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Federated Digital Twins and XR for Cultural Heritage: A Collaborative Framework

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***Abstract* – Complex visitor flows, architectural constraints, and data privacy concerns increasingly challenge emergency evacuation planning in cultural heritage sites. This study presents a novel Federated Digital Twin framework integrated with Extended Reality technologies to enhance safety and coordination during emergencies across multiple museums. The federated digital twin leverages federated learning to enable decentralized, privacy-preserving simulation and decision-making without sharing sensitive visitor or infrastructure data. Extended Reality technologies provide immersive, real-time guidance for visitors, including adaptive evacuation routes and scenario-based drills. This approach facilitates cross-institutional collaboration, supports dynamic risk assessment, and ensures responsive evacuation strategies tailored to each museum's layout and visitor profile. By combining predictive modeling with real-time Extended Reality-assisted feedback, the framework improves evacuation efficiency, reduces bottlenecks, and improves general visitor safety during emergencies.**

keywords:-Federated Digital Twin (FDT), Cultural Heritage, Extended Reality (XR), Emergency Evacuation, Privacy-Preserving Simulation

I. INTRODUCTION

The digital transformation of cultural heritage reshapes how societies engage with, preserve, and interpret historical narratives and artifacts. Technologies such as Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), collectively known as Extended Reality (XR), have emerged as powerful tools for creating immersive and interactive experiences at museums and heritage sites. These tools improve visitor engagement through multisensory storytelling and provide remote and underserved audiences with unprecedented access to cultural resources [5, 6].

Despite these advances, several significant challenges remain. Many cultural institutions operate in technological and operational silos that lack interoperable systems that allow them to collaborate across locations while safeguarding sensitive data. Consequently, opportunities for intelligent, personalized, and real-time visitor experiences are often limited. Moreover, managing crowd flows, ensuring safety during emergencies, and optimizing artifact environmental conditions still rely heavily on static or manually updated systems, which lack the adaptability required for modern digital ecosystems [9].

Digital Twin (DT) technology presents a promising solution for addressing these challenges. DT is a dynamic digital representation of a physical system or asset that evolves based on real-time data and simulations. In the museum context, DTs can model and monitor visitor behavior, spatial dynamics, energy use, and emergency evacuation routes, enabling predictive analytics and operational efficiency [1, 13]. However, traditional DT implementations are often centralized, raising concerns about data governance, privacy, and scalability, particularly when applied across multiple institutions.

This study introduces the concept of **Federated Digital Twins (FDTs)** to enhance emergency evacuation management in cultural heritage sites. FDTs extend traditional digital twin models by incorporating federated learning decentralized approach that enables multiple museums and heritage institutions to collaboratively train AI models for evacuation optimization without sharing sensitive raw visitor or infrastructure data. This allows each site to maintain control over its digital assets and privacy while contributing to a shared, intelligent framework that learns from diverse evacuation scenarios and responses across locations [12, 2, 14]. The approach ensures institutional data sovereignty and privacy preservation while enabling improved, collective insights for adaptive, efficient, and safe evacuation strategies

At the user interface level, XR technologies provide real-time, immersive interactions with federated digital replicas to enhance emergency evacuation preparedness and response. Visitors receive adaptive, context-aware guidance through XR devices that simulate evacuation routes, alert to hazards, and offer step-by-step instructions tailored to dynamic conditions. Museum staff utilize operational dashboards that integrate predictive analytics on visitor flow, environmental risks, and evacuation readiness, enabling proactive decision-making. These dashboards are synchronized across institutions via federated learning, allowing coordinated emergency management without compromising sensitive data. This integrated FDT-XR framework addresses the critical need for resilient, intelligent evacuation systems in cultural heritage sites. It not only improves visitor safety and situational awareness during emergencies but also empowers institutions to collaboratively optimize evacuation strategies while maintaining full control over their data. This study proposes a novel methodology for distributed emergency evacuation management that supports sustainable, technology-enhanced cultural preservation and public safety.

II. RELATED WORK

The integration of advanced digital technologies into cultural heritage management has gained significant momentum in recent years. Digital Twins (DTs), defined as dynamic digital replicas of physical assets, have been extensively studied for their potential to monitor, simulate, and optimize cultural-heritage environments [1, 10]. For instance, Tao et al. [1, 15] presented an overview of DT applications in the industry, highlighting their adaptability to complex systems, which can be extended to heritage sites. However, most existing DT implementations operate in centralized environments, limiting their scalability and raising concerns regarding data privacy and institutional autonomy. Federated Learning (FL) has emerged as a promising solution to these challenges because it enables decentralized collaborative model training without sharing raw data [2]. This approach has been widely adopted in healthcare [3] and smart city applications [4, 10] where data privacy is paramount. Despite its advantages, FL remains underexplored in the context of cultural heritage, particularly for distributed Digital Twins that require cooperation among multiple institutions with diverse datasets and operational constraints [14].

