Heritage Science

RESEARCH

Open Access

Archaeometa: leveraging blockchain for secure and scalable virtual museums in the metaverse

Omer Aziz[1*], Muhammad Shoaib Farooq[1†], Adel khelifi[2†] and Mahdia Shoaib[1†]

Abstract

The rapid evolution of the digital landscape has catalyzed the integration of blockchain technology within the domain of cultural heritage, particularly in virtual museums within the Metaverse. This study introduces ArchaeoMeta, a novel framework designed to leverage blockchain technology to enhance security, authenticity, and visitor interaction in a virtual museum environment. Utilizing smart contracts deployed on the Ethereum Sepolia testnet, the framework manages visitor interactions and secures digital artifacts, addressing challenges associated with scalability and user experience under varying loads. The performance evaluation involved simulating user interactions, scaling up to ten thousand concurrent users, to assess the impact on transaction latency, gas usage, and blockchain size. Findings reveal significant scalability challenges, as transaction latency and blockchain size increased with the number of users, highlighting areas for optimization in managing high user traffic within the blockchain infrastructure. This study contributes to the understanding of blockchain applications in cultural heritage, suggesting that while ArchaeoMeta offers a robust platform for virtual museums, enhancements in scalability through layer-2 solutions or alternative blockchain platforms are essential for its practical implementation. The framework sets a precedent for future research in the convergence of blockchain technology and cultural heritage preservation, promising a transformative impact on how digital cultural experiences are curated and consumed.

Keywords Virtual museums, Virtual reality (VR) , Augmented reality (AR), Digital transformation, Cultural heritage, Blockchain in museums, Extended reality (XR), Neurodiversity, Digital accessibility, Immersive technologies

Introduction

Museums are institutions that collect, preserve, and display cultural, historical, artistic, and scientific artifacts and specimens for public education and enjoyment. They play a pivotal role in conserving and presenting the diversity of human accomplishments and natural wonders. Museums often facilitate educational and research opportunities, enabling the public to engage with and appreciate the richness of human culture and the natural world. Serving as invaluable repositories of history, they provide insights into ancient civilizations, lifestyles, and cultural evolutions [1]. Through exhibits and artifacts, museums vividly illustrate how people lived across different eras, showcasing technological advancements, artistic achievements, and historical events. Visitors and

†Muhammad Shoaib Farooq and Adel khelifi have contributed equally to this work.

*Correspondence:
Omer Aziz
F2018288006@umt.edu.pk
[1] Department of Computer Science, University of Management and Technology, Lahore 54770, Punjab, Pakistan
[2] Department of Computer & IT, Abu Dhabi University, Zayed City 59911, Abu Dhabi, United Arab Emirates

students gain tangible connections to history, deepening their understanding of their cultural heritage. By exploring museum collections, people engage in experiential learning, grasp historical contexts, and develop an appreciation for the multifaceted aspects of human civilization, thereby reinforcing museums as dynamic educational tools that enrich our understanding of history and foster a lifelong respect for our shared heritage [2].

The term Metaverse refers to a collective of fully immersive digital environments where users interact through 3D avatars [3]. Characterized by sociality, multitechnology convergence, and hyper-spatio-temporality, the Metaverse employs major technologies such as Artificial Intelligence, Augmented Reality, Virtual Reality, Mixed Reality, Blockchain, Edge Computing, Networking, and the Internet of Things [4]. The term gained prominence when Facebook's CEO rebranded the company as Meta. In this virtual space, users engage in a myriad of activities including socializing, connecting, learning, working, shopping, playing, and more [5]. Users can also purchase property or assets within the virtual world. Metaverse applications are increasingly popular across various domains such as education, gaming, shopping, industrial practices, concerts, and amusement parks.

The decline in interest and attendance among younger generations in traditional museums is primarily due to their growing use of digital devices and social media platforms. Accustomed to digital experiences, this generation may find traditional museums less appealing. Moreover, traditional museum collections are often scattered, requiring specific times and spaces for exhibitions [6]. The gradual decline in museum attendance reflects shifting leisure preferences, a trend that predates the COVID-19 pandemic but was exacerbated by it, leading to prolonged closures of museums. This shift pushed people further into digital spaces, prompting institutions to explore innovative methods such as augmented reality and interactive exhibits to create immersive and engaging experiences that resonate with visitors' interests. A control group was established to analyze the performance of the digital museum setup. Two museums were selected for comparison: Museum-A, which uses a traditional display mode, and Museum-B, which employs a digital display. The study compared outcomes across four dimensions: interactive comparison, entertainment comparison, experience comparison, and content richness comparison. Results indicated that the digital museum outperformed the traditional museum in each aspect.

