STM JOURNALS

Recent Trends in
Sensor Research & Technology

ISSN: 2393-8765
Volume 12, Issue 3, 2025
September–December
DOI (Journal): 10.37591/RTSRT

https://journals.stmjournals.com/rtsrt

Review RTSRT

IoT and Smart Sensors for Structural Health Monitoring: Trends, Challenges, and Future Directions

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Abstract

Structural health monitoring (SHM) plays a critical role in ensuring the safety, resilience, and sustainability of civil infrastructure systems. In recent years, the convergence of Internet of Things (IoT) technologies and smart sensor systems has revolutionized the field of SHM. This integration enables continuous, real-time monitoring, facilitates predictive maintenance, and reduces the costs associated with structural inspections. IoT-based SHM frameworks leverage wireless sensor networks, cloud computing platforms, and intelligent data analytics to detect structural anomalies at an early stage, allowing proactive intervention and improved lifecycle management of infrastructure. Meanwhile, advancements in smart sensor technology—such as MEMS-based accelerometers, fiber optic sensors, and self-powered devices—have enhanced the sensitivity, accuracy, and durability of SHM systems. However, several challenges remain, including issues of energy efficiency, data security, network scalability, and ensuring the robustness of sensors in extreme environments. The emergence of technologies such as edge computing, digital twin integration, and machine learning-driven diagnostics is addressing many of these concerns and shaping the next generation of SHM solutions. This review paper systematically examines current trends in IoT-enabled SHM, recent technological advancements, and the key challenges that must be overcome. In addition, it highlights future directions aimed at developing scalable, intelligent, and resilient SHM systems for widespread adoption. By synthesizing existing knowledge and emerging solutions, this study provides valuable insights for researchers, practitioners, and policymakers seeking to advance the field of IoT-based SHM.

Keywords: Structural health monitoring (SHM), civil infrastructure, Internet of Things (IoT), smart sensor systems

INTRODUCTION

Civil infrastructure systems, such as bridges, buildings, dams, and transportation networks, are critical assets that must be continuously monitored to ensure their safety, reliability, and performance. Structural health monitoring (SHM) is a multidisciplinary field that focuses on the use of sensor technologies and data-analysis techniques to assess the structural integrity of these systems over time [1]. Traditionally, SHM has relied on wired sensors and manual inspections, which can be costly, labor-intensive, and limited in terms of temporal and spatial resolution [2]. Recent advancements in the Internet of Things (IoT) and smart sensor technologies have transformed the SHM landscape [3]. IoT-based SHM systems enable wireless, distributed, and real-time monitoring of civil structures, thereby offering significant improvements in efficiency, scalability, and accuracy [4]. Smart sensors, such as micro-electro-mechanical system (MEMS) accelerometers, fiber optic sensors, piezoelectric sensors, and wireless sensor nodes, play a vital role in these systems by capturing various physical parameters, including strain, acceleration, temperature, displacement, and

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Received Date: May 28, 2025
Accepted Date: July 02, 2025
Published Date: December 15, 2025

Citation: Himank Sharma, Preeti, Garima Kanaujia. IoT and Smart Sensors for Structural Health Monitoring: Trends, Challenges, and Future Directions. Recent Trends in Sensor Research & Technology. 2025; 12(3): 1–6p.

vibration [5]. The integration of cloud computing and edge computing with IoT platforms allows efficient data storage, processing, and real-time analytics [6]. Advancements in machine learning and artificial intelligence (AI) have enabled sophisticated data interpretation techniques that can detect subtle changes in structural behavior and predict potential failures [7]. Despite these promising developments, several challenges must be addressed to enable widespread deployment of IoT-based SHM systems. Key issues include ensuring energy efficiency and enabling the long-term autonomous operation of wireless sensors [8], addressing cybersecurity and data privacy concerns [9], achieving interoperability among heterogeneous sensor networks [10], and developing robust algorithms capable of processing large-scale SHM data [11].

Recent research has explored innovative solutions, such as energy harvesting [12], edge-based processing architectures [13], and the use of digital twin models to enhance SHM capabilities [14]. The field is evolving rapidly with growing interest in developing cost-effective, scalable, and resilient monitoring systems for infrastructure management.

This review aims to provide a comprehensive overview of the current trends in IoT and smart sensors for SHM, analyze key technological advancements, and identify the main challenges and future directions in the field. The subsequent sections include an overview of the methodology, a literature review of recent case studies, a discussion of emerging solutions, and recommendations for future research.

METHODOLOGY

The methodology adopted for this review involves a systematic examination of recent literature related to IoT-based Structural Health Monitoring (SHM) and smart sensor technologies. The following steps were implemented to ensure a comprehensive and objective analysis.

