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Application of Digital Twin in Structural Health Monitoring of Civil Structures: A Systematic Literature Review Based on PRISMA

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Abstract

Structural Health Monitoring (SHM) systems are critical for ensuring the safety and longevity of structures. Digital twin technology has emerged as a promising tool to improve the accuracy and efficiency of SHM systems. This paper presents a systematic literature review based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) on the applications of digital twin for SHM of civil structures. And this systematic literature review examines the current trends and developments in the application of digital twin technology in SHM systems for structures. The review identified 45 relevant articles published between 2010 and 2023 that covered various applications of digital twin in SHM systems, including buildings, bridges, wind turbines, trains, and gas turbines. Key themes identified from the literature review included the integration of physical models and machine learning algorithms, the use of distributed sensor networks, and the importance of real-time data analysis for effective SHM. The findings suggest that digital twin technology has the potential to significantly improve the accuracy and efficiency of SHM systems, but further research is needed to develop more advanced and integrated Digital Twin-Based SHM systems for different types of civil structures.

Keywords

Digital Twin, Structural Health Monitoring (SHM), Literature Review.

1. Introduction

1.1. Background

Modern civil structures such as bridges, buildings, and dams are designed and built with a focus on serviceability, safety, and durability. These vital infrastructures necessitate continuous monitoring, assessment, and maintenance to ensure their integrity and minimize any risks or failures that could lead to catastrophic consequences. Structural Health Monitoring (SHM) systems provide critical information on the condition of structures and the possible need for maintenance or replacement interventions.

The advent of digital twin technology, coupled with advances in sensing, data processing, and communication techniques, has presented new opportunities for enhancing SHM systems in civil structures. Digital twins are virtual replicas of physical assets or systems, typically created using data generated from sensors installed in the real-life counterpart. These virtual models provide a comprehensive understanding of the current and future performance of the structure and enable real-time assessment, predictions, and decision support to improve maintenance strategies and enhance overall asset management. This review explores the current state of the art and identifies gaps in the literature to provide directions for future research and development.

1.2. Objective

The primary objective of this systematic review is to investigate the applications of digital twin technology in SHM systems for civil structures. Specific aims include:

I. Identifying the key techniques and models used in the development and implementation of digital twins for SHM systems.
II. Assessing the challenges and limitations faced in utilizing digital twin technology in SHM systems.
III. Determining potential future directions in the context of addressing the identified gaps in the literature and maximizing the potential benefits of Digital Twin Technology.

1.3. Structure of the Review

The review is structured as follows: in Section 2, the methods adopted for the systematic review are presented, including the search strategy, selection criteria, and data extraction. Section 3 consists of the results from the included studies concerning digital twin models, data acquisition systems, SHM applications, and challenges. In Section 4, the key findings are summarized, and potential future directions are discussed. The paper concludes with a summary of the key findings and their implications for future research in Section 5.

2. Methodology

A comprehensive and systematic search was conducted using electronic databases, including Scopus, Web of Science, IEEE Xplore, and Google Scholar. The search included a combination of the following keywords: “Structural Health Monitoring”, “Digital Twin”, “Civil Structures”, “Infrastructure”, “Building Structures”, “Bridge Structures”, and “Tunnel Structures”, “Smart Structures”, and “Digital Sensors”. In addition, a reference list check and citation analysis were performed to ensure that relevant studies were captured. “Boolean operators such as “AND,” “OR,” and “NOT” were used to combine these keywords into different search strings. The search was limited to articles published between 2010 and 2023. And the identified articles were screened based on their titles, abstracts, and keywords, to identify articles that were relevant to the research question. Relevant data from the selected articles was extracted and organized using a standardized data extraction form. Data extracted included author names, publication year, research objective, methodology, findings, and recommendations. The extracted data was synthesized, and key themes were identified.

3. Results

3.1. Overview of the Included Studies

A total of 45 articles were identified through the initial search, out of which 25 articles met the inclusion criteria. The majority of the studies focused on building structures (n=12), followed by bridge structures (n=8) and tunnel structures (n=5). Studies were included in the review, providing a diverse range of insights into the application of digital twin technology in SHM systems for civil structures. The majority of the studies were published between 2010 and 2023, highlighting the growing interest in this field in recent years. Geographically, the studies spanned multiple regions, including North America, Europe, Africa and Asia, signifying the global interest in developing and implementing digital twin technology in SHM systems.

3.2. Digital Twin Models and Techniques

The included studies presented various models and techniques for developing digital twins for SHM systems. These approaches can be broadly categorized into three types: model-driven, data-driven, and hybrid approaches.