Metaverse Museums, like their traditional counterparts, utilize modern digital technologies to present history, culture, and art in immersive ways. They are crucial for engaging a generation that increasingly favors digital spaces over traditional learning methods. Metaverse Museums are globally accessible, breaking geographical barriers and allowing worldwide exploration of collections. They prioritize visitor participation and interaction, facilitating collaboration on projects and participation in virtual events and lectures. These digital venues also contribute to the preservation of cultural heritage, ensuring accessibility for future generations and promoting long-term cultural sustainability by mitigating risks associated with physical decay or destruction.

The declining interest and reduced attendance among the younger generation in traditional museums pose a significant challenge. This trend, compounded by an increased focus on social apps and digital devices, diminishes the appeal of cultural institutions. The situation worsened during the COVID-19 pandemic with the enforced closure of museums. Addressing this disengagement and finding effective strategies to attract and retain younger visitors through the incorporation of innovative technologies and the creation of compelling, immersive experiences is imperative. This study addresses the following research questions:

- How can blockchain technology enhance the security and authenticity of digital artifacts in virtual museums?
- What are the scalability challenges of deploying a blockchain-based virtual museum framework?
- How do transaction latency and gas costs impact user experience in a high-traffic virtual museum environment?

This article introduces a novel framework ArchaeoMeta, an innovative framework that utilizes blockchain technology to boost security, authenticity, and visitor engagement in virtual museum settings. Implemented on the Ethereum testnet, ArchaeoMeta employs smart contracts to regulate visitor interactions and secure digital artifacts, targeting scalability and user experience challenges across various loads. The performance evaluation involved simulating user interactions with up to ten thousand concurrent users to analyze the effects on transaction latency, gas consumption, and blockchain size expansion. Results indicated pronounced scalability issues as both transaction delays and blockchain size expanded with user increases, underscoring the need for optimization in handling substantial user traffic on the blockchain infrastructure. This study enriches the discourse on applying blockchain in cultural heritage, indicating that while ArchaeoMeta provides a solid foundation for virtual museums, scalability improvements through layer-2 solutions or alternative blockchain platforms are crucial for its effective deployment. The

framework pioneers ongoing research at the intersection of blockchain technology and cultural heritage preservation, heralding a significant shift in how digital cultural experiences are designed and engaged with. The key contributions of this paper are:

- Introduction of the ArchaeoMeta framework for virtual museums.
- Deployment of the framework on the Ethereum Sepolia testnet.[1]
- Performance evaluation under varying loads, highlighting scalability challenges.
- Recommendations for future enhancements using layer-2 solutions.

The paper is structured into five sections, each contributing to the exploration of digital reconstruction and virtual reality for cultural heritage preservation. Section "Introduction" introduces the research, underscoring its significance and outlining its objectives. Section "Literature review" presents a comprehensive review of existing literature, setting the stage for the study. Section "Proposed framework" describes the proposed framework, detailing the methodologies chosen for digital reconstruction and virtual reality development. Section "Implementation and Deployment" presents the research results, showcasing findings derived from the framework's application. Finally, Section "Evaluation" offers a summary, discussing key findings, their implications, and suggesting future research directions. References are meticulously cited throughout the paper to ensure proper attribution.

Literature review

This section provides a detailed overview of all selected papers. The selected articles were thoroughly researched to assess their relevance and contributions. It begins by discussing the search results obtained through the defined search string. The section then addresses the evaluation scores assigned to the selected papers. Finally, it offers comprehensive discussions aimed at analyzing the findings and integrating key insights from the literature.

The related research in the field of Metaverse museums or Digital Museums encompasses a broad array of strategies and implementations. Some studies focus on theoretical frameworks, while others concentrate on practical design considerations for virtual spaces. Our review utilizes information from multiple research articles to better understand and develop Metaverse museums. Examples of Metaverse museums examined in this paper include the Louvre in Virtual Reality, the Museum of Other Realities, and the British Museum in Augmented Reality. VR Visionaries: Exhibition Hall of Contemporary Art, Los Angeles, also provides unique experiences and insights for our study of the evolving landscape of virtual cultural institutions.

Museums are embracing the digital era, a transformation accelerated by the impact of COVID-19. Museums currently offer virtual events like tours and lectures on their websites, but they have not yet constructed a complete museum in Virtual Reality or the Metaverse. The shift from real to digital could be cost-effective, eliminating expenses for labels, text on walls, and reducing the need for visitors to crowd close to artworks to read physical communication. Since the pandemic, individual screen time has increased, with smart devices becoming a major part of people's lives. The Metaverse offers fresh opportunities for museums to reach a broader and more diverse audience. The alignment of real and virtual aspects of museums can enhance the visitor's experience, reducing the historical separation and inequality between museums and visitors [7].

