Intelligent Federated Digital Twin for Cultural Heritage: Collaborative Preservation and Visitor Experience

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***Abstract*—This paper proposes an Intelligent Federated Digital Twin framework to enhance the management, preservation, and visitor experience across distributed cultural heritage museums. Leveraging federated learning and digital twin technologies, the proposed framework allows geographically distributed institutions to collaboratively train AI models for predictive maintenance, visitor behavior analytics, and emergency response simulations, while preserving data sovereignty. This approach enables real-time monitoring, adaptive services, and coordinated conservation strategies without compromising the privacy of sensitive heritage data. A use case involving the two museums demonstrates the system's capability to dynamically adapt to visitor flow and environmental conditions. The framework is scalable and can be extended across multiple institutions to strengthen sustainable cultural heritage management in smart cities.**

***Index Terms*—Federated Digital Twin, Cultural Heritage, Smart Museums, Federated Learning, Visitor Experience, Real-Time Monitoring, Preservation**

I. Introduction

Cultural heritage preservation has become an increasingly important challenge in a rapidly evolving digital age. Museums, galleries, and archaeological sites act as custodians of a nation's historical and cultural wealth [1]. However, they face increasing pressures to preserve artifacts and monuments while also providing engaging and adaptive experiences for visitors. Traditional preservation methods, while valuable, often lack the precision and foresight offered by emerging technologies like Digital Twins (DTs) [2]. A Digital Twin is a digital replica of a physical asset, system, or environment, which allows real-time monitoring and simulation of physical conditions to predict and mitigate risks [3]. While the application of DTs in cultural heritage is a promising direction, most implementations have been centralized, with individual museums or heritage sites developing isolated systems [4]. This limits the scalability, collaborative potential, and cross-institutional insights that could be gained from combining data across multiple sites. As cultural institutions increasingly become part of smart cities, there is a need for systems that enable shared intelligence without compromising data privacy. Federated Digital Twin (FDT) technology, which allows decentralized data processing while preserving local data autonomy, can address these challenges [5], [6]. In the context of cultural heritage, a Federated Digital Twin (FDT) system enables multiple institutions to collaborate on shared tasks, such as predictive maintenance, visitor behavior analysis, and emergency response planning, without transferring sensitive data to a central location. This paper proposes an Intelligent Federated Digital Twin (IFDT) framework designed to support collaborative cultural heritage preservation and adaptive visitor experiences across distributed museums. The IFDT framework integrates AI-driven predictive analytics and federated learning to optimize operations and enhance the preservation of artifacts and monuments in real time. By enabling local digital twins to collaborate on a federated platform, museums can dynamically adjust to environmental changes, visitor flow, and maintenance needs, improving both the efficiency of preservation efforts and the quality of visitor engagement.

A. Contributions

The primary contribution of this paper is the introduction of a novel Intelligent Federated Digital Twin (IFDT) framework tailored to the unique needs of cultural heritage institutions. The IFDT framework offers several key innovations that can significantly transform how museums manage their collections and interact with visitors:

1) Federated Learning for Preservation: Enables museums to collaboratively improve models for artifact conservation and visitor behavior without sharing sensitive data.
2) Real-Time Visitor Optimization: Monitors crowd density and environmental conditions to personalize experiences, manage flow, and enhance safety.
3) Emergency Simulation: Simulates coordinated evacuation and disaster responses across museums, ensuring artifact and visitor safety.
4) Scalability for Smart Cities: Easily extends to multiple sites and smart city networks, fostering collaboration on heritage preservation and sustainability.

B. AI and Federated Digital Twin

The convergence of Artificial Intelligence (AI) and Federated Digital Twin (FDT) technologies offers a transformative approach for managing complex, distributed systems such as cultural heritage institutions. AI enhances the functionality of each digital twin by enabling intelligent analysis, anomaly detection, predictive maintenance, and real-time decision-making based on continuously collected sensor data. Federated Learning (FL), a subset of AI, allows decentralized digital twins deployed in different museums to collaboratively train shared machine learning models without exchanging raw data, thereby ensuring privacy, security, and compliance with data governance policies. This approach empowers institutions to benefit from collective intelligence while maintaining control over their local datasets. In the context of cultural heritage, AI-driven FDTs can optimize artifact preservation, adaptively manage visitor flows, and simulate emergency scenarios using predictive analytics. By combining AI and FDT, museums can transition from reactive to proactive management, leading to more resilient, efficient, and intelligent heritage conservation systems [5], [7].

II. Proposed Methodology

The proposed methodology for the Intelligent Federated Digital Twin (IFDT) framework integrates Digital Twin technology, Federated Learning, and Real-Time Analytics to address key challenges in cultural heritage institutions. It begins with a sensor-based data collection from each museum, capturing environmental conditions, visitor behavior, and artifact status. Edge processing ensures quick, localized insights. Using Federated Averaging, each museum trains models on local data while sharing only model updates, ensuring privacy and enabling collaborative predictive modeling for artifact preservation and visitor flow. Real-time monitoring allows adaptive responses, such as rerouting visitors, regulating environmental conditions, and simulating emergency evacuations. The performance of the system is evaluated through metrics such as artifact preservation rates, visitor satisfaction, and emergency response efficiency. Designed for scalability, the IFDT framework supports integration across multiple sites and into smart city ecosystems for improved cultural heritage management as illustrated in Figure 1.

III. Expected Outcomes

The Intelligent Federated Digital Twin (IFDT) framework is expected to deliver significant outcomes in cultural heritage preservation, visitor experience, and operational efficiency. It enhances artifact conservation through real-time monitoring and predictive analytics, enabling proactive responses to environmental threats. Visitor experiences are optimized through adaptive crowd management and personalized tours, improving engagement and accessibility. The framework strengthens emergency preparedness by simulating evacuations and guiding safe, efficient responses. Federated learning fosters secure collaboration among museums, improving shared models and strategies without compromising data privacy. Designed for scalability, the IFDT framework can integrate with smart city systems, supporting urban-wide cultural heritage management and coordinated emergency response.

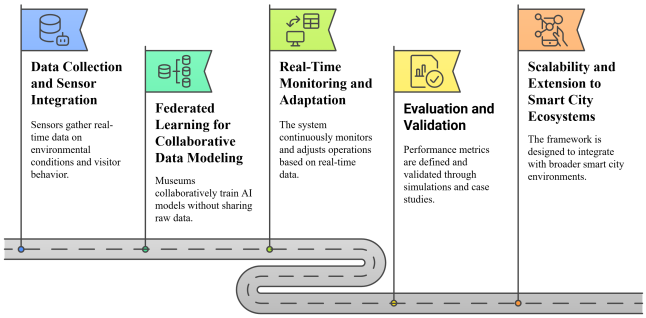

Fig. 1. Intelligent Federated Digital Twin Framework

IV. Conclusion

The proposed Intelligent Federated Digital Twin (IFDT) framework presents a transformative approach to cultural heritage preservation and visitor management. Using cutting-edge technologies such as federated learning and digital twin systems, this framework has the potential to revolutionize the way museums and heritage sites operate, ensuring that cultural treasures are preserved, visitors have engaging experiences, and safety protocols are optimized.

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