Extended Reality (XR) technologies, including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), have demonstrated remarkable benefits in enhancing visitor engagement and accessibility to museums and archaeological sites. Bekele et al. [5] provide a comprehensive survey of XR applications in cultural heritage, emphasizing immersive storytelling and educational potential. Similarly, Anwar et al, [6] discussed how XR fosters co-creation and participatory experiences, expanding traditional museology. However, most XR systems rely on static content and lack real-time integration of operational data and adaptive visitor management.

Several recent studies have explored the intersection of DTs and XR in cultural heritage contexts. GarcÃa et al. [7] developed a DT-based VR platform for cultural site preservation that enables remote interaction with accurate 3D reconstructions. However, their model is limited to single-site applications and does not consider cross-institutional collaboration. In contrast, Chen et al. [8] proposed a cloud-based DT framework for museum environmental monitoring, but did not address privacy or federated learning mechanisms.

Furthermore, crowd management and emergency evacuation have become critical research areas within heritage sites, particularly considering the impact of tourism and safety regulations. Caliendo et al. [9] employed DTs to simulate pedestrian flows and optimize evacuation routes in museums, demonstrating improved safety outcomes. Integrating FL with these simulations can enhance predictive capabilities by leveraging data from multiple venues, as suggested by recent federated pedestrian modeling approaches [11].

In summary, while the literature demonstrates significant progress in Digital Twins (DTs), Federated Learning (FL), and Extended Reality (XR) individually, their integrated application in a federated digital twin framework for emergency evacuation in cultural heritage settings remains underexplored. This study addresses this gap by developing a secure, collaborative, and immersive platform that enables multiple cultural institutions to jointly simulate, analyze, and enhance emergency evacuation procedures. The proposed framework supports real-time coordination, privacy-preserving data sharing, and adaptive XR-assisted evacuation guidance, ensuring visitor safety while preserving institutional autonomy and data privacy.

III. FEDERATED DIGITAL TWIN AND XR FRAMEWORK FOR CULTURAL HERITAGE

The proposed framework introduces a comprehensive and adaptive architecture that combines Federated Digital Twins (FDT) with Extended Reality (XR) technologies to support the immersive, intelligent, and secure management of cultural heritage sites. This architecture is structured into four interdependent layers, each responsible for distinct yet interconnected functions that collectively support the digital transformation of physical museums into smart, collaborative, and interactive virtual ecosystems, as illustrated 1.

The foundational layer, known as the **Perception Layer**, serves as the sensory interface between the physical and digital realms. It incorporates a wide array of IoT-based devices, including temperature and humidity sensors, RFID and motion detectors, XR-enabled cameras, and visitor tracking systems. This layer continuously collects real-time data that characterizes environmental conditions and human activities within the museum spaces. Key parameters such as crowd density, visitor trajectories, exhibit interaction frequency, and ambient environmental variables are monitored and logged. These data streams are essential for situational awareness, allowing higher layers to adapt simulations and analytics to the evolving real-world context.

Built upon this is the **Local Digital Twin Layer**, which functions as the intelligent replica of individual museum entities. This layer hosts dynamic digital models representing physical assets, infrastructure, and human behaviors within the heritage space. Leveraging 3D modeling, XR visualization, and embedded simulation engines, it enables real-time replication and scenario testing. The local digital twins operate autonomously to interpret incoming sensory data, visualize operational states, and anticipate future behaviors through predictive analytics. These include modeling visitor movement patterns, identifying potential congestion zones, and computing evacuation routes under different emergency conditions. As each museum evolves, so too does its digital twin, forming a continuously synchronized cyber-physical mirror.

To ensure cross-institutional learning while preserving data sovereignty and privacy, the **Federated Learning Coordination Layer** acts as a secure, decentralized intelligence-sharing mechanism. Rather than pooling sensitive raw data from multiple sites, each digital twin trains its local machine learning model on its own data. Periodically, only the learned model parameters are transmitted to a global aggregator, which synthesizes a federated model. This global model is then shared back to each site, enriching their local intelligence with global insights. This layer ensures scalability, privacy compliance (e.g., GDPR), and equity in knowledge contribution and access, fostering a collaborative network of museums that learn from each other while respecting institutional boundaries. In museum environments, relevant data for federated learning includes real-time visitor trajectories, interaction heatmaps with exhibits, evacuation drill performance metrics, and environmental conditions (e.g., temperature, humidity). These data points are labeled according to event type, visitor demographics, and response times to support supervised learning in evacuation optimization models.