The use of technology to modernize culture and heritage spaces is gaining attention and popularity. The field of museology is undergoing changes due to advancements in digital technology, with immersive exhibitions becoming particularly popular. Web 3.0 is more advanced and creates challenges for the museum community. Virtual spaces allow users to socialize, build their own structures, and even create buildings, such as museums. This paper [8] explores the potential of 3D environments in museums, emphasizing how they offer a more immersive and social experience compared to the conventional web. It also discusses examples of cultural institutions thriving in these virtual spaces.

In this paper [9], a virtual platform is designed for the Chime Bells of Marquis Yi of Zeng, one of China's most treasured cultural heritage sites. The Chime Bells are available for tourists to view only from a distance; they are not allowed to touch or manipulate the chime bells and other exhibits in any manner while viewing. The paper creates an engaging and instructive museum environment in which visitors can fully immerse in the real hall of Chime Bells and even create music by ringing the bells. Laser scanning techniques are employed to visualize the Chime Bells of Marquis Yi of Zeng and all other displays. 3D models are constructed and optimized using the PBR (Physically Based Rendering) workflow. Utilizing LOD (Level of Detail) for specific elements ensures consistent detail while minimizing rendering costs. A roaming system for scenes is

[1] The Ethereum Sepolia testnet is a testing environment that allows developers to deploy and test smart contracts without the costs associated with the main Ethereum network.

implemented, facilitating user interaction with exhibits for multimedia information and enhancing overall interactivity and orientation. A multiplayer mode is also provided to encourage multiple visitors to communicate and share their experiences.

The Metaverse, viewed as the internet's next evolution, provides an open virtual shared environment. It's the perfect platform for showcasing virtual realities, bridging the gap between the actual and virtual worlds, and offering immersive experiences that transcend time and place. This study [10] focuses on the digitization, reconstruction, and virtual reality development of Meret-Neith's tomb in Umm El Qa'ab, the First Dynasty King's cemetery in Abydos, Egypt. The tomb is precisely digitally recreated using photogrammetry. In light of the current digital revolution, the study investigates the use of virtual reality to convey important historical events and remote examples of ancient architecture. The aim is to fully immerse guests in a virtual environment, giving them the opportunity to actively participate and form opinions by taking on the role of characters in the historical setting. The study focuses on the rebuilding of early dynastic Egyptian archaeological sites; Queen Meret-Neith's tomb in Umm el Qa'ab, which dates to 2950 BC, serves as an example. Remote architectural and cultural heritage that has been digitized makes previously inaccessible places virtually accessible. Virtual exhibitions have the power to transform the way that cultural heritage is experienced and communicated in the realms of education and entertainment by fostering emotional bonds between viewers and the artifacts on display [11].

In this paper [12], the authors propose ArtVerse, a novel human–machine collaborative creation paradigm for art in the Metaverse. The system utilizes machines to perform creation, exploration, and evaluation, assuming the human role within the artistic process. It establishes a decentralized art organization within the Metaverse comprising Human Painters, Digital Painters, and Robotic Painters. Human Painters provide training to machines, while Robotic and Digital painters collaborate as a unified machine entity. NFTs are employed to secure users' assets, like artwork, and track the steps involved in the creation of masterpieces. They also designed a group for digital painters to mimic the social collaboration seen among human painters. This adds a social aspect to the artistic platform. Participants can work together on art projects by sharing their painting knowledge and models, and they also vote on painting experiments. To secure these collaborations, they used Smart contracts (Table 1).

Navarrete Trilce [16] integrated digital technology with heritage museums, allowing cultural heritage to be shared digitally. This approach aims to attract more people to engage in cultural tourism while enhancing the transmission of cultural heritage.

CyArk, a non-profit organization, is committed to the widespread dissemination of cultural heritage through digital channels. Their mission aims to connect diverse audiences with heritage by leveraging digital documentation and creating immersive experiences across web, mobile, and other platforms. This initiative is designed to spark reflection, conversation, and imagination. As part of their Resonant project, CyArk has developed a remarkable virtual reality (VR) experience centered around the Balcony House at Mesa Verde National Park. This virtual reconstruction, achieved through advanced techniques like photogrammetry and LIDAR, offers a unique opportunity for users to engage deeply with the narratives embedded within the historical site. By navigating the digital replica of Balcony House, users interact with a virtual notebook and a walkie-talkie, exploring various narratives and completing missions. This immersive journey allows individuals to traverse the reconstructed structure, connecting with stories that span time and cultures, thereby providing a captivating and educational experience [22].

