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Structural Health Monitoring in the Age of AI: Sensors, Digital Twins, and Autonomous Inspection — A Review

Aravinth R[1], Dhivya A [2], Dr. Vennila A[3]

[1]*M.E. Structural Engineering, Kumaraguru College of Technology*
[2]*M.E. Structural Engineering, Kumaraguru College of Technology*
[3]*Associate Professor, Department of Civil Engineering, Kumaraguru College of Technology*

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Abstract: *Structural Health Monitoring (SHM) has become an important technology for assessing the safety, performance, and remaining service life of civil, mechanical, and aerospace structures. Traditional inspection methods depend heavily on periodic visual surveys and localized non-destructive testing. Recent advances in sensing, wireless communication, artificial intelligence (AI), robotics, and digital technologies are changing SHM from periodic inspection toward continuous, automated, and predictive monitoring. This review discusses major recent trends in SHM, with particular attention to fiber-optic sensors, wireless sensor networks and the Internet of Things (IoT), machine learning and deep learning, computer-vision-based inspection, unmanned aerial vehicles (UAVs), digital twins, edge-cloud computing, and energy-harvesting sensor systems. Research shows that fiber-optic sensing provides advantages such as low weight, corrosion resistance, electromagnetic immunity, and suitability for embedding in structures. AI-based methods can improve automated damage detection and classification, while UAVs can collect visual and sensor data from difficult-to-access locations. Digital twins provide a pathway for combining measurements with numerical models to support near-real-time assessment and predictive maintenance. Despite these developments, challenges remain in data quality, environmental variability, model interpretability, sensor durability, standardization, cybersecurity, and reliable field validation. Future SHM systems are likely to combine heterogeneous sensors, physics-based models, AI, autonomous inspection, and digital twins to provide continuous and risk-informed infrastructure management*

Keywords: *Structural health monitoring, smart sensors, fiber-optic sensors, wireless sensor networks, machine learning, deep learning, UAV, digital twin, IoT, predictive maintenance*

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1. INTRODUCTION

Infrastructure such as bridges, buildings, tunnels, dams, offshore structures, and transportation systems gradually deteriorates because of aging, repeated loading, environmental exposure, corrosion, fatigue, and extreme events. Early identification of deterioration is essential for preventing unexpected failures and reducing maintenance costs. Structural Health Monitoring (SHM) provides a systematic approach for observing structural behavior through sensors, data acquisition, signal processing, and damage-assessment methods. Conventional SHM has traditionally relied on wired sensors, periodic measurements, modal testing, and visual inspection. Although these approaches remain valuable, they can be expensive and difficult to apply continuously to large infrastructure. The development of wireless sensing, IoT connectivity, advanced fiber-optic sensors, computer vision, and AI has created new possibilities for automated and continuous monitoring. Machine learning is increasingly being incorporated into SHM because modern structures can generate large volumes of heterogeneous data. Recent reviews identify IoT, big-data analytics, mobile devices, UAVs, virtual/augmented reality, and digital twins as important components of next-generation SHM systems (Malekloo et al., 2021). The purpose of this review is to summarize the principal technological trends shaping SHM and discuss their advantages, limitations, and likely future development.

2. EVOLUTION OF STRUCTURAL HEALTH MONITORING

The development of SHM can broadly be viewed in four stages.

The first stage involved conventional visual inspection and periodic non-destructive evaluation. Engineers mainly relied on manual observations, localized measurements, and experience-based decisions. The second stage introduced permanently installed sensors and automated data acquisition. Accelerometers, strain gauges, displacement sensors, temperature sensors, and other transducers enabled continuous measurement of structural response.

The third stage was characterized by wireless sensor networks and IoT technologies. Sensors could communicate with gateways and cloud platforms, reducing the dependence on extensive cabling and enabling remote monitoring. The current stage is increasingly characterized by AI-assisted interpretation, autonomous inspection, digital twins, edge computing, and multi-modal sensing. Instead of simply collecting measurements, modern systems attempt to automatically determine whether observed changes indicate damage and, increasingly, predict future structural behavior (Malekloo et al., 2021).

3. ADVANCED SENSOR TECHNOLOGIES

3.1 Fiber-Optic Sensors

Fiber-optic sensors (FOSs) are among the important developments in modern SHM. Fiber Bragg grating (FBG), distributed fiber-optic sensing, and related technologies can measure strain, temperature, vibration, and other structural parameters. Their major advantages include small size, low weight, resistance to electromagnetic interference, corrosion resistance, and the ability to be embedded into structural materials. These characteristics make them attractive for bridges, tunnels, buildings, and other civil infrastructure (Wu et al., 2020).

An important trend is the move from point sensing toward distributed sensing. Distributed systems can provide measurements over much larger portions of a structure, improving the possibility of identifying localized damage that could be missed by sparsely placed conventional sensors. However, widespread deployment still requires improvements in installation procedures, interrogation equipment, long-term reliability, data interpretation, and cost.