Finally, the **XR Interaction Layer** transforms the underlying intelligence and simulations into tangible user-facing experiences. Through immersive XR interfaces, such as augmented reality (AR) headsets, virtual reality (VR) tours, and haptic interaction devices, visitors can engage with dynamically updated virtual exhibits that reflect real-time environmental and behavioral data.For instance, during a fire drill, visitors can wear AR glasses that overlay evacuation arrows and hazard warnings in real-time based on their current location. In another scenario, VR headsets in staff training simulate panic-driven crowd movements, helping curators learn optimal intervention points. XR kiosks may also guide disabled visitors through tactile-based or audio-enhanced evacuation paths. Personalized tour paths can be generated based on user preferences and crowd dynamics, while curators gain tools for remotely managing exhibit conditions, guiding visitor flows, and simulating emergency response strategies. This layer not only enhances accessibility and inclusivity by offering remote and adaptive experiences but also democratizes cultural heritage by allowing global users to virtually explore and learn from historically significant spaces.

Collectively, this four-layer architecture introduces a novel approach to emergency evacuation in cultural heritage sites by integrating edge computing, federated AI, and Extended Reality (XR) into a unified framework. It establishes an adaptive infrastructure for real-time risk monitoring, predictive evacuation modeling, and immersive XR-assisted guidance for visitors and staff. The framework supports data-driven decentralized decision-making while enabling secure collaboration among multiple heritage institutions. By ensuring situational awareness, rapid response, and cross-institutional coordination during emergencies, this architecture represents a significant advancement toward building resilient, intelligent, and visitor-safe digital museum ecosystems.

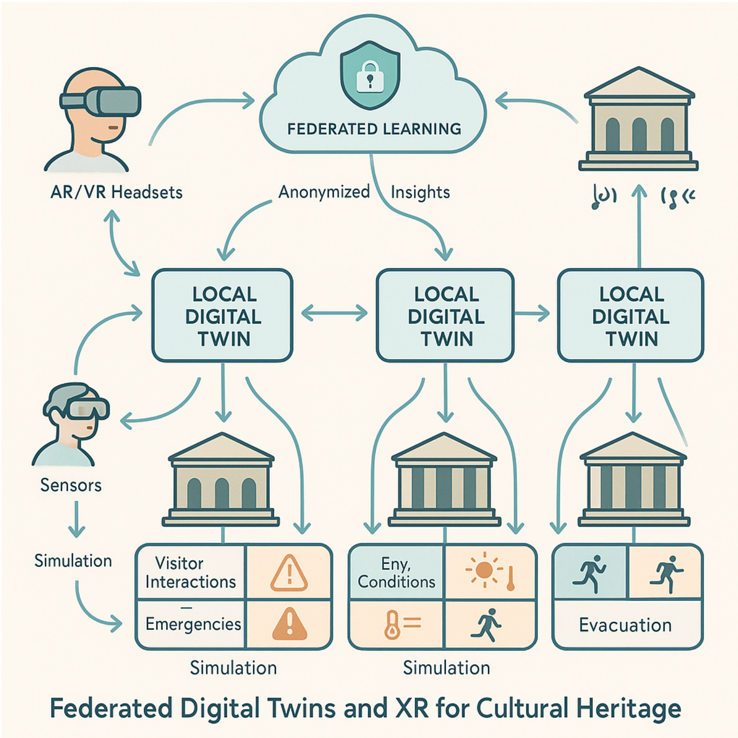

Fig. 1. Proposed Framework

IV. CONTRIBUTIONS

The proposed architecture is expected to yield several critical outcomes that advance the state of the art in emergency evacuation planning and management within cultural heritage institutions. First, it will provide a real-time digital mirror of physical museum environments through accurate and continuously synchronized digital twins, powered by IoT sensory data. These digital representations will enable institutions to monitor visitor density, detect risk conditions (e.g., smoke, fire, overcrowding), and simulate evacuation scenarios, thereby supporting rapid, informed decision-making during emergencies.

Second, the federated learning coordination mechanism will allow museums to collaboratively improve their evacuation models by sharing learned patterns and strategies, without exposing sensitive raw data. This ensures privacy, complies with international data protection laws, and supports scalable deployment across multi-site museum networks. As a result, the framework establishes a decentralized yet cohesive ecosystem for intelligent and coordinated emergency preparedness.

