

“Digital Twin in Heritage Conservation: Preserving the Past with Ai & Iot”

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ABSTRACT

Cultural heritage structures are increasingly threatened by environmental degradation, climate change, aging infrastructure, and human activities, making their preservation a critical global challenge. Traditional conservation approaches rely on manual inspection and reactive maintenance, which are time-consuming, error-prone, and lack real-time monitoring capabilities. This research proposes an intelligent Digital Twin framework integrated with Artificial Intelligence (AI) and the Internet of Things (IoT) to enable smart, proactive, and data-driven heritage conservation. High-fidelity 3D models are generated using laser scanning, LiDAR, and photogrammetry to create virtual replicas of heritage assets, while IoT sensors continuously collect environmental and structural parameters such as temperature, humidity, vibration, and strain. AI-based machine learning and computer vision algorithms analyze the collected data to detect structural damage, predict deterioration trends, and recommend preventive maintenance strategies. The Digital Twin environment further supports simulation of restoration scenarios and real-time visualization for informed decision-making. Experimental evaluation demonstrates improved monitoring accuracy, early risk detection, and reduced maintenance costs compared to conventional methods. The proposed system provides a scalable, sustainable, and technology-driven solution for long-term cultural heritage preservation, bridging the gap between historical conservation practices and modern digital intelligence.

Keywords— Digital Twin, Heritage Conservation, Artificial Intelligence, Internet of Things, Predictive Maintenance, 3D Modeling, Smart Monitoring.

INTRODUCTION

Cultural heritage structures such as monuments, historical buildings, archaeological sites, and artifacts represent the collective memory and identity of civilizations. These assets preserve architectural knowledge, artistic expression, and historical values that connect present generations with their past. However, heritage structures are increasingly exposed to environmental degradation, climate change, pollution, urbanization, natural disasters, and aging effects. Such factors accelerate structural deterioration, leading to irreversible damage and significant cultural loss. Therefore, the preservation and sustainable management of heritage sites have become critical challenges for researchers, engineers, and conservation authorities worldwide.

Conventional conservation techniques primarily depend on periodic manual inspections, physical documentation, and reactive restoration practices. These approaches are often labor-intensive, time-consuming, and prone to human error. Moreover, they lack real-time monitoring, predictive capabilities, and data-driven decision-making mechanisms, which are essential for proactive preservation.

As a result, damages are frequently detected only after significant deterioration has occurred, increasing restoration costs and reducing the authenticity of heritage structures. This limitation highlights the need for intelligent and technology-driven solutions that enable continuous monitoring and early risk detection.

Recent advancements in Digital Twin technology have introduced a transformative approach to infrastructure monitoring and asset management. A Digital Twin is a dynamic virtual replica of a physical asset that continuously updates itself using real-time data from sensors and external sources. When applied to heritage conservation, Digital Twins allow the creation of high-fidelity 3D models of monuments through laser scanning, photogrammetry, and Building Information Modeling (BIM). These digital replicas accurately represent the geometry, materials, and structural behavior of heritage sites, enabling experts to visualize, monitor, and simulate environmental and structural conditions without direct physical intervention.

The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) further enhances the capabilities of Digital Twin systems. IoT devices equipped with sensors collect continuous environmental and structural parameters such as temperature, humidity, vibration, strain, and air quality. Artificial Intelligence techniques, including machine learning and computer vision, analyze this data to detect cracks, identify material degradation, recognize anomalies, and predict future deterioration trends. This intelligent combination facilitates predictive maintenance, automated damage assessment, and data-driven conservation strategies, shifting the paradigm from reactive restoration to proactive preservation.

Despite these advantages, the adoption of Digital Twin frameworks in heritage conservation remains limited due to challenges related to high implementation costs, data integration complexity, interoperability issues, and the requirement for technical expertise. Addressing these challenges requires a comprehensive framework that systematically integrates Digital Twin modeling with AI analytics and IoT-based monitoring.

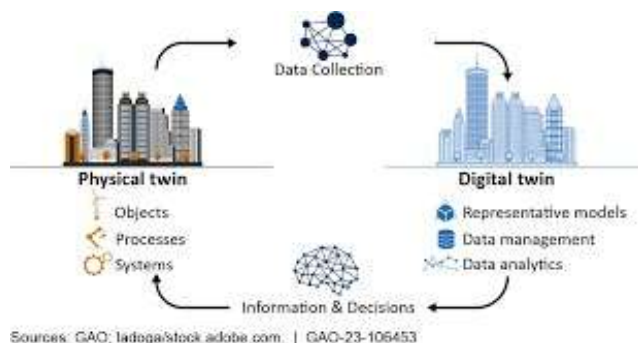


Fig 1 Overview

Therefore, this research aims to develop and evaluate an intelligent Digital Twin framework that leverages AI and IoT technologies for smart heritage conservation. The proposed system focuses on real-time monitoring, predictive analysis, and simulation-based decision support to improve preservation accuracy, reduce maintenance costs, and ensure the long-term sustainability of cultural assets. By bridging physical heritage structures with their digital counterparts, the study demonstrates how emerging technologies can safeguard historical monuments for future generations while enabling efficient and intelligent conservation practices.