Mason Marco [23] created a digital museum using 3D display technology, which offers more interaction with visitors compared to traditional museums. Visitors can experience 3D animation elements in this 3D-based digital museum. Extended reality (XR) and virtual museums (VM) have been adopted by museums over the past two decades to support neurodiverse populations and meet varying generational expectations while focusing on community engagement and inclusivity. Initially, XR technologies enhanced exhibits in physical museums for educational purposes, but soon expanded to entire virtual museums and room-sized environments. It is now increasingly common for museums and UNESCO World Heritage Sites to feature digital twins. These virtual experiences assist neurodiverse visitors in preparing for their physical visits. This chapter explores how XR experiences and existing methods such as social stories and sensory maps can support neurodiverse visitors and their families both before and during museum visits [24]. Techniques such as digital storytelling, sensory maps, and adaptive extended reality (XR) reach individuals with autism, ADHD, ADD, and other cognitive challenges. The proposed "story map" combines these elements into a personalized, narrative-driven digital expression of museum collections, offering support prior to the visit. Additionally, head-mounted displays (HMDs) and virtual reality (VR), which minimize external distractions and are particularly beneficial for those with stimuli sensitivity, allow individuals with sensory processing disorders to navigate the museum environment more comfortably, enhancing

Table 1 Comparison between literature review and our work

Study	Year	Domain	Blockchain	Augmented reality	Artificial intelligence	NFT	Virtual reality	Mixed reality	Photogrammetry	Metaverse museum
[4]	2023	Museums and the Metaverse: Emerging Technologies for Enhanced Inclusivity and Engagement	x	x	x	x	x	✓	x	x
[7]	2023	Museums in the Metaverse: Emerging Trends in Computational Art and Life	✓	x	x	✓	x	x	x	x
[8]	2022	Museums in the Digital Era	✓	✓	✓	x	✓	x	x	x
[9]	2022	Digital Showcase of the Chime Bells of Marquis Yi of Zeng	x	✓	x	x	✓	✓	x	x
[10]	2018	Techniques for Reconstructing Cultural Heritage	x	✓	x	x	✓	✓	x	x
[11]	2022	Digital Recreation of Meret-Neith's Tomb	x	✓	x	x	✓	x	x	x
[12]	2023	Art Verse	✓	✓	x	✓	x	x	x	x
[13]	2020	Creation and Implementation of a Mixed Reality Spatial Tour Guide for the Egyptian Museum	x	✓	x		x	✓	x	x
[14]	2023	3D Reconstruction of Historical Buildings for Virtual Reality Documentation	x	x	x	x	✓	✓	x	x
[15]	2017	Qingdao Agricultural University: Calligraphy and Art Museum	x	x	x	x	✓	x	x	x
[16]	2019	Review of the Evolution of Virtual Museums	x	x	x	x	x	x	x	✓
[17]	2018	Tomb of Sultan Husayn Shah	x	✓	x	x	✓	x	✓	x
[18]	2020	Educational Content Museum	x	✓	x	x	x	x	x	x
[19, 20] , [21]	2020, 2021, 2023	Techniques for Reconstructing Cultural Heritage	x	✓	x	x	✓	✓	x	x
[22]	2020	Balcony House at Mesa Verde National Park	x	x	x	x	✓	x	✓	x
[23–26]	2020, 2021, 2022, 2023	Next Generation Museum: A Metaverse Journey into Culture	x	✓	✓	x	✓	x	x	x
This Study	2024	Revitalizing Heritage: The Metaverse Museum Experience	✓	✓	✓	✓	✓	✓	✓	✓

focus and attention span. Zollo Lamberto [25] enhances traditional museums with digital innovation and virtual environments by integrating internet communication technology, aiming to boost the museums' competitive edge and appeal to tourists. Article [26] analyzes the MetaSea pilot project, which aims to create a marine museum to enhance the educational and entertainment aspects of underwater archaeological heritage. This study targets Generation Z, individuals born between 1996 and 2010, noted for their extensive use of social media. The authors discuss the digital transformation of museums, aimed at making them more appealing to culture enthusiasts by enhancing visitor experience, engagement, and profitability. Technologies such as artificial intelligence personalize visitor experiences, while edge computing transforms raw data into valuable insights. Virtual reality creates immersive environments, and augmented reality overlays digital elements onto the real environment, enhancing interaction and engagement in museums. The MetaSea project seeks to improve enjoyment of underwater archaeological areas, preserve artifacts of underwater origin, study marine organisms and biodiversity, and facilitate the enjoyment of underwater archaeological sites through virtual reality and underwater communication, leveraging the 5 G network for safety and accessibility.

As shown in Table 1, The novelty of our proposed framework ArchaeoMeta lies in its holistic approach. Where individual papers have examined components such as 3D visualization, interactive platforms, or digital curation, ArchaeoMeta synthesizes these into a unified framework. It embodies a comprehensive strategy that begins with user interface optimization, extends through application and integration modules designed for immersive content interaction, and culminates in a museum showcase that leverages advanced rendering techniques. Crucially, ArchaeoMeta extends the narrative by incorporating governing bodies within its ecosystem, ensuring that virtual spaces adhere to curatorial and ethical standards akin to their physical counterparts. The inclusion of smart contracts for artifact security marks a pioneering step towards integrating Web 3.0 technologies with cultural dissemination, offering a forward-thinking approach to museum design and management.