Moreover, the immersive XR interaction layer will enhance both visitor safety and staff preparedness. Visitors will benefit from real-time, context-aware evacuation guidance through wearable or mobile XR devices, while curators and emergency personnel can access predictive dashboards and simulation-based training. XR will also support remote emergency planning and scenario walkthroughs, enabling better coordination between geographically dispersed institutions. This approach promotes inclusive safety planning by accommodating vulnerable populations such as individuals with disabilities or limited mobility.

In general, the integration of digital twin technology, federated learning, and XR within a layered architecture offers a transformative solution for emergency evacuation in cultural heritage settings. It empowers museum staff and policymakers with real-time situational awareness, fosters secure and cooperative inter-museum risk mitigation strategies, and enhances visitor safety through immersive, intelligent interfaces. Beyond technical innovation, this framework has social and cultural importance: it redefines how institutions prepare for and respond to emergencies, ensuring the protection of both human life and valuable heritage assets. The anticipated outcomes of this research can inform disaster resilience policies, inspire further academic exploration, and serve as a model for safe, smart cultural infrastructure worldwide.

V. USE CASE SCENARIO

To illustrate the practical application of the proposed framework, consider a hypothetical collaboration among four museums **Museum A**, **Museum B**, **Museum C**, and **Museum D**âparticipating in a national smart heritage initiative aimed at improving emergency preparedness. These museums are geographically distributed and differ significantly in terms of architecture, visitor flow patterns, and technological infrastructure. While they all share a common goal of enhancing evacuation efficiency and visitor safety, concerns over data privacy and system interoperability prevent the use of a centralized solution. Instead, each institution implements the proposed *Federated Digital Twin (FDT)* and *Extended Reality (XR)* framework to collaboratively optimize emergency response while maintaining control over its local data.

Each museum deploys IoT sensors to collect real-time data on visitor movement, environmental conditions, and potential hazard indicators. This data feeds into a local digital twin that models the unique spatial and behavioral dynamics of the museum. For example, **Museum A**, located in a historic multi-level building, focuses on simulating congestion in narrow corridors and staircases. In contrast, **Museum B**, designed as a single-floor open gallery, emphasizes monitoring wide visitor dispersal and external evacuation paths. Each local system trains a machine learning model based on its specific conditions. Rather than sharing sensitive raw data, the museums exchange only model parameters through a federated learning mechanism. A central aggregator synthesizes these parameters into a shared evacuation model and redistributes the improved model back to each museum, enhancing local performance through collective insights.

To deliver these insights to both staff and visitors, the XR Interaction Layer is activated. During routine evacuation drills, **Museum C** equips visitors with AR glasses that project real-time evacuation arrows, alert icons, and contextual safety instructions tailored to their precise location and nearby crowd behavior. Meanwhile, staff at **Museum D** engage with VR-based training simulations that immerse them in realistic emergency scenarios, including fire, crowd panic, and mobility-impaired visitor support. These XR applications not only improve operational readiness but also promote inclusive safety planning by offering adaptive interfaces for diverse user needs.

This hypothetical scenario illustrates how the integration of FDT and XR technologies can enable multiple museums to enhance emergency preparedness while maintaining data sovereignty collaboratively. By supporting decentralized decision-making, immersive guidance, and federated intelligence, the framework offers a scalable and privacy-respecting approach to building resilient, smart cultural heritage environments.

VI. CONCLUSIONS AND FUTURE WORK

This paper introduced a novel framework that integrates Federated Digital Twins (FDT) with Extended Reality (XR) technologies to improve emergency evacuation management in cultural heritage institutions. The proposed architecture leverages decentralized learning, real-time simulation, and immersive interfaces to enhance visitor safety, institutional coordination, and privacy-preserving decision-making. Through a four-layer designâcomprising the perception, local digital twin, federated learning coordination, and XR interaction layersâthe system supports adaptive evacuation strategies while maintaining data sovereignty across institutions.

A hypothetical use case involving four distinct museums demonstrated how the framework can be applied in practice. Each museum benefits from collective intelligence without exposing sensitive data, while XR tools enhance the situational awareness of both visitors and staff. The integration of predictive analytics and immersive technologies contributes to a resilient and intelligent cultural heritage ecosystem that supports real-time risk assessment and inclusive safety planning.

Future work will focus on the real-world implementation and validation of the proposed framework in active museum environments. This includes developing lightweight XR applications for mobile and wearable devices, integrating the system with national emergency response infrastructures, and conducting performance evaluations using simulation platforms such as AnyLogic. In addition, advanced machine learning methodsâsuch as reinforcement learning and transfer learningâwill be explored to further enhance the adaptability and accuracy of evacuation modeling. Long-term goals include expanding the framework to support broader smart city contexts and informing policy development for digital heritage risk management and emergency preparedness.

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