1. *Literature selection:* An initial pool of scholarly articles was compiled from reputed databases, such as IEEE Xplore, Elsevier Scopus, SpringerLink, and MDPI. Peer-reviewed journal articles, conference proceedings, and authoritative reviews published between 2010 and 2022 were prioritized.
2. *Inclusion criteria:* Studies that focused on the integration of IoT technologies and smart sensors for SHM applications were included. Particular emphasis was placed on research that addressed the following:
   - Wireless sensor networks (WSNs)
   - MEMS-based accelerometers and fiber optic sensors
   - Energy harvesting for SHM
   - Cloud computing and edge computing architecture
   - Artificial intelligence (AI) and machine learning (ML) techniques for SHM data analysis
   - Digital twin-based SHM frameworks
3. *Data extraction:* Relevant data points were extracted from the selected studies, including:
   - Sensor types used
   - Communication protocols
   - Data acquisition and processing methods
   - Case studies and real-world deployments
   - Identified challenges and limitations
   - Proposed future directions
4. *Synthesis:* The extracted data were synthesized to highlight recent trends, categorize existing solutions, and identify gaps in current research.
5. *Tabular presentation:* To aid comparative analysis, key findings from the selected studies are summarized in a tabular format in the following section.

LITERATURE REVIEW

As shown in Table 1, recent research efforts have explored various IoT and smart sensor technologies, cloud-based platforms, and energy-efficient systems for real-time structural health monitoring (SHM) across different infrastructure types.

Table 1. Systematic review on emerging trends and critical insights regarding the integration of IOT and smart sensors in SHM.

Study/reference	Focus/contribution	Sensor type	IoT integration	Key insights
[1]	MEMS accelerometers for SHM of cable-stayed bridge	MEMS accelerometers	Wireless data collection	Demonstrated prototype validation on a real bridge
[2]	Survey of energy sources for SHM	Various	IoT + energy harvesting	Reviewed techniques for long-term sensor autonomy
[3]	Edge computing overview	N/A	Edge computing for SHM	Highlighted the potential of edge architectures
[4]	Real-time SHM using IoT and cloud	Strain sensors, accelerometers	IoT + cloud	Real-time monitoring via a cloud-enabled system
[5]	Cloud-based digital twinning + DL	Multiple sensors	Cloud + AI	Used deep learning for structural assessment
[6]	Wireless acceleration sensing	Accelerometers	Wireless sensing	Validated Martlet wireless sensing system
[7]	High-temperature SHM sensors review	Multiple (high temperature)	IoT-enabled	Reviewed SHM sensor advancements for harsh conditions
[8]	SHM sensor network on highway bridge	Accelerometers, strain gauges	Wireless SHM network	Long-term highway bridge monitoring
[9]	RTOS-based wireless SHM system	Accelerometers	Wireless, RTOS	Real-time SHM demonstrated benefits
[10]	Wireless smart sensors for earthquake monitoring	Accelerometers	Wireless	Earthquake-specific SHM system
[11]	Next-gen wireless sensor validation	Accelerometers	IoT wireless	Validated high-fidelity DAQ platform
[12]	Real-time seismic monitoring	Accelerometers	Intelligent wireless	Developed the xShake system for seismic SHM
[13]	Time synchronization for wireless SHM	Accelerometers	Wireless time sync	High-precision sync method validated
[14]	SHM under impact loads	Accelerometers	Intelligent wireless	xImpact system for impact SHM
[15]	Vibration energy harvesting for bridges	Vibration energy harvesting nodes	Energy-harvesting IoT	Achieved energy-neutral sensor operation
[16]	Aircraft vibration monitoring network	Accelerometers	Low-power wide-area IoT	Multihop low-power network for aircraft SHM
[17]	Energy harvesting review	Various	IoT + energy harvesting	Summarized energy harvesting strategies
[18]	Modular SHM framework using clustering	Various	IoT SHM + clustering	Validated on an operational wind turbine
[19]	Wireless SHM of railroad bridges	Accelerometers	Wireless IoT	Autonomous wireless SHM for railroad
[20]	End-to-end wireless SHM system	Accelerometers	Full wireless SHM	Autonomous bridge monitoring solution
[21]	Damage detection using wireless smart sensors	Accelerometers	Wireless	Decentralized receptance-based detection
[22]	Cloud-based bridge monitoring repository	Multiple sensors	Cloud IoT	Cloud-integrated SHM data repository

RESULTS AND DISCUSSION

A systematic review of the selected literature highlights several emerging trends and critical insights regarding the integration of IoT and smart sensors in SHM.