Results

Proposed framework

The ArchaeoMeta is our novel framework that is designed to serve as a bridge between traditional museum experiences and the boundless possibilities of the metaverse. It is a pioneering effort to encapsulate the essence of physical artifacts within their digital twins, ensuring that each virtual replica retains the cultural significance and educational value of its real-world counterpart. As visitors navigate the space using their avatars, they are not merely passive viewers but active participants in a cultural dialogue that transcends physical boundaries. The guide avatars, potentially leveraging AI, provide contextual storytelling, enriching the visitor's journey through personalized interactions. These narratives are carefully crafted by archaeologists and museum experts to ignite curiosity and deepen understanding, embodying the museum's educational mission. Behind the scenes, governing bodies employ sophisticated data analytics to monitor visitor engagement, adjusting exhibits in real-time to heighten interest and desire. This iterative loop creates a responsive and adaptive environment, one that evolves with its audience. By intertwining the immersive capabilities of virtual reality with the strategic engagement model of AIDA, "ArchaeoMeta" promises not only to preserve the past through technological innovation but also to redefine the museum experience for future generations. ArchaeoMeta framwork has been presented in Fig. 1.

The Fig. 1 illustrates the conceptual flow of a virtual museum novel framework named as ArchaeoMeta, underpinned by the AIDA (Attention, Interest, Desire, Action) model. At the core, archaeologists play a pivotal role, designing digital replicas of artifacts that are then showcased within the museum. These replicas are managed digitally, suggesting a dynamic and interactive exhibit space. Visitors interact with the museum through avatars, indicating an immersive virtual experience where they can tour the museum space. Governing bodies oversee museum management, ensuring that the operations align with institutional objectives and cultural mandates. The guide avatars function as intermediaries, possibly providing information and enhancing the visitors' experience. This virtual cycle emphasizes collaboration, digital curation, and an engaging learning environment facilitated by advanced technologies in the metaverse.

Layered architecture

Presenting the Metaverse Museum project's framework, a six-layered architecture that has been painstakingly created to improve the administration and visitor experience within the metaverse museum. The names of these levels are shown in Fig. 2, and each is essential to the operation of the project. The overall functionality and interactions of the major parts are depicted in Fig. 2, which clarifies the complex relationships that support the museum's smooth operation. In our project, we will be utilizing blockchain smart contracts to enhance the security of our artifacts. Layered Architecture of Metaverse Museum The 6-layred architecture of ArchaeoMeta has been presented in Fig. 2.

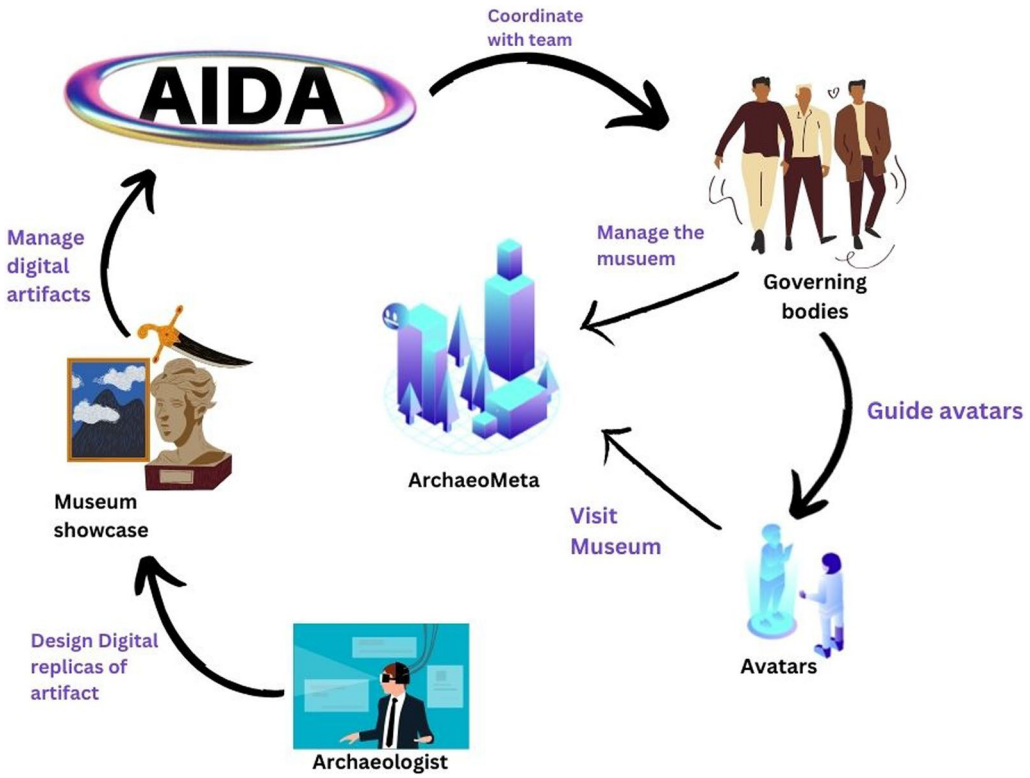

Fig. 1 Archaeometa: A novel Proposed framework in a Virtual Museum within the Metaverse

