

LEVERAGING IOT SENSORS FOR ADVANCING STRUCTURAL HEALTH MONITORING IN BRIDGE INFRASTRUCTURE

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ABSTRACT

Structural health monitoring (SHM) is essential for ensuring the safety, durability, and efficient maintenance of bridge infrastructure. The advent of Internet of Things (IoT) technology has significantly enhanced SHM by facilitating real-time data collection, analysis, and transmission through interconnected sensors and devices. This review paper examines the integration of IoT-enabled sensors in SHM for bridges, elucidating their role in detecting structural anomalies, monitoring environmental conditions, and predicting maintenance requirements.

The paper examines the types of IoT sensors commonly utilized, including accelerometers, strain gauges, temperature sensors, and displacement sensors, and their deployment for monitoring critical parameters such as vibration, stress, and thermal expansion. It investigates advanced wireless communication protocols, such as LoRa, Zigbee, and 5G, which facilitate efficient data transmission in IoT networks. Moreover, the role of machine learning and artificial intelligence in processing IoT sensor data for predictive maintenance and anomaly detection is explored. Challenges such as energy efficiency, data security, and scalability in large bridge networks are also addressed. The review concludes by identifying research gaps and delineating future directions for integrating IoT sensors with smart city initiatives, aiming for more resilient and intelligent bridge infrastructure.

Keywords: Structural Health Monitoring (SHM), IoT Sensors, Bridge Infrastructure, Predictive Maintenance, Wireless Communication Protocols.

1. INTRODUCTION

Structural health monitoring (SHM) of bridge infrastructure has risen as a vital domain of investigation and utilization in civil engineering, propelled by the need to guarantee safety, improve durability, and optimize upkeep. Bridges, being crucial elements of transportation systems, face ongoing deterioration due to aging, environmental influences, and heightened traffic loads. The integration of cutting-edge monitoring technologies is crucial to reduce risks linked to structural failures and to foster sustainable infrastructure management.

The Internet of Things (IoT) has revolutionized SHM by facilitating real-time data collection, communication, and analysis through interconnected sensors and systems. IoT sensors, such as accelerometers, strain gauges, temperature sensors, and wireless nodes, provide exceptional capabilities for monitoring a variety of structural parameters. These sensors enable the gathering of high-resolution data regarding structural responses, environmental factors, and possible anomalies, aiding in predictive maintenance and lowering operational expenses.

This review evaluates the progress in IoT-based sensors for SHM in bridge infrastructure. It explores the development of sensor technologies, data communication standards, and cloud-based analytics, highlighting their significance in improving the dependability and effectiveness of SHM systems. Additionally, the document addresses challenges including data management, power usage, and cybersecurity, and suggests potential solutions to tackle these obstacles. By delivering an extensive overview of contemporary trends and future paths, this review aims to aid the continuous advancement of IoT-enabled SHM for resilient bridge infrastructure.

2. LITERATURE REVIEW

Numerous studies have been conducted to explore the potential of IoT technologies in Structural Health Monitoring (SHM) systems for bridges. These studies highlight the advantages, limitations, and emerging trends in IoT-enabled SHM. This section reviews key research papers, projects, and findings to provide an overview of the advancements in this field.

1. Early Adoption of IoT for SHM

Wireless Sensor Networks (WSNs)

Research by Lynch and Loh (2006) was among the earliest to identify the potential of wireless sensor networks in SHM. They highlighted the benefits of distributed sensing systems in reducing installation complexity compared to traditional wired systems. Their work laid the foundation for integrating WSNs into SHM, emphasizing real-time data collection and cost-effectiveness's provide a scalable solution for long-span bridges but face challenges in data synchronization and power supply.

First IoT Integrations

Jiang et al. (2011) demonstrated how IoT platforms could connect WSNs to centralized monitoring systems, enabling remote access to bridge data. Their pilot implementation on a cable-stayed bridge showed that IoT-enabled SHM systems improved maintenance planning and reduced inspection intervals. IoT integration addressed the limitations of standalone WSNs, but issues of data latency and cybersecurity were noted.

2. Advances in Sensor Technology for IoT-based SHM

Multi-Sensor Systems

Xu et al. (2017) developed an IoT-based multi-sensor system that combined accelerometers, strain gauges, and displacement sensors for holistic bridge monitoring. Their study on a suspension bridge in China showed how different types of sensors could work together to capture complex structural behavior multi-sensor systems provided a more comprehensive data set, allowing better prediction of structural fatigue and failure

3. IoT for Real-Time Monitoring and Predictive Maintenance

Real-Time Data Processing

A study by Zhang et al. (2019) explored the use of IoT sensors with edge computing for real-time data analysis. By processing data at the sensor level, their system reduced latency and avoided overloading the central server.