3.2 Wireless Sensor Networks and IoT

Wireless Sensor Networks (WSNs) have reduced the need for extensive sensor cabling and have enabled monitoring systems to be deployed over large structures. IoT technologies further connect these sensors to edge devices, databases, and cloud platforms. The combination of sensing, wireless communication, and data analytics allows engineers to monitor infrastructure remotely and potentially receive automated warnings when unusual behavior occurs. This is particularly useful for large bridge networks and geographically distributed infrastructure. A recent railway bridge study demonstrated an IoT-enabled SHM architecture using low-cost wireless accelerometers, edge computing, cloud analytics, and a digital twin. Long-term vibration data were used to identify abnormal spectral patterns (Armijo & Zamora-Sanchez, 2024).

4. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

AI and machine learning (ML) represent one of the most significant recent trends in SHM. Conventional approaches often require engineers to define damage-sensitive features manually. ML can instead learn relationships between measured structural responses and structural conditions from data.

Commonly investigated algorithms include:

- Support Vector Machines (SVM)
- Random Forests
- k-Nearest Neighbors (KNN)
- Artificial Neural Networks (ANN)
- Convolutional Neural Networks (CNN)
- Recurrent Neural Networks (RNN)
- Autoencoders
- Ensemble learning methods

Research has demonstrated the usefulness of ML for identifying damage and distinguishing damaged from undamaged structural states. For example, Kurian and Liyanapathirana reported effective damage classification using ML algorithms, with Random Forest showing strong performance in their investigated dataset (Kurian & Liyanapathirana, 2019).

4.1 Deep Learning

Deep learning has expanded the capability of SHM by allowing complex patterns to be extracted directly from large datasets. CNNs are particularly useful for image-based damage detection, while recurrent architectures can analyze sequential sensor measurements. Deep-learning methods have been investigated for identifying cracks, corrosion, delamination, vibration anomalies, and other forms of deterioration. Their major advantage is the potential for automated feature extraction. However, deep-learning models often require large and representative datasets. A model trained under laboratory conditions may perform poorly in the field because of differences in temperature, traffic, lighting, sensor placement, material properties, and structural configuration. Thus, generalization remains a major research challenge.

4.2 Explainable and Physics-Informed AI

A growing research direction is the combination of data-driven models with structural mechanics. Purely data-driven AI may identify anomalies without clearly explaining their physical meaning. Physics-informed machine learning attempts to incorporate governing physical relationships into the learning process. This can reduce dependence on large datasets and improve physical consistency. Hybrid AI-physics models are therefore promising for damage localization, response prediction, and remaining-life assessment. Another emerging area is Explainable AI (XAI), which seeks to make model decisions understandable to engineers. This is particularly important because SHM decisions can affect public safety.

5. COMPUTER VISION AND IMAGE-BASED SHM

Computer vision has become increasingly important because cameras can inspect large surface areas without requiring sensors to be physically attached to every location. Image-processing and deep-learning techniques can detect visible defects such as cracks, spalling, corrosion, surface deterioration, damaged connections, and deformation. The increasing availability of high-resolution cameras, automated image analysis, and AI has made vision-based inspection a major research area. One limitation is that image-based techniques mainly detect visible surface conditions. Internal defects may remain undetected. Lighting, shadows, weather, camera angle, image quality, and occlusion can also affect detection accuracy. For this reason, future SHM is likely to combine computer vision with vibration, strain, acoustic, and other sensing technologies rather than relying on images alone.

6. UAV-BASED STRUCTURAL HEALTH MONITORING

Unmanned Aerial Vehicles (UAVs), commonly called drones, offer a way to inspect locations that are difficult or dangerous for human inspectors to access. UAV-based SHM can collect photographs, videos, thermal images, and other sensor measurements. These data can subsequently be analyzed using computer vision and AI. A recent scientometric review identified four major research clusters in drone-based SHM: UAV-enabled vision monitoring; integration of drones with advanced sensors and AI; drone-based modal analysis, energy harvesting, and deep learning; and automation and robotics (Fayyad et al., 2024). An important future direction is autonomous inspection, in which a UAV determines inspection paths, identifies regions requiring additional measurements, and communicates results to a digital-twin platform.

Challenges include flight safety, regulatory restrictions, weather sensitivity, image quality, autonomous navigation, battery limitations, and reliable interpretation of collected data.

7. DIGITAL TWINS FOR STRUCTURAL HEALTH MONITORING

Digital twins are emerging as an important component of next-generation SHM. A digital twin is a digital representation of a physical structure that is continuously or periodically updated using measurements from the real structure. A digital-twin-based SHM system can combine sensor measurements, structural models, historical data, environmental information, machine-learning predictions, and visualization tools. This approach can move SHM beyond simple damage detection toward condition assessment and predictive maintenance. For example, a neural-network-based digital twin for reinforced-concrete bridges was developed using fiber-optic sensing. The study demonstrated the ability to convert sensor measurements into structural quantities and an interactive digital representation (Hielscher et al., 2023).

Similarly, an IoT and digital-twin system for railway bridge monitoring combined low-cost wireless accelerometers with edge and cloud computing (Armijo & Zamora-Sanchez, 2024). The major challenge is developing digital twins that remain accurate as structures age and their properties change.