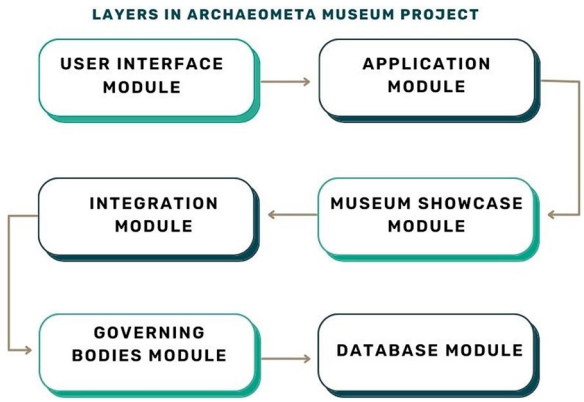

Fig. 2 The ArchaoMeta Framework: A Six-Layered Architecture for the Metaverse Museum, Enhancing Administration and Visitor Interactions through Blockchain Technology

User Interface Module In this case, the User Interface Module provides an easy-to-use portal for users to engage with the Metaverse museum in the metaverse. The immersive museum experience is enhanced by augmented reality (AR) and virtual reality (VR) technology, which users interact with through avatars to connect them deeply to the digital universe. This module allows avatars to operate as a link between real users and the fascinating world of digital artifacts. It also includes a permissions check, so users, especially those without bought digital tickets, can enter the museum safely and easily.

Application Module In the Metaverse museum, the Application Module serves as the central operational center, supervising essential functions. It effectively controls user interactions inside the museum, guaranteeing avatars visiting the digital artifacts a smooth and enjoyable experience. In order to guide avatars, the module also acts as a communication link between them and Governing Bodies. In addition, it works closely with AIDA to coordinate the design and production of digital artifacts, which adds to the dynamic content of the museum exhibit.

Integration Module Key components of the metaverse museum project are connected by the Integration Module, which serves as an essential connection. It acts as the channel for smooth communication between the Governing Bodies Module and the Archaeologist Module. Furthermore, this module is essential for collaborating with regulatory agencies in order to oversee projects and guarantee that archaeological

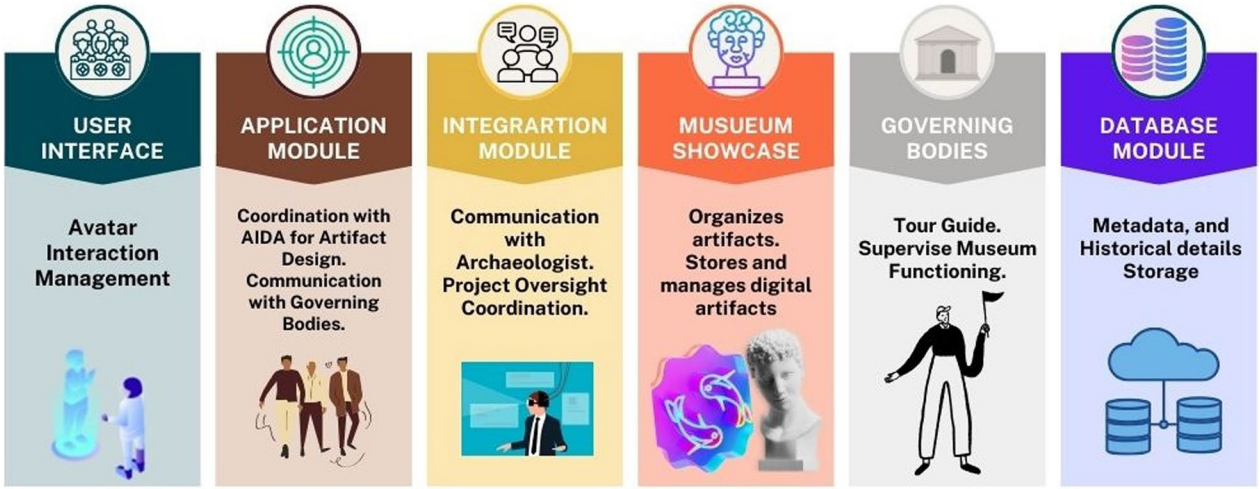

Fig. 3 The Stratified Architecture of the Metaverse Museum: An Overview of the Six Integrated Layers Enabling Interactive Experiences and Secure Artifact Management

advancements follow rules and regulations. This module effectively integrates the creative endeavors of archaeologists with the strategic vision set forth by the governing bodies, promoting peace and collaboration.