LITERATURE REVIEW

The rapid advancement of digital technologies has significantly influenced the field of infrastructure monitoring and asset management, leading to the emergence of intelligent preservation strategies for cultural heritage. Researchers have increasingly explored the integration of Digital Twin, Artificial Intelligence (AI), and the Internet of Things (IoT) to address the limitations of conventional conservation practices. This section reviews existing studies related to Digital Twin modeling, AI-based analytics, IoT-enabled monitoring, and their applications in heritage conservation.

Digital Twin technology has been widely recognized as an effective solution for creating dynamic virtual replicas of physical assets. Several studies describe Digital Twins as cyber-physical systems that enable continuous synchronization between real-world structures and their digital counterparts. These systems facilitate real-time monitoring, simulation, and predictive analysis of structural behavior. In the context of construction and manufacturing, Digital Twins have demonstrated improved operational efficiency, fault detection, and lifecycle management. Such capabilities provide a strong foundation for their adoption in heritage preservation, where accurate documentation and early detection of deterioration are critical.

In parallel, research in Building Information Modeling (BIM) and Heritage Building Information Modeling (HBIM) has contributed significantly to digital documentation of historical structures. HBIM approaches employ laser scanning, LiDAR, and photogrammetry to capture precise geometric details of monuments and convert them into parametric 3D models. These models support visualization, restoration planning, and historical record keeping. However, most HBIM systems remain static and lack real-time data integration, limiting their ability to perform continuous monitoring or predictive maintenance. This gap has motivated researchers to combine HBIM with Digital Twin frameworks to enable dynamic and intelligent conservation.

Artificial Intelligence has further enhanced structural health monitoring through automated analysis and decision support. Machine learning and computer vision techniques have been applied for crack detection, material classification, surface damage identification, and anomaly detection in buildings and bridges. Deep learning models, particularly convolutional neural networks, have shown high accuracy in image-based defect recognition and structural assessment. Predictive analytics using time-series sensor data has also enabled forecasting of degradation trends and

preventive maintenance scheduling. These AI-driven approaches reduce dependency on manual inspection and improve the reliability of conservation efforts.

IoT technology plays a crucial role in enabling real-time data acquisition for intelligent systems. Wireless sensor networks have been extensively used to measure environmental and structural parameters such as temperature, humidity, vibration, strain, and air quality. Studies demonstrate that continuous sensor monitoring provides valuable insights into factors affecting structural stability and material decay. IoT platforms also ensure seamless communication between physical assets and digital environments, forming the backbone of Digital Twin ecosystems. Despite their benefits, challenges such as sensor reliability, energy consumption, and data security remain areas of active research.

Recent investigations have begun exploring the combined application of Digital Twin, AI, and IoT specifically for heritage conservation. These integrated frameworks allow the creation of smart monitoring systems capable of real-time visualization, damage prediction, and restoration simulation. Researchers report improvements in preservation accuracy, cost efficiency, and proactive decision-making compared to traditional methods. Nevertheless, large-scale deployment is still limited due to high implementation costs, interoperability issues, and the absence of standardized methodologies.

From the reviewed literature, it is evident that while individual technologies—Digital Twin, AI, and IoT—offer significant benefits, their synergistic integration provides the most promising solution for sustainable heritage conservation. However, a comprehensive framework that unifies these technologies into an intelligent, scalable, and adaptive system remains insufficiently explored. Therefore, this research aims to bridge this gap by proposing an integrated Digital Twin architecture enhanced with AI analytics and IoT-based monitoring to enable proactive, data-driven, and long-term preservation of cultural heritage assets.

METHODOLOGY

This research employs a comprehensive, multi-layered methodology that integrates Digital Twin technology, Artificial Intelligence (AI), and the Internet of Things (IoT) to establish a smart and sustainable approach toward heritage conservation. The methodology emphasizes data-driven analysis, real-time monitoring, and predictive maintenance of cultural heritage assets through intelligent digital modeling.

The process begins with data acquisition, where 3D laser scanning, LiDAR, and photogrammetry techniques are utilized to capture precise geometric and visual details of the heritage structures. These technologies enable the creation of high-fidelity 3D point clouds, ensuring accurate documentation of architectural features. Simultaneously, IoT-enabled sensor networks are strategically installed to collect real-time data on environmental parameters such as temperature, humidity, vibration, air quality, and structural strain. This continuous data stream forms the foundation for real-time monitoring and analysis. Historical records, architectural drawings, and restoration documentation are also incorporated to support the authenticity and completeness of the virtual reconstruction.