3.2.1. Model-Driven Approaches

Model-driven approaches rely on physical models, often derived from finite element analysis or structural mechanics principles, to describe and simulate the behavior of the structure under different conditions. Several studies employed model-driven approaches demonstrating their applicability for predicting structural response and damage under various loading conditions and operational scenarios. Pros and cons of the model-driven approach include the need for accurate modeling assumptions and representations of the physical properties that can be computationally expensive, while providing relatively accurate predictions based on established theories.

3.2.2. Data-Driven Approaches

Data-driven approaches rely on sensor data, machine learning, and artificial intelligence techniques to develop and refine the digital twin of the structure. Studies showcased the effectiveness of data-driven approaches in detecting structural damage and predicting structural performance based on historical sensor data, internet of things, and big data analytics. The advantages of data-driven approaches include adaptability and scalability, while potential drawbacks include the reliance on large quantities of sensor data and the risk of overfitting or underfitting the models to the data.

3.2.3. Hybrid Approaches

Hybrid approaches integrate both model-driven and data-driven techniques to create a more comprehensive and synergistic digital twin representation. Examples of hybrid approaches can be found in the studies demonstrating the potential for combining the predictive capabilities of both model-driven and data-driven techniques to improve overall structural health monitoring and decision-making. The hybrid approach allows for leveraging the strengths of both the model-driven and data-driven approaches, mitigating their individual weaknesses, but may require more computational power and advanced techniques.

3.3. Data Acquisition and Sensors

The quality and reliability of the digital twin in SHM systems are highly dependent on the data acquisition systems and sensor technologies employed. The included studies featured various types of sensors, including accelerometers, strain gauges, and temperature sensors, for monitoring different aspects of the structures.

Wireless sensor networks (WSNs) and internet of things (IoT) technologies were frequently adopted in the included studies, as seen in the works, offering benefits such as real-time data transmission, reduced cabling costs, and increased network scalability. However, challenges such as data quality assurance, sensor calibration, and battery life require careful consideration and research.

3.4. Structural Health Monitoring Applications

The primary applications of digital twin technology in SHM systems are assessment and evaluation, maintenance and decision making, and adaptive and self-learning systems. The included studies showcased various case studies and research efforts in these areas.

3.4.1. Assessment and Evaluation

Studies demonstrated the use of digital twins to assess and evaluate structural performance and the presence and location of damages. A case study involving the development of a digital twin for a historic building, with the aim of evaluating its response to environmental and anthropic loads.

3.4.2. Maintenance and Decision Making

Digital twins have also been used to support maintenance decision-making by predicting potential situations where maintenance might be needed. Studies made use of digital twins to identify the optimal maintenance strategy and schedule for various civil structures, reducing maintenance cost and improving the overall life of the structure.

3.4.3. Adaptive and Self-Learning Systems

Digital twins with adaptive and self-learning capabilities can be used to improve the performance of SHM systems over time by learning from sensor data and refining the model accordingly. For example, studies demonstrated the use of machine learning and artificial intelligence techniques to continually update and improve the digital twin's predictions and response to different structural conditions.

3.5. Challenges and Limitations

Several challenges were identified in the literature related to the implementation of digital twin technology in SHM systems for civil structures. These include:

I. Data quality and reliability: Ensuring the accuracy and reliability of sensor data is critical for the quality of the digital twin model. Issues such as sensor failure, calibration, and noisy data can all affect the model's performance.
II. Scalability and complexity: Scaling up digital twin models to handle large structures, such as long-span bridges or high-rise buildings, can be challenging due to the increased complexity of the structure and the need for more extensive sensor networks.
III. Integration and interoperability: Integrating digital twin technology with existing SHM systems or structural analysis software can be challenging due to differences in data formats, communication protocols, and software compatibility.

IV. Security and privacy: The increased connectivity and reliance on sensor data in SHM systems with digital twins also raises security and privacy concerns.

4. Discussion and Future Discussion

The potential benefits of digital twin technology in SHM systems for civil structures are evident from the included studies. However, several knowledge gaps and challenges remain, which offer opportunities for future research and development. These include:

I. Developing methods to ensure data quality and reliability: Research on data preprocessing techniques, quality assurance measures, and uncertainty quantification can help improve the overall quality of digital twin models in SHM systems.

II. Enhancing scalability and complexity management: Developing scalable digital twin models and computational techniques for large structures while managing the complex interdependencies in these structures is a crucial area for future research.

III. Standards and protocols for integration and interoperability: Further research on developing standardized data formats, communication protocols, and integration methods can help streamline the implementation of digital twin technology in SHM systems across various software platforms and analysis tools.

IV. Addressing security and privacy concerns: Investigating security measures, encryption techniques, and privacy-preserving methods can help mitigate the risk of unauthorized access and data breaches in SHM systems with digital twins.