Museum Showcase Module The digital repository that houses the metaverse museum's central exhibit is called the Museum Showcase Module. It functions as an all-inclusive storage facility, carefully organizing the enormous collection of digital artifacts that archaeologists have painstakingly created. In order to create a structured and engaging setting for avatars to explore and enjoy the rich history displayed in the metaverse, this module organizes these objects into the museum showcase. In order to guarantee the caliber and consistency of the objects on display, the module also includes a Showcase Evaluation point when the showcase is created, improving the entire experience for visitors to the metaverse museum.

Governing Bodies Module A variety of tasks are taken on by the Governing Bodies Module to provide the best possible operation and user experience in the virtual museum. It directs avatars through the museum's exploration, manages its general operation, and sets rules to promote a good atmosphere. Furthermore, this module adds strong security and privacy supervision to its list of duties. It works with the Networking Infrastructure layer to implement secure communication protocols, actively monitors and enforces security measures, and creates ethical guidelines to prevent misconduct. All of these measures work together to protect the safety, privacy, and ethical integrity of avatars as they travel through the metaverse museum.

Database Module The core repository of the metaverse museum's infrastructure is the Database Module. It is committed to preserving data about digital artifacts and painstakingly records metadata, historical information, and classification for every item. This module makes sure that the storage system is well-organized and structured, which makes it easier to maintain and retrieve important data efficiently. This improves the user experience as the avatar explores the virtual museum.

The hierarchical structure

The Layered Design of the Metaverse Museum: Exploring the Six Essential Layers for Enhanced Visitor Interaction and Protective Artifact Stewardship as described in Fig. 3. The six-layered architecture depicted in the diagram provides a robust foundation for the Metaverse Museum, facilitating an enriched, interactive, and educational experience for visitors. The first layer, the User Interface, is centered around Avatar Interaction Management, allowing visitors to navigate the museum's digital space as avatars, offering an immersive tour unlike any physical counterpart. This layer is crucial for creating first impressions and ensuring ease of access, which in turn fosters greater engagement with the museum's offerings.

Moving deeper, the Application Module works in tandem with AIDA principles to ensure that each artifact's presentation captures the visitor's attention, maintains interest, and stimulates a desire to learn, eventually leading to meaningful interactions with the exhibit. The Integration Module serves as the communication hub, streamlining collaboration between the archaeologists responsible for content authenticity and the overarching project management team to ensure seamless operations.

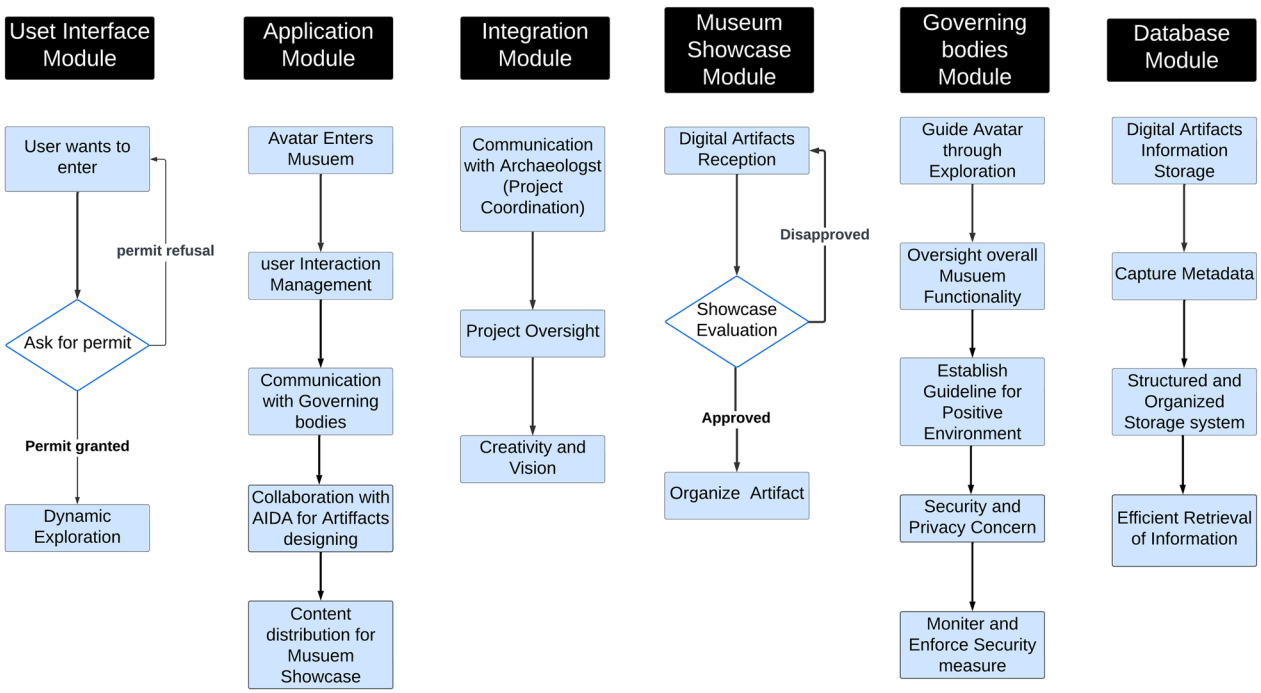

Fig. 4 Process Flow of the Interactive and Operational Dynamics of the Six Layered of ArchaoMeta Framework of Virtual Museum Experience