8. EDGE AND CLOUD COMPUTING

Large-scale SHM systems can generate enormous quantities of sensor data. Sending every measurement to a remote cloud server can increase communication costs, latency, and energy consumption. Edge computing addresses this problem by processing data close to the sensor or monitoring site. Initial signal processing, feature extraction, and anomaly detection can occur locally, while more computationally intensive analysis can be performed in the cloud. Hybrid edge-cloud architectures are therefore becoming attractive for near-real-time SHM. The railway bridge case study described above demonstrates how edge processing and cloud analytics can be combined in a practical monitoring system (Armijo & Zamora-Sanchez, 2024).

9. ENERGY HARVESTING AND SELF-POWERED SHM

Long-term monitoring requires reliable power. Replacing batteries in thousands of sensors is expensive and sometimes impractical. Energy harvesting is therefore receiving increasing attention. Potential energy sources include structural vibration, wind, solar energy, thermal gradients, and human or traffic-induced motion. Recent research has investigated piezoelectric energy harvesting to power FBG-based monitoring systems. A building-envelope study integrated a piezoelectric generator, supercapacitor, power-conditioning circuit, fiber-optic sensing, and an IoT gateway (Pracucci et al., 2024). Although self-powered SHM is promising, harvested energy is often variable and insufficient for continuous high-power operation. Energy-aware sensing, low-power electronics, duty cycling, and efficient communication will therefore remain important.

10. MULTI-MODAL AND AUTONOMOUS SHM

The future of SHM is increasingly moving toward multi-modal monitoring. Instead of relying on a single sensor type, systems can combine vibration, strain, acoustic emission, temperature, images, displacement, and environmental measurements. Data fusion can improve robustness because different sensing technologies observe different aspects of structural behavior. For example, fiber-optic sensors can measure strain while UAV-based cameras identify visible surface deterioration. The combination of autonomous UAVs, wireless sensors, AI, and digital twins could ultimately provide a closed monitoring loop: Sense → Communicate → Analyze → Diagnose → Predict → Decide → Inspect/Repair.

This represents a transition from conventional condition monitoring toward intelligent infrastructure management.

11. KEY CHALLENGES

Despite rapid technological development, several issues must be addressed before advanced SHM becomes routine.

11.1 Environmental and Operational Variability

Temperature, humidity, traffic, wind, loading, and seasonal changes can alter structural responses even when no damage is present. AI systems must distinguish these normal variations from genuine deterioration.

11.2 Data Scarcity

Real structural failures are relatively rare, so field datasets containing confirmed damage are limited. This creates difficulties for supervised learning. Transfer learning, synthetic data, unsupervised learning, physics-based simulation, and continual learning may help address this problem.

11.3 Model Interpretability

Engineers and infrastructure owners need to understand why an AI system has produced a warning. Black-box predictions can be difficult to trust in safety-critical applications.

11.4 Sensor Durability

Sensors installed in real structures must survive moisture, corrosion, vibration, temperature variation, mechanical damage, and long service periods.

11.5 Standardization and Validation

Laboratory demonstrations do not automatically guarantee successful field performance. Standardized datasets, benchmark problems, long-term field studies, and common evaluation metrics are needed.

11.6 Cybersecurity and Data Management

IoT-connected SHM systems create new cybersecurity risks. Unauthorized access or manipulation of monitoring data could result in incorrect maintenance decisions. Secure communication, authentication, data integrity, and privacy should therefore become part of SHM system design.

12. FUTURE RESEARCH DIRECTIONS

Several research directions are likely to shape SHM over the coming years.

First, physics-informed AI can combine the strengths of structural mechanics and machine learning. Second, digital twins can evolve from visualization platforms into predictive decision-support systems. Third, autonomous UAV and robotic inspection may reduce the need for hazardous manual inspections. Fourth, distributed and self-powered sensors could make continuous monitoring more practical. Fifth, edge AI can enable rapid local detection while reducing communication requirements. Another important direction is uncertainty quantification. An SHM system should not only state that damage is likely; it should also estimate confidence and uncertainty. This is essential for risk-based decisions. Finally, SHM is likely to become increasingly integrated with asset-management systems. Instead of treating monitoring as a separate engineering activity, sensor data and AI predictions can be used to determine inspection priorities, maintenance timing, rehabilitation strategies, and remaining useful life.

13. CONCLUSION

Recent developments show that structural health monitoring is moving from periodic, manually interpreted inspection toward continuous, connected, intelligent, and predictive infrastructure management. Fiber-optic sensors, wireless networks, IoT, AI, computer vision, UAVs, digital twins, edge computing, and energy harvesting are among the most important trends. The literature indicates that combining these technologies can improve the speed, scale, and automation of structural assessment (Malekloo et al., 2021). owever, technological progress alone is not sufficient. Reliable SHM requires robust sensors, high-quality field data, physically meaningful AI models, uncertainty assessment, cybersecurity, standardized validation, and integration with engineering decision-making. The most promising future systems will therefore be hybrid platforms that combine multi-modal sensing, physics-based modeling, AI, autonomous inspection, and digital twins. Such systems have the potential to transform infrastructure maintenance from reactive repair to proactive and predictive management.

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