard ensures that maintenance authorities receive early alerts, visual insights, and historical structural trends to support quick decision-making. Although the system still requires considerations such as sensor calibration, secure communications, and ensuring reliability under environmental disturbances, its advantages strongly outweigh the challenges and position it as an efficient solution for smart and sustainable infrastructure management.

- Ensures continuous 24/7 structural visibility, overcoming limitations of periodic manual inspections.
- Low-power IoT sensor design significantly reduces overall deployment and maintenance cost.
- Edge computing minimizes data transmission and increases battery life for long-term monitoring.
- AI-based models improve early damage detection accuracy and minimize false alarms.
- System transitions maintenance from reactive to predictive, enhancing safety and reliability.
- Adaptable to multiple infrastructure types such as bridges, dams, high-rise buildings, and industrial structures.
- Dashboard delivers real-time alerts, risk scoring, and historical trend analysis for decision support.
- Reduces structural failure risk, downtime, and emergency repair costs, improving public safety and sustainability.

System Workflow:

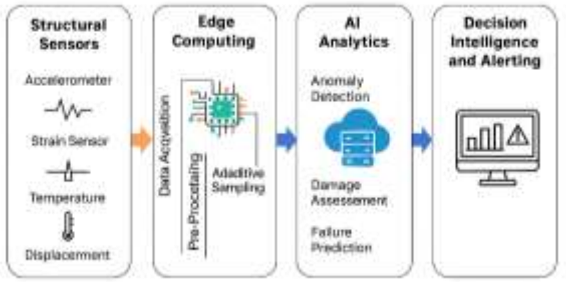

Fig 5.1 System Architecture

The system architecture illustrates the complete workflow of the AI-enabled Structural Health Monitoring (SHM) framework using low-power IoT sensors. Structural sensing begins at the left side of the diagram, where different types of sensors—such as accelerometers, strain gauges, temperature sensors, and displacement sensors—continuously measure key physical parameters from the infrastructure. The collected signals are transmitted to the Edge Computing layer, where the onboard microcontroller performs pre-processing operations such as noise filtering, feature extraction, and adaptive sampling to reduce data transmission burden and conserve battery energy. The filtered and compressed data is then sent to the AI Analytics layer, where machine learning and deep learning models perform anomaly detection, damage assessment, and failure prediction based on historical and real-time information. The output of these algorithms is forwarded to the Decision Intelligence and Alerting layer, which converts analytical results into actionable insights through dashboards, warning notifications, and risk scoring. This enables engineers and maintenance authorities to make informed decisions proactively, improving public safety and reducing the risk of sudden structural failure. Overall, the system architecture highlights the smooth integration of IoT sensing, edge processing, and AI-driven analytics for scalable, real-time, and cost-efficient structural monitoring.

VI.CONCLUSION

The proposed AI-enabled Structural Health Monitoring system using low-power, cost-efficient IoT sensors demonstrates a highly effective solution for continuous and intelligent infrastructure safety management. By integrating real-time sensing with edge-level preprocessing and advanced AI analytics, the framework overcomes the major limitations of traditional SHM approaches, such as high deployment cost, manual inspection dependency, and delayed fault identification. The system ensures uninterrupted monitoring of critical parameters—including vibration, strain, temperature, and displacement—and provides early warnings of structural abnormalities through predictive modeling rather than relying on reactive maintenance. The low-power communication techniques and optimized data transmission significantly extend sensor lifetime, making the solution scalable, energy-efficient, and suitable for long-term field deployment across various types of structures. Overall, the research confirms that the combination of IoT and AI can greatly enhance structural reliability, minimize maintenance costs, prevent catastrophic failures, and support the development of resilient and smart infrastructure environments.

REFERENCES

[1] Harms, T., Lynch, J. P., & Sheng, L. (2016). “SmartBrick: A Low-Power Wireless Sensor Platform for Long-Term Structural Health Monitoring.” Journal of Civil Structural Health Monitoring.

[2] Oruklu, E., Singhal, G., & Asyhari, A. T. (2017). “Sustainable Wireless Sensor Networks for Structural Health Applications: A Comprehensive Review.” IEEE Sensors Journal.

[3] Abdulkarem, M., Samsudin, K., Rokhani, F. Z., & A’zam, N. (2020). “Wireless Sensor Networks for Structural Health Monitoring: A Review.” Sensors.

[4] Lin, Y., Xu, G., & Wang, Y. (2018). "IoT-Enabled Bridge Condition Monitoring Using Multi-Sensor Data." Automation in Construction.

[5] Kim, S. & Pakzad, S. (2019). "Cloud-Based Structural Monitoring of Smart Buildings Using IoT Sensing Nodes." Smart Materials and Structures.

[6] Gopal, R., & Krishnan, S. (2021). "IoT-Based Road Bridge Vibration Monitoring and Warning System." Measurement and Control.

[7] Suresh, P. & Agarwal, A. (2020). "IoT Applications in Structural Condition Assessment: Challenges and Opportunities." International Journal of Civil Infrastructure.

[8] Sharma, A., Singh, R., & Rai, M. (2021). "1D-CNN-Based Vibration Feature Learning for Structural Damage Detection." Engineering Structures.

[9] Liang, R., Zhang, Y., & Chen, X. (2022). "Structural Damage Identification Using CNN with FEA-Generated Data Augmentation." Computers and Structures.

[10] Plevris, V. (2020). "Artificial Intelligence Applications in Structural Health Monitoring for Smart Infrastructure." Applied Sciences.

[11] Kumar, J. & Plevris, V. (2023). "AI-Driven SHM: Recent Innovations and Future Directions." Structural Control and Health Monitoring.

[12] Wang, D., Zhang, H., & Li, Y. (2022). "Deep Learning Approaches for Structural Condition Monitoring: A Systematic Review." Measurement.

[13] Buckley, B., Xiao, Y., & Schurr, D. (2021). "Edge-Enabled SHM Using Low-Power Microcontroller Platforms for Battery-Efficient Monitoring." IEEE Internet of Things Journal.

[14] Patel, M. & Thakor, A. (2022). "Comprehensive Review of AI-Based SHM Systems." Journal of Intelligent & Fuzzy Systems.

[15] Gao, F., & Lee, J. (2023). "AI-Powered IoT Platform for Real-Time Structural Health Analysis and Decision Support." Sensors and Actuators A: Physical.