Journal of Engineering for THERMAL ENERGY AND POWER

ISSN: 1001-2060
Vol. 24 No. 2, 2021

SMART AND SUSTAINABLE CIVIL INFRASTRUCTURE USING IOT, MACHINE LEARNING, AND STRUCTURAL HEALTH MONITORING TECHNIQUES

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Received: 14/07/2021

Revised: 26/07/2021

Accepted: 03/09/2021

DOI: 10.12060/jet-ep-v24.i2-2

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Abstract

The rapid growth of urbanization and aging infrastructure has increased the demand for smart and sustainable civil infrastructure systems. Traditional inspection and maintenance approaches are often reactive, labor-intensive, and inefficient. The integration of Internet of Things (IoT), Machine Learning (ML), and Structural Health Monitoring (SHM) techniques has emerged as a transformative solution to enhance infrastructure safety, resilience, and sustainability. This review article presents a comprehensive overview of recent advancements in smart civil infrastructure enabled by IoT-based sensing, data-driven machine learning models, and SHM systems. Key applications, methodologies, benefits, challenges, and future research directions are discussed, highlighting the potential of intelligent technologies to support predictive maintenance, optimize resource utilization, and reduce environmental impacts.

Keywords: Smart infrastructure; Sustainable development; Internet of Things (IoT); Machine learning; Structural health monitoring; Predictive maintenance

1. INTRODUCTION

Civil infrastructure such as bridges, buildings, roads, and dams plays a crucial role in socio-economic development. However, many existing structures worldwide are aging and subjected to increased loads, environmental degradation, and extreme climate events. Conventional inspection methods are typically periodic, manual, and costly, often failing to detect early-stage damage.

Smart and sustainable civil infrastructure aims to integrate digital technologies to improve monitoring, decision-making, and lifecycle management. IoT enables real-time data acquisition through distributed sensors, while machine learning techniques extract meaningful patterns from large datasets. Structural Health Monitoring (SHM) systems leverage these technologies to assess structural condition, detect damage, and predict future performance. Together, IoT, ML, and SHM contribute to safer, more resilient, and environmentally

ISSN: 1001-2060
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sustainable infrastructure systems.

2. LITERATURE REVIEW

Recent studies highlight the growing adoption of IoT-based sensor networks for monitoring structural parameters such as strain, vibration, temperature, displacement, and corrosion. Wireless sensor networks (WSNs) have reduced installation costs and improved scalability in SHM applications.

Machine learning algorithms, including artificial neural networks (ANN), support vector machines (SVM), decision trees, and deep learning models, have been widely applied for damage detection, anomaly identification, and remaining useful life prediction. Deep learning approaches, such as convolutional neural networks (CNN) and recurrent neural networks (RNN), show superior performance in handling complex and high-dimensional SHM data.
Researchers have also emphasized the role of smart infrastructure in sustainability by enabling predictive maintenance, minimizing material waste, and reducing carbon emissions. Despite these advancements, challenges such as data quality, sensor reliability, cybersecurity, and model interpretability remain critical research gaps.

3. METHODOLOGY

This review adopts a systematic qualitative approach to analyze existing research on smart and sustainable civil infrastructure. Relevant peer-reviewed journal articles, conference papers, and technical reports were examined, focusing on the integration of IoT, ML, and SHM technologies.
The reviewed studies were categorized based on:

- Type of infrastructure (bridges, buildings, pavements, etc.)
- Sensing technologies and data acquisition methods
- Machine learning algorithms and analytical frameworks
- SHM objectives (damage detection, condition assessment, prediction)
- Sustainability outcomes (cost reduction, lifecycle extension, energy efficiency)

This classification enabled a comparative assessment of methodologies and identified emerging trends and limitations.

4. RESULTS AND DISCUSSION

The review reveals that IoT-based SHM systems significantly enhance real-time monitoring and data availability. Machine learning models improve damage detection accuracy and enable predictive maintenance strategies, reducing unexpected failures.
Key findings include:

- Wireless and low-power IoT sensors improve scalability and long-term monitoring.
- ML-driven SHM systems outperform traditional model-based methods in complex environments.
- Predictive maintenance reduces lifecycle costs and environmental impacts.
- Integration of digital twins with SHM is an emerging trend for smart infrastructure management.

However, practical implementation faces challenges related to data management, interoperability, sensor durability, and lack of standardized frameworks.

ISSN: 1001-2060
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5. CONCLUSION

The integration of IoT, machine learning, and structural health monitoring techniques represents a paradigm shift toward smart and sustainable civil infrastructure. These technologies enable real-time condition assessment, data-driven decision-making, and proactive maintenance, contributing to improved safety, resilience, and sustainability.

While significant progress has been made, future research should focus on developing robust, secure, and interpretable ML models, standardized SHM frameworks, and scalable IoT architectures. Addressing these challenges will accelerate the widespread adoption of intelligent infrastructure systems and support sustainable urban development.

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