Advancements in Sensor Technologies

Modern SHM systems are increasingly utilizing MEMS-based accelerometers [1, 6, 9] and fiber-optic sensors, which offer advantages in terms of size, weight, and power consumption. Specialized sensors for high-temperature environments [7] and energy-harvesting-enabled sensors [15, 17] are enabling new applications in harsh operational settings.

Wireless Sensor Networks and Communication Protocols

Wireless sensor networks (WSNs) form the backbone of IoT-enabled SHM systems [4, 8, 9]. Advances in low-power communication protocols such as LPWAN, ZigBee, and Wi-Fi have facilitated the deployment of scalable and cost-effective SHM networks [16]. Synchronization challenges in WSNs were addressed using innovative time synchronization methods [13].

Cloud and Edge Computing

The combination of cloud computing [4, 5, 22] and emerging edge computing paradigms [3] allows distributed data processing and real-time decision-making. Cloud-based platforms enable centralized data storage and advanced analytics, whereas edge computing reduces latency and bandwidth requirements by processing data locally.

AI and Digital Twin Integration

Artificial intelligence (AI) and digital twins enhance the capabilities of SHM systems [5, 14]. Machine learning models are used for anomaly detection, damage prediction, and lifecycle assessment. Digital twins enable virtual simulations of structural behavior under various loading scenarios.

Energy Management

Energy efficiency remains a key concern in autonomous SHM systems [2, 12, 15, 17]. Energy harvesting technologies, including vibration and solar-based harvesting, are promising for achieving the long-term autonomous operation of sensor nodes.

Key Challenges

Despite significant progress, several challenges persist:

- Ensuring robust and durable sensor operation in harsh environments [7]
- Addressing cybersecurity and data privacy in IoT networks [9]
- Achieving interoperability among diverse sensor systems [10]
- Developing reliable and explainable AI models for SHM diagnostics [5]

Future Directions

Future research should focus on:

- Advanced energy-harvesting mechanisms for fully autonomous SHM
- Scalable edge-based architecture for real-time processing
- Integration of blockchain technologies for secure SHM data handling
- Comprehensive digital twin frameworks for predictive maintenance
- Standardization efforts to enable interoperability across IoT-SHM platforms.

CONCLUSION

The integration of Internet of Things (IoT) technologies with Structural Health Monitoring (SHM) systems has significantly advanced the way civil infrastructure is monitored, assessed, and managed. The evolution of smart sensors, wireless communication, cloud computing, and edge computing has provided real-time, scalable, and efficient monitoring solutions to improve infrastructure safety and reduce maintenance costs. IoT-based SHM systems leverage advanced sensor types, such as MEMS accelerometers, fiber optics, and energy-harvesting devices, which offer enhanced accuracy, durability, and operational autonomy in various environmental conditions.

One of the key advantages of these modern systems is their ability to detect structural anomalies early, which enables proactive intervention and mitigates the risks of catastrophic failures. Furthermore, machine learning and artificial intelligence play crucial roles in interpreting large volumes of sensor data, leading to the development of predictive maintenance models and more accurate diagnostics.

However, despite these advancements, several challenges must be addressed to ensure the widespread adoption of IoT-based SHM systems. These challenges include ensuring energy efficiency, overcoming cybersecurity and data privacy concerns, and achieving interoperability between different sensor networks and platforms. Additionally, the robustness and durability of sensors under extreme conditions and the development of reliable AI models for SHM diagnostics remain significant hurdles.

Future research should focus on refining energy-harvesting techniques to autonomously power sensor nodes, creating scalable edge-based architectures for faster data processing, and exploring blockchain integration for secure data handling. The establishment of standardized protocols and frameworks is also crucial for enabling seamless integration across different SHM systems. By addressing these challenges and harnessing emerging technologies, IoT-enabled SHM can lead to more resilient, cost-effective, and sustainable infrastructure systems in the future.