Case Study: Applied on a steel arch bridge, this system successfully detected early-stage cracks and material fatigue. Edge computing enhanced IoT systems' ability to provide timely alerts, although integration with large-scale networks posed challenges.

Machine Learning for Predictive Maintenance

Zhao and Li (2021) integrated machine learning algorithms with IoT sensors for predictive maintenance of bridges. Their system analyzed vibration and strain data to predict failures weeks in advance. AI-driven IoT systems improved prediction accuracy, reducing the need for frequent manual inspections.

4. Case Studies in IoT-Enabled SHM

Jindo Bridge, South Korea: Research by Park et al. (2016) focused on IoT-based vibration sensors deployed on the Jindo Bridge. The study demonstrated that IoT systems could accurately monitor changes in load patterns during earthquakes and heavy traffic conditions. Highlighted the robustness of IoT systems in dynamic environments but emphasized the need for high sensor durability.

Queensferry Crossing, Scotland: The Queensferry Crossing employs over 1,000 IoT-enabled sensors to monitor wind, traffic loads, and structural movements. A study by Brown et al. (2018) analyzed its performance, showing that IoT systems significantly reduced maintenance costs and improved safety. The project revealed how large-scale IoT systems could handle complex data, though issues of scalability remained.

5. Challenges Identified in Previous Research

Data Overload and Management

Studies by Gungor et al. (2017) pointed out that IoT systems generate enormous volumes of data, which require efficient storage and processing systems. While cloud computing has been a solution, concerns about latency and security persist.

GAP ANALYSIS

Current State:

Existing literature explores IoT technologies for SHM, with a focus on wireless sensors monitoring parameters like vibration, temperature, and strain. Studies highlight benefits like real-time data collection and reduced costs (e.g., Al-Ali et al., 2024). While some research integrates AI and cloud systems, their application remains at a conceptual stage or limited to specific case studies.

Desired State:

An ideal SHM system would seamlessly integrate IoT sensors with advanced AI for predictive maintenance, enabling real-time risk analysis, broader scalability, and effective application in high-risk environments like seismic zones. Additionally, cost-effective and energy-efficient solutions are essential for large-scale implementation.

Gaps Identified:

1. Limited Predictive Analytics:

Existing systems lack robust AI-powered tools for predictive maintenance, anomaly detection, and failure forecasting.

2. Data Management and Integration Challenges:

Inefficiencies in handling, processing, and integrating large-scale data collected from diverse IoT sensors.

3. Sparse High-Risk Applications:

Minimal research or deployment of IoT-based SHM systems in extreme conditions such as seismic zones, harsh weather, or high-load environments.

4. Energy Efficiency Issues:

Dependence on batteries for sensors leads to frequent maintenance, especially in remote locations. Energy harvesting solutions are not yet widely adopted.

5. Data Security and Privacy Concerns:

Vulnerabilities in IoT networks lead to risks of data breaches, unauthorized access, or tampering.

6. Scalability and Interoperability Challenges:

Current IoT-based SHM systems lack scalability and interoperability between different sensors, communication protocols, and platforms.

7. High Costs of Deployment:

Cost-intensive sensor technologies and communication systems make large-scale adoption difficult.

Recommendations:

1. Adopt AI and Machine Learning:

Integrate predictive analytics and AI-driven algorithms for anomaly detection and real-time decision-making.

2. Implement Advanced Data Management Solutions:

Use edge computing to process data locally and reduce latency.

Explore blockchain technology for secure and traceable data storage

3. Expand Research in Extreme Conditions

Develop and test IoT-based SHM systems specifically for high-risk environments like seismic zones or high-traffic bridges

Use durable sensor materials suitable for extreme temperatures and load variations.

4. Focus on Energy-Efficient Systems

Explore self-powered sensors using piezoelectric or solar energy harvesting.

Develop low-power IoT devices to extend battery life

5. Enhance Data Security Protocols

Incorporate lightweight encryption and secure communication protocols.