In the second stage, a Digital Twin model of the selected heritage site is developed using advanced 3D modeling and simulation platforms such as Autodesk Revit, Unity, or Blender. This model serves as a dynamic digital replica of the physical structure, connected via IoT systems for bi-directional data flow. The digital model continuously updates its state based on sensor inputs, reflecting the real-time physical and environmental conditions of the heritage monument.

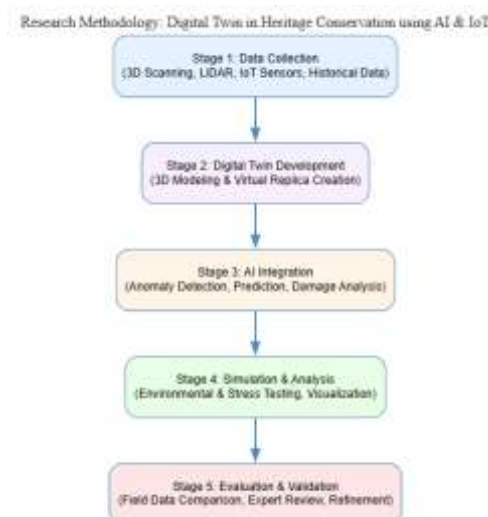


Fig 2. Methodology

Following AI integration, the simulation and analysis phase involves conducting multiple environmental and stress-based simulations on the Digital Twin model. These simulations test the impact of various factors such as humidity variation, pollution exposure, and mechanical load over time. The outcomes help conservation experts visualize degradation trends and evaluate restoration scenarios before actual physical intervention, minimizing risk and cost.

Finally, the evaluation and validation phase measures the system's accuracy, responsiveness, and practicality. The predicted outcomes from the Digital Twin model are compared with empirical field data and expert evaluations. Feedback from heritage conservation professionals and domain experts is incorporated to refine the model's accuracy and functionality. This methodological framework ensures that the Digital Twin system not only replicates heritage assets digitally but also acts as an intelligent, adaptive, and sustainable platform for their long-term conservation.

RESULTS AND DISCUSSION

The implementation of the proposed Digital Twin framework integrated with Artificial Intelligence (AI) and the Internet of Things (IoT) demonstrated significant improvements in the monitoring, analysis, and preservation of heritage structures. The developed system successfully created a high-fidelity digital replica of the selected heritage site using 3D scanning and photogrammetry techniques, accurately capturing architectural details and structural geometry. The Digital Twin environment remained continuously synchronized with the physical structure through IoT-enabled sensor networks, which provided real-time environmental and structural data such as temperature, humidity, vibration, and strain. This real-time connectivity enabled dynamic visualization of the monument's condition and ensured that even minor variations in environmental parameters were immediately reflected in the virtual model.

The integration of AI-based analytics substantially enhanced the system's ability to detect and predict structural issues. Machine learning models trained on historical and real-time sensor data effectively identified abnormal patterns associated with material degradation and environmental stress. Computer vision algorithms accurately detected surface cracks, erosion, and biological growth from captured images, reducing dependency on manual inspection. The predictive models forecasted potential deterioration trends, allowing maintenance teams to schedule preventive actions before severe damage occurred. Compared to conventional inspection-based methods, the proposed framework demonstrated faster detection rates, improved accuracy, and reduced response time, thereby minimizing restoration costs and risks.

Furthermore, the simulation capabilities of the Digital Twin enabled conservation experts to evaluate multiple restoration scenarios without physical intervention. Environmental simulations representing humidity fluctuations, pollution exposure, and structural load variations helped assess the long-term impact of external factors on the heritage asset. These virtual experiments provided valuable insights into structural behavior and supported informed decision-making. The use of interactive visualization tools and dashboards improved the interpretability of analytical results, allowing stakeholders to understand complex data more effectively and plan appropriate conservation strategies.

From an operational perspective, the integrated framework improved efficiency by automating data collection, analysis, and reporting processes. Continuous monitoring reduced the need for frequent manual surveys, while predictive maintenance minimized unexpected failures and emergency repairs. The system also supported digital documentation and virtual accessibility, enabling researchers, historians, and visitors to explore the heritage site remotely. However, the results also indicated certain practical challenges, including high initial setup costs, large data storage requirements, and the need for technical expertise to manage AI and IoT components. Despite these limitations, the overall performance demonstrated that the benefits of the proposed approach outweigh the constraints, particularly for long-term and large-scale conservation projects.

Overall, the findings confirm that the synergy between Digital Twin technology, AI-driven analytics, and IoT-based sensing provides a reliable, accurate, and proactive solution for heritage conservation. The proposed system not only enhances structural health monitoring and predictive maintenance but also transforms traditional reactive restoration practices into intelligent, data-driven preservation strategies. These results validate the effectiveness of the framework and highlight its potential for broader adoption in sustainable cultural heritage management.

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