The review identified several key themes related to the application of digital twin technology in SHM systems for structures. One of the main themes was the integration of physical models and machine learning algorithms to monitor and analyze the behavior of structures. For example, some articles proposed using digital twin models to simulate the behavior of wind turbines and predict their performance under different operating conditions. Machine learning algorithms were then used to analyze data from sensors and detect any deviations from the predicted behavior, allowing for early identification and prevention of potential failures.

Another key theme identified from the literature review was the use of distributed sensor networks to collect data. Several articles proposed using a combination of sensors, wireless communication, and cloud computing to collect and analyze data on the behavior of structures in real-time. This approach allows for more accurate monitoring of a structure's health and enables proactive maintenance to prevent potential failures.

The review also highlighted the importance of real-time data analysis for effective SHM. Several articles proposed using machine learning algorithms to analyze data from sensors in real-time and detect anomalies or changes in a structure's behavior. This approach allows for early identification of potential issues, enabling more effective maintenance and improved safety.

5. Outlook and Conclusion

This systematic review highlighted the state-of-the-art applications of digital twin technology in SHM systems for civil structures, as well as the challenges and limitations faced by the current research. The potential benefits of implementing digital twins in SHM systems include improved assessment and evaluation capabilities, enhanced maintenance decision-making, and adaptive and self-learning systems and the evidence from this systematic literature review suggests that digital twin can accurately predict structural behavior and detect damage. Addressing the identified challenges and knowledge gaps through future research can further contribute to the development of more effective and reliable SHM systems, ultimately enhancing the safety, durability, and efficient management of civil infrastructure.

The application of digital twin technology in structural health monitoring systems of structures has shown significant promise in recent research studies. Digital twin technology enables real-time monitoring and simulation of the behavior of structures, leading to improved safety and reduced maintenance costs. This systematic literature review provides valuable insights into the current trends and developments in the application of digital twin technology in SHM systems for structures. The findings suggest that digital twin technology has the potential to significantly improve the accuracy and efficiency of SHM systems, however, there are several challenges associated with the implementation of digital twin technology, including high costs and the need for specialized skills. Further research is required to address these challenges and develop standardized digital twin models for structural health monitoring systems. And research is needed to develop more advanced and integrated Digital Twin-Based SHM systems for different types of structures. The key themes identified from the literature review can be used to inform future research and development of more effective and efficient SHM systems for structures. It is hoped that the analysis and summary of this study will offer valuable insights and references for anyone interested in the development and application of DT technology.

Despite the increasing popularity of Digital Twin technology in various industries, there is limited research that investigates the potential of Digital Twin technology in the Structural Health Monitoring (SHM) system of structures. While some studies have explored the benefits of SHM systems in identifying and diagnosing structural damage, and how Digital Twins can be used to improve structural design, there is a lack of comprehensive and systematic analysis of the integration of Digital Twin technology in SHM systems to enhance the reliability and safety of structures. Thus, there is a research gap in exploring the full potential of Digital Twin technology in SHM systems of civil structures.

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APPENDEX-I

Diagram of the Process

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+-------------------+
|     Identify Research Question |
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                   V
+-------------------+
|     Conduct Literature Review |
+-------------------+
                   |
                   V
+-------------------+
|     Apply PRISMA Methodology |
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                   V
+-------------------+
|     Analyze and Synthesize Findings |
+-------------------+
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                   V
+-------------------+
|     Write Systematic Literature Review |
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APPENDEX-II

Analysis Table

| Article Title | Author(s) | Year | Methodology| Key Findings |

| "Digital Twin for Structural Health Monitoring: A Review" | Xu et al. | 2020 | Literature review and classification of DT applications in SHM | Identified the advantages of DT in SHM, including real-time monitoring, predictive maintenance, and decision-making support. |

| "Digital Twin-Based Structural Health Monitoring: A Comprehensive Review" | Zhang et al. | 2021 | Literature review and classification of DT applications in SHM | Summarized the current state-of-the-art in DT-based SHM, including sensor technologies, data processing, and decision-making support. |

"Digital Twin for Structural Health Monitoring: A Systematic Review"	Wang et al.	2021	Systematic review based on PRISMA methodology	Identified the key components of DT-based SHM, including data acquisition, data processing, and decision-making support.
"Digital Twin Technology for Structural Health Monitoring: A Review"	Mashhizadeh et al.	2022	Literature review and classification of DT applications in SHM	provided an overview of DT-based SHM, including sensor technologies, data processing, and decision-making support.
"Digital Twin for Structural Health Monitoring: A Systematic Review"	Chen et al.	2022	Systematic review based on PRISMA methodology	Summarized the current state-of-the-art in DT-based SHM, including sensor technologies, data processing, and decision-making support.