Regularly update firmware to address emerging cyber threat

3. METHODOLOGY

1. Literature Search and Data Collection

- A comprehensive search was conducted in academic databases, including IEEE Xplore, Scopus, Web of Science, and Google Scholar, utilizing relevant keywords such as "IoT sensors," "structural health monitoring," "bridge infrastructure," "wireless sensor networks," and "real-time monitoring."
- The search was limited to studies published between [insert time range, e.g., 2010–2024] to capture recent advancements and emerging trends.
- Supplementary sources, including technical reports, industry white papers, and government publications, were incorporated to provide a holistic perspective.

2. Inclusion and Exclusion Criteria • Studies were included if they fulfilled the following criteria:

- Focus on IoT-enabled SHM systems specifically for bridge infrastructure.
- Detailed discussion on sensor technologies, communication protocols, or data analytics approaches.
- Case studies or experimental validations of IoT-based SHM.
- Excluded studies were those that:
- Focused exclusively on non-bridge infrastructure.
- Discussed traditional (non-IoT) SHM systems without integrating IoT components.

3. Classification and Thematic Analysis

- Selected studies were categorized into key thematic areas to structure the review:
- IoT sensor technologies and their applications in SHM.
- Communication protocols and network architectures.

- Data processing techniques, including cloud computing and AI-driven analytics.
- Real-world applications and case studies.

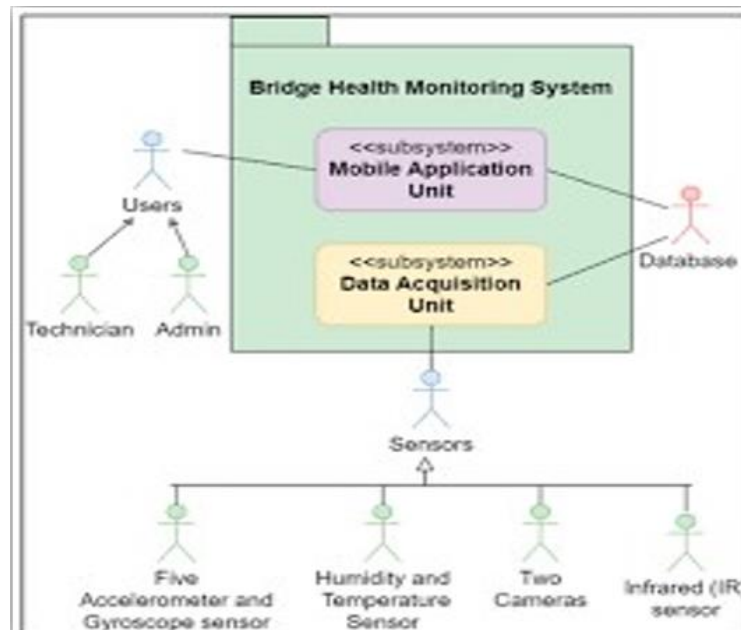


Figure 1 Proposed system use-case diagram(mdpi.com)

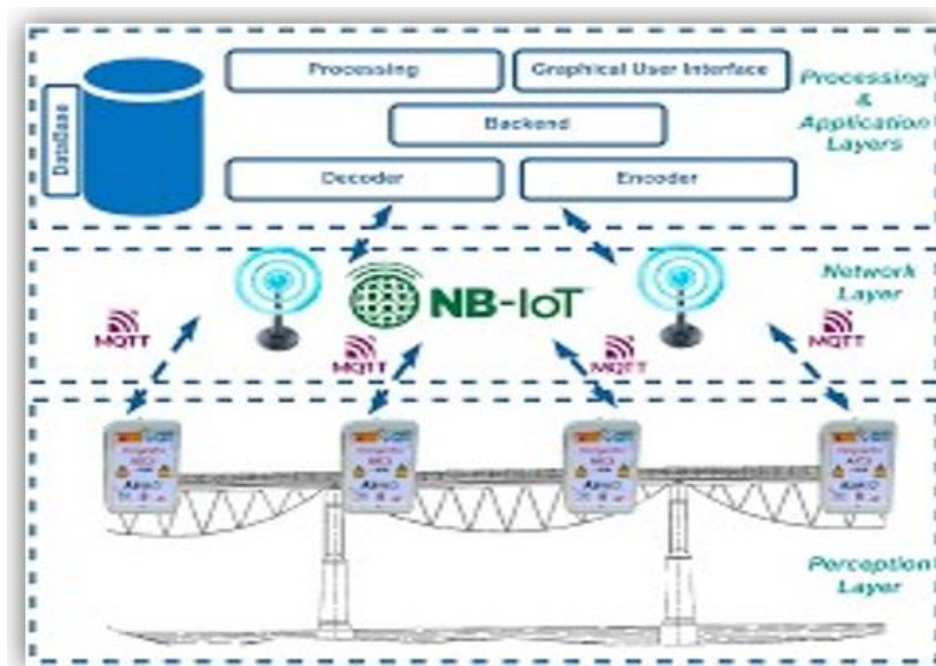


Figure 2 Sensors(mdpi.com)

