

A Literature Review on Low-Cost Structural Health Monitoring Using IoT Sensors and Python-Based Analytics

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Abstract - Structural Health Monitoring (SHM) plays a vital role in the maintenance and safety of civil infrastructure. Traditional SHM systems, although accurate, are expensive and often impractical for widespread deployment. This paper presents a comprehensive literature review of low-cost SHM systems leveraging Internet of Things (IoT) sensors and Python-based data analytics. The review covers foundational SHM principles, recent developments in sensor technologies, data acquisition platforms such as ESP32, and the role of Python in data visualization, real-time monitoring, and machine learning. We also discuss gaps in the current research and identify future directions for scalable, affordable SHM solutions.

Key Words: Structural Health Monitoring (SHM), Internet of Things (IoT), Low-cost sensors, Wireless sensor networks, Python analytics.

1.INTRODUCTION

The rapid deterioration of civil infrastructure such as bridges, buildings, and transport systems has raised significant concerns worldwide. Structural Health Monitoring (SHM) has emerged as a critical solution to assess, detect, and predict structural damage in real-time. Traditionally, SHM systems relied on expensive hardware, complex installation procedures, and centralized data processing, making them less accessible for widespread or cost-sensitive applications. In the Indian context, the urgency for improved SHM solutions is amplified by alarming statistics: as of 2025, only 451 out of 16,519 bridges in Maharashtra had been inspected, with 136 requiring urgent repair and five declared unsafe. Despite this, less than 1% of the Ministry of Road Transport & Highways' budget is allocated to maintenance [1]. Moreover, out of 1,873 major infrastructure projects tracked by MoSPI, over 779 projects faced delays and 449 projects reported significant cost overruns. These trends underscore the pressing need for scalable, cost-effective, and adaptable SHM solutions. Recent advances in IoT (Internet of Things) technologies and open-source data analytics tools like Python offer an unprecedented

opportunity to democratize SHM systems. IoT-enabled wireless sensors allow for distributed, low-cost monitoring without the need for intrusive wiring, while Python-based platforms enable real-time data processing, anomaly detection, and predictive analysis through machine learning and signal processing algorithms. This research focuses on designing and implementing a low-cost SHM framework that leverages commercially available sensors, microcontrollers, and Python-based analytical tools. The goal is to develop a system capable of detecting early-stage structural deterioration by monitoring changes in vibration patterns, modal responses, and environmental parameters, all with minimal resource requirements [2].

Structural Health Monitoring (SHM) has become an important tool for ensuring the safety and durability of bridges, buildings, and other civil structures. Early studies by [3] introduced SHM as a systematic way to detect structural damage, while [4] highlighted the role of wireless sensor networks in improving monitoring efficiency. Over time, research expanded to include advanced approaches such as digital twins [5] and displacement and strain measurement techniques [6], showing how new technologies can strengthen SHM practices. Recent works have also focused on affordable, software-driven, and IoT-based solutions. [7] and [8] showed how Python-based systems and accelerometer data could be applied for real-time monitoring. [9] and [10] further demonstrated reliable IoT and wireless vibration monitoring systems. However, high-end SHM setups remain costly, especially for developing regions. This motivates the present research to design a low-cost SHM system using IoT sensors and Python-based analytics, aiming to deliver accurate, scalable, and practical solutions for real-world infrastructure. By emphasizing affordability, modularity, and adaptability, this approach aims to make SHM accessible for local government agencies, rural infrastructure projects, and developing nations. The study further explores how such systems can be integrated into existing maintenance regimes to enable proactive infrastructure management

and reduce the risks associated with delayed repairs and catastrophic failures.

2. Background and Motivation

Structural Health Monitoring (SHM) has been an important research area for ensuring the safety of bridges, buildings, and other civil structures. Early works, such as [3], introduced SHM as a key method for detecting structural damage, while [4] reviewed wireless sensor networks as effective tools for monitoring. Recent studies have explored advanced approaches, including digital twin models [5] and displacement measurement techniques [6], showing the growing use of modern technologies in SHM. Researchers like [7] have successfully used Python-based systems and accelerometer data for real-time monitoring, proving that low-cost solutions can be reliable. Similarly, [9] and [10] demonstrated IoT-based SHM systems and wireless vibration monitoring, confirming the potential of affordable and scalable methods. These studies highlight the motivation for developing SHM systems that are not only accurate but also cost-effective, making them practical for widespread use, especially in developing regions.

3. Key Components of Low-Cost SHM Systems

3.1 Sensors

Sensors like accelerometers (i.e ADXL345), strain gauge paired with HX711 amplifiers, and temperature sensors are vital for capturing structural behavior. Low-cost alternatives such as MPU6050 and ADXL345 provide reliable data suitable for basic monitoring tasks.

3.2 Microcontrollers and Communication

Microcontrollers such as Arduino and ESP32 are commonly used to interface with sensors. These devices support wireless communication protocols like Wi-Fi and Bluetooth, allowing remote data transmission without expensive infrastructure.

3.3 Software and Data Analytics

Python plays a central role in data processing and visualization. Libraries like NumPy, Pandas, and Matplotlib help in data visualization, storage, cleaning, analysis, and plotting. Machine learning models in Python can also be applied for anomaly detection and predictive maintenance.

4. Case Studies and Related Work

Several research works have successfully demonstrated the potential of low-cost Structural Health Monitoring (SHM) systems. [3] introduced SHM as a vital tool for infrastructure safety, while [4] reviewed the use of wireless sensors, proving their effectiveness in structural monitoring. [7] applied Python-based SHM on reinforced concrete frames and achieved promising results in detecting structural responses. [8] used accelerometer

data for bridge monitoring and validated the system's efficiency. Similarly, [9] developed a real-time SHM system using IoT, showing accurate and reliable performance. More recently, [10] demonstrated successful vibration monitoring in civil structures using low-cost wireless systems. Together, these studies highlight that affordable SHM systems can deliver accurate results and are feasible for real-world use.

5. Challenges and Research Gaps

Despite progress, there are challenges like data accuracy, sensor calibration, power management, and cyber security. There is also a need for standardized testing and long-term validation. More research is required to improve reliability and integration with smart city platforms.

6. Future Directions

Future research in Structural Health Monitoring (SHM) should focus on making systems more energy-efficient, reliable, and adaptable. Using AI, edge computing, and hybrid sensor networks can improve data processing and reduce dependence on high-bandwidth communication. Standardized open-source frameworks and integration with tools like BIM can support wider adoption. Adaptive systems that adjust to environmental and structural conditions will be useful for long-term use, especially in remote or resource-limited areas.

7. CONCLUSIONS

Low-cost SHM systems using IoT sensors and Python-based analytics show great promise. They offer scalable and accessible solutions for infrastructure safety. Continued innovation and collaboration across disciplines will help bridge the gap between research and real-world deployment.

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