REFERENCES

1. Bedon C, Bergamo E, Izzi M, Noè S. Prototyping and validation of MEMS accelerometers for structural health monitoring—the case study of the Pietratagliata cable-stayed bridge. J Sens Actuator Netw. 2018;7(3):30. doi:10.3390/jsan7030030.
2. Cao S, Li J. A survey on ambient energy sources and harvesting methods for structural health monitoring applications. Adv Mech Eng. 2017;9(4):1687814017696210. doi:10.1177/1687814017696210.
3. Cao K, Liu Y, Meng G, Sun Q. An overview on edge computing research. IEEE Access. 2020;8:85714–85728. doi:10.1109/ACCESS.2020.2991734.
4. Chang HF, Lin TK. Real-time Structural Health Monitoring System Using Internet of Things and Cloud Computing. arXiv. 2019. doi:10.48550/arXiv.1901.00670.
5. Dang HV, Tatipamula M, Nguyen HX. Cloud-based digital twinning for structural health monitoring using deep learning. IEEE Trans Ind Inf. 2021;18(6):3820–3830. doi:10.1109/TII.2021.3115119.
6. Dong X, Zhu D, Wang Y, Lynch JP, Swartz RA. Design and validation of acceleration measurement using the Martlet wireless sensing system. In: Proc Smart Mater Adapt Struct Intell Syst. ASME; 2014. doi:10.1115/SMASIS2014-7611.
7. Dutta C, Kumar J, Das TK, Sagar SP. Recent advancements in the development of sensors for the structural health monitoring (SHM) at high-temperature environment: a review. IEEE Sens J. 2021;21(14):15904–15916. doi:10.1109/JSEN.2021.3075535.
8. Fraser M, Elgamal A, He X, Conte JP. Sensor network for structural health monitoring of a highway bridge. J Comput Civ Eng. 2010;24(1):11–24. doi:10.1061/(ASCE)CP.1943-5487.0000005.
9. Fu Y, Mechitov K, Hoskere V, Spencer J. Development of RTOS-based wireless SHM system: benefits in applications. In: Proc Int Conf Smart Infrastruct Constr. 2016:27–29. doi:10.1680/tfitsi.61279.149.
10. Fu Y, Zhu L, Hoang T, Mechitov K, Spencer BF Jr. Demand-based wireless smart sensors for earthquake monitoring of civil infrastructure. In: Proc SPIE Sensors Smart Struct Technol Civ Mech Aerosp Syst. 2018. doi:10.1117/12.2296634.
11. Fu Y, et al. Development and full-scale validation of high-fidelity data acquisition on a next-generation wireless smart sensor platform. Adv Struct Eng. 2019;22(16):3512–3533. doi:10.1177/1369433219866093.
12. Fu Y, et al. xShake: intelligent wireless system for cost-effective real-time seismic monitoring of civil infrastructure. Smart Struct Syst. 2021;28(4):483–497. doi:10.12989/sss.2021.28.4.483.

13. Fu Y, et al. Efficient and high-precision time synchronization for wireless monitoring of civil infrastructure subjected to sudden events. Struct Control Health Monit. 2020;28(1):e2643. doi:10.1002/stc.2643.
14. Fu Y, et al. xImpact: intelligent wireless system for cost-effective rapid condition assessment of bridges under impacts. Sensors. 2022;22(15):5701. doi:10.3390/s22155701.
15. Gaglione A, et al. Energy neutral operation of vibration energy-harvesting sensor networks for bridge applications. In: Proc Int Conf Embedded Wireless Syst Netw. 2018. doi:10.17863/CAM.21287.
16. Gao S, Shang F, Du C. Design of multichannel and multihop low-power wide-area network for aircraft vibration monitoring. IEEE Trans Instrum Meas. 2019;68(12):4887–4895. doi:10.1109/TIM.2019.2897037.
17. Grossi M. Energy harvesting strategies for wireless sensor networks and mobile devices: a review. Electronics. 2021;10(6):661. doi:10.3390/electronics10060661.
18. Häckell MW, Rolfes R, Kane MB, Lynch JP. Three-tier modular structural health monitoring framework using environmental and operational condition clustering for data normalization: validation on an operational wind turbine system. Proc IEEE. 2016;104(8):1632–1646. doi:10.1109/JPROC.2016.2566602.
19. Hoang T, Spencer BF Jr. Autonomous wireless smart sensor for monitoring of railroad bridges. Adv Bridge Eng. 2020;1:1–27. doi:10.1186/s43251-020-00014-7.
20. Hoang T, et al. Autonomous end-to-end wireless monitoring system for railroad bridges. Adv Bridge Eng. 2020;1:1–27. doi:10.1186/s43251-020-00014-7.
21. Jang S, Spencer BF Jr, Sim SH. A decentralized receptance-based damage detection strategy for wireless smart sensors. Smart Mater Struct. 2012;21(5):055017. doi:10.1088/0964-1726/21/5/055017.
22. Jeong S, Zhang Y, Hou R, Lynch JP, Sohn H, Law KH. A cloud-based information repository for bridge monitoring applications. In: Proc SPIE Sensors Smart Struct Technol Civ Mech Aerosp Syst. 2016. doi:10.1117/12.221906