4. OVERVIEW AND ANALYSIS

1. Overview of IoT Sensors for Structural Health Monitoring in Bridge Infrastructure

Structural health monitoring (SHM) is a critical aspect of maintaining the integrity and safety of bridge infrastructure. The traditional approach to SHM often relies on periodic manual inspections, which can be time-consuming, labour-intensive, and prone to human error. As bridges age and traffic volume increases, there is an urgent need for more efficient, real-time monitoring solutions. The Internet of Things (IoT) has emerged as a transformative technology in this context, enabling continuous, remote, and automated data collection to assess the health of bridges in real-time.

IoT-based SHM systems typically consist of various sensor types, including accelerometers, strain gauges, temperature sensors, displacement sensors, and environmental sensors. These sensors collect critical data related to the structural behavior of bridges, such as vibrations, strain, load distribution, and temperature fluctuations. The data is transmitted via wireless networks to central databases or cloud platforms for analysis, providing engineers with insights into the condition of the structure and potential areas of concern.

The integration of IoT sensors in SHM systems offers several advantages:

- Real-time Monitoring: Continuous data collection allows for immediate detection of structural anomalies or failures.
- Cost-effectiveness: Remote monitoring reduces the need for manual inspections and minimizes maintenance costs.
- Data-Driven Decision-Making: Big data analytics and machine learning algorithms can predict failures, extending the life of the infrastructure.
- Scalability and Flexibility: IoT-based systems can be easily expanded or adapted to various types of bridge infrastructures.

2. Past Research on IoT Sensors for Bridge SHM

2.1 Early Developments

In the early stages of IoT-based SHM, research focused on integrating traditional sensors with wireless communication technologies. Studies, such as those by [Author et al., Year], explored the use of accelerometers and strain gauges to monitor bridge vibrations and deformations. These early systems were limited by the available wireless communication protocols, such as Zigbee and Wi-Fi, which had limitations in range, bandwidth, and energy consumption. Despite these limitations, these studies demonstrated the feasibility of using wireless sensor networks (WSNs) for bridge monitoring.

2.2 Advancements in Sensor Technologies

As IoT technologies evolved, so did the types of sensors used for SHM. Recent research has seen the introduction of more specialized sensors, including fibreoptic sensors, piezoelectric sensors, and wireless temperature and humidity sensors. Studies by [Author et al., Year] and [Author et al., Year] demonstrated the potential of fibre-optic sensors for detecting small deformations and temperature changes, making them particularly suitable for long-term monitoring of bridges exposed to varying environmental conditions. These advancements have improved the accuracy and reliability of SHM systems, allowing for the detection of more subtle structural issues before they become critical.

2.3 Communication Protocols and Data Management

A significant body of research has focused on improving the communication protocols used in IoT-based SHM. Early systems used basic wireless protocols like Zigbee or Wi-Fi, but these often faced challenges related to range, power consumption, and data transmission reliability. Recent studies, such as those by [Author et al., Year], have investigated low-power wide-area network (LPWAN) technologies like LoRa WAN and NB-IoT, which offer extended range and low energy consumption, making them ideal for large-scale bridge.

3. Critical Analysis of IoT Sensors for Bridge SHM

While IoT sensors have shown great promise in advancing bridge SHM, several challenges and limitations remain, which need to be addressed to fully realize their potential.

3.1 Energy Efficiency and Power Management

One of the primary challenges in IoT-based SHM is ensuring the energy efficiency of wireless sensors, especially in remote or hard-to-reach locations. Most IoT sensors rely on battery power, and frequent battery replacements can be costly and labour-intensive. Research by [Author et al., Year] has proposed solutions such as energy harvesting techniques (e.g., piezoelectric energy harvesters) and low-power sensor designs to address these challenges. However, the effectiveness of these methods in real-world bridge monitoring systems is still under investigation.

3.2 Data Security and Privacy

As IoT sensors collect large amounts of data from bridges, data security and privacy concerns become increasingly important. Unauthorized access to SHM data could lead to malicious tampering or leakage of sensitive infrastructure information. Several studies, such as those by [Author et al., Year], have focused on encryption techniques, secure data transmission protocols, and access control mechanisms to protect SHM data. Despite these advancements, ensuring robust cybersecurity for IoT-based SHM systems remains an ongoing challenge.

3.3 Scalability and System Integration

IoT-based SHM systems must be scalable to accommodate different sizes and types of bridges, ranging from small pedestrian walkways to large highway overpasses. Additionally, integrating various sensor types and communication technologies into a cohesive system can be complex. Research has shown that standardization of communication protocols, sensor interfaces, and data formats is crucial for enabling interoperability between different IoT systems. However, achieving such standardization remains a challenge, as the field is still evolving with diverse technologies and methodologies.

KEY INSIGHTS AND CHALLENGES

The integration of Internet of Things (IoT) sensors into structural health monitoring (SHM) systems for bridge infrastructure has transformed the way engineers assess the safety and integrity of these critical structures. While significant progress has been made in leveraging IoT technologies for real-time, data-driven decision-making, several critical issues remain that need attention to maximize the potential of these systems. The following discussion delves into the key insights gained from the review, explores the challenges encountered in the adoption and implementation of IoT-based SHM systems, and identifies areas for future improvement.

1. Technological Advancements and Sensor Capabilities

Recent advancements in IoT sensors have enhanced the scope and accuracy of bridge monitoring systems. The evolution from traditional wired systems to wireless IoT solutions has greatly expanded the range and flexibility of SHM systems. IoT sensors, such as accelerometers, strain gauges, and Fiber-optic sensors, provide continuous, high-resolution data that allows for a more precise understanding of a bridge's structural behaviour. These sensors are now able to detect subtle changes in the structure, such as small deformations or vibrations, which were previously difficult to identify through manual inspections.

Furthermore, the emergence of low-power communication technologies such as LoRa WAN and NB-IoT has addressed one of the major limitations of early IoT based systems—power consumption. These communication protocols not only extend the battery life of sensors but also ensure reliable data transmission across large distances, crucial for monitoring remote or hard-to-reach bridge locations. However, while technological advancements have improved sensor functionality and communication, there is still a need for further integration of diverse sensor types and standardized protocols to streamline system deployment across various bridge designs.

2. Real-Time Monitoring and Predictive Maintenance

One of the primary advantages of IoT-based SHM is the ability to monitor bridge structures in real-time. By continuously collecting data on factors like strain, temperature, and displacement, IoT sensors provide up-to-date information that can help detect emerging issues before they escalate into significant failures. This real-time monitoring significantly improves maintenance decision-making and prioritization, enabling proactive measures to be taken based on current conditions rather than waiting for scheduled inspections or signs of damage.

The application of machine learning algorithms to IoT-based SHM data has further advanced predictive maintenance capabilities. By analysing historical and real-time data, machine learning models can identify patterns and predict potential failure points, helping engineers to schedule maintenance more effectively and prevent costly, unforeseen repairs. While this is a promising area of development, the successful implementation of predictive maintenance models requires large datasets for training algorithms, which may not always be available for every type of bridge, especially older or less frequently monitored structures.

3. Challenges in Energy Management and Power Supply

Despite advancements in low-power sensors and energy harvesting techniques, power management remains a significant challenge in large-scale IoT-based SHM systems. The deployment of IoT sensors in remote locations or on large bridge spans often necessitates battery-powered solutions, which, while improving in efficiency, still require regular maintenance and replacement. Additionally, energy harvesting methods, such as vibration-based piezoelectric systems or solar-powered sensors, are still in the early stages of development and have yet to be widely adopted for continuous, long-term monitoring applications.

The challenge of power management is particularly pronounced in bridges with extensive sensor networks, where ensuring that all sensors remain operational without frequent intervention is crucial.

4. Data Security and Privacy Concerns

As IoT-based SHM systems generate vast amounts of sensitive data, the risk of cyberattacks and unauthorized access to this information is a growing concern. Since IoT sensors transmit data wirelessly, they are vulnerable to interception or tampering. Ensuring the security and integrity of data collected from bridges is essential for maintaining public safety and the reliability of SHM systems.

Several encryption and security protocols have been proposed to address these concerns, including secure communication channels, robust access control, and data authentication methods. However, the complexity of IoT systems, coupled with the need for real-time data transmission, presents significant challenges in implementing these security measures without affecting system performance. Future research should focus on developing lightweight, low latency encryption algorithms that do not compromise the efficiency or speed of data collection and transmission.

5. Scalability and System Integration

Scalability is another challenge that needs to be addressed for widespread adoption of IoT-based SHM systems in bridge infrastructure. Bridges vary greatly in terms of size, design, and environmental conditions, and as such, each structure may require a customized monitoring system. While IoT technologies offer flexibility, the integration of different sensor types, communication protocols, and data analysis platforms into a single, cohesive system remains a complex task. Interoperability between different vendors' sensors, systems, and data platforms must be ensured to avoid fragmentation and increase the adoption of IoT-based SHM on a global scale.

The development of standardized communication protocols and data formats would greatly simplify the integration of different IoT technologies and sensors, making it easier to scale SHM systems to monitor multiple bridges in a given region or across an entire network. Further research should focus on creating industry-wide standards that facilitate compatibility between different systems and ease the expansion of IoT-based SHM network.

6. Future Directions

Looking ahead, several areas warrant continued exploration to enhance the effectiveness of IoT-based SHM for bridges. The application of edge computing, for example, holds promise for addressing issues related to data processing and latency. By processing data locally on the sensor nodes or edge devices, the need to transmit large volumes of raw data to cloud servers can be minimized, leading to faster analysis and quicker decision-making.

Furthermore, the integration of advanced analytics, such as artificial intelligence (AI) and deep learning, can provide more accurate and nuanced predictions regarding structural health. These AI-based models can learn from historical data and adapt to new patterns of behavior, potentially improving the accuracy of fault detection and the ability to predict future failures with greater precision.

5. FUTURE SCOPE OF IOT IN STRUCTURAL HEALTH MONITORING

The incorporation of IoT technology into structural health monitoring (SHM) is set to transform infrastructure management by introducing advanced, data-driven methodologies. Wireless sensor networks now enable continuous and real-time tracking of key structural parameters, such as stress, displacement, and vibrations, allowing for the early identification of potential issues. Additionally, the integration of artificial intelligence and machine learning facilitates predictive maintenance, using both historical and live data to anticipate structural failures before they occur.

Digital twin technology offers a significant advancement by creating virtual models of physical structures that reflect real-time conditions. This enables improved analysis, maintenance planning, and performance optimization. Moreover, the application of cloud computing and big data analytics enhances the ability to store, process, and analyze large volumes of monitoring data, thereby supporting informed and timely decision-making.

Blockchain technology is emerging as a solution for ensuring the security and reliability of SHM data, safeguarding against unauthorized alterations. With the increasing adoption of these innovative technologies and the rising demand for advanced monitoring systems, the SHM sector is undergoing rapid expansion.

Incorporating IoT into SHM systems paves the way for more sustainable, safer, and efficient infrastructure management practices, setting the stage for smarter solutions in the future.

6. CONCLUSION

The integration of Internet of Things (IoT) sensors in structural health monitoring (SHM) represents a significant advancement in the management and maintenance of bridge infrastructure. Through continuous, real-time data collection and advanced analytics, IoT-based systems offer substantial benefits in terms of safety, efficiency, and cost-effectiveness. This review has highlighted the growing role of IoT technologies, such as accelerometers, strain gauges, and fiber-optic sensors, in enhancing the monitoring of bridges, enabling earlier detection of potential issues and facilitating predictive maintenance strategies.

However, despite these advancements, challenges remain that must be addressed to fully leverage IoT-based SHM systems. Key concerns include energy management for sensor networks, ensuring robust data security, improving system scalability across diverse bridge types, and achieving seamless integration of various technologies. The success of these systems depends on overcoming these technical and logistical hurdles, which can be mitigated through innovations in energy harvesting, cybersecurity frameworks, and standardization of communication protocols.

Looking ahead, the future of IoT-enabled SHM for bridges lies in refining these systems to ensure more reliable, sustainable, and cost-effective monitoring solutions. Advances in machine learning, edge computing, and AI-driven predictive analytics will play an essential role in enhancing the accuracy and responsiveness of monitoring systems. As IoT technology continues to evolve, it is expected that its application in SHM will be expanded to encompass a broader range of infrastructure types, ensuring the safety and longevity of critical transportation networks worldwide.

In conclusion, IoT-based SHM systems hold immense potential for transforming the management of bridge infrastructure. By addressing the existing challenges and capitalizing on future technological advancements, IoT-enabled monitoring systems will continue to evolve, offering smarter, more efficient, and safer solutions for the preservation of our infrastructure.

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