The Museum Showcase layer is where the artifacts come to life; it's designed to store and manage digital representations of artifacts, presenting them in thematic, educational, and storytelling formats that resonate with a diverse audience.

Governing Bodies oversee the entire operation, analogous to a tour guide's role in a traditional museum, providing supervision, direction, and quality assurance to maintain the museum's integrity. Lastly, the Database Module forms the bedrock of the museum, a repository where metadata and historical details of each artifact are securely stored and managed. This layer employs blockchain technology to not only secure data but also to authenticate the provenance of each digital artifact, ensuring that the cultural heritage is preserved and protected for future generations to appreciate and learn from within this virtual domain.

As these layers interact seamlessly, they enable effective communication and coordination among stakeholders. The architecture ensures optimal operation, a positive user experience, and data transparency within the virtual museum. To further illustrate the project's intricacies, a comprehensive data flow diagram for each module will be presented, showcasing the smooth interaction and flow of information across the various layers of the $Metaverse_{M}useum$ framework.

Process flow

The process flow diagram provided showcases a comprehensive six-module framework designed to deliver a seamless virtual museum experience. Figure 4 has presented the Operational Workflow of the Virtual Museum with a detailed representation of the six interlinked layers governing user access and artifact management.

At the commencement of this experience lies the User Interface Module, where the user's journey begins by requesting entry. Depending on whether access is granted, the user-through their avatar embarks on a dynamic exploration path within the museum, or faces

a permit refusal, indicating a robust permission system ensuring controlled access and interaction as explained in 1.

Algorithm 1 User Interface Module Smart Contract

```
procedure requestAccess
    Implementation of access request logic
end procedure

procedure grantAccess(userAddress)
    Only callable by admin or via specific logic
    users[userAddress].hasAccess = true
    emit AccessGranted(userAddress)
end procedure
```

The Application Module captures the essence of visitor engagement, managing the avatars' interactions within the museum and facilitating the communication of these experiences with the governing bodies. This module works closely with the AIDA model to design artifacts that captivate visitors, emphasizing the importance of strategically curated content that resonates with the audience as explained in 2.

Algorithm 2 Application Module Smart Contract

```
procedure logInteraction(action)
    emit AvatarInteraction(msg.sender, action)
end procedure
```

The Integration Module forms the communicative backbone, enabling project coordination and providing a platform for archaeologists to share their expertise, fostering an environment where project oversight is synonymous with creativity and vision. This is pivotal for ensuring the content is both accurate and engaging as explained in 3.

Algorithm 3 Integration Module Smart Contract

```
procedure logCommunication(message)
    emit CommunicationLogged(msg.sender, message)
end procedure
```

In the Museum Showcase Module, digital artifacts are received and undergo an evaluation process that maintains the museum's high standards of exhibition. Once approved, the artifacts are meticulously organized to enhance educational value and aesthetic appeal as explained in 4.

Algorithm 4 Museum Showcase Module Smart Contract

```
procedure addArtifact(_name, _description)
    artifacts.push(Artifact(artifacts.length, _name, _description, false))
    emit ArtifactAdded(artifacts.length - 1, _name)
end procedure

procedure approveArtifact(_id)
    Only callable by curator role
    Artifact storage artifact = artifacts[_id]
    artifact.isDisplayed = true
    approvedArtifacts[_id] = true
    emit ArtifactApproved(_id, true)
end procedure
```

The Governing Bodies Module oversees the museum's functionality, focusing on guiding avatars, ensuring a positive environment, and addressing security and privacy concerns as explained in 5.

Algorithm 5 Governing Bodies Module Smart Contract

```
procedure addGuide(_guide)
    guides[_guide] = true
    emit GuideAdded(_guide)
end procedure

procedure removeGuide(_guide)
    guides[_guide] = false
    emit GuideRemoved(_guide)
end procedure
```

Lastly, the Database Module is critical for maintaining a structured and organized storage system for digital artifacts, capturing essential metadata, and allowing for the efficient retrieval of information. This module is especially significant as it employs advanced security measures to preserve the integrity and authenticity of the artifacts, embodying the museum's commitment to protecting cultural heritage in the digital realm as explained in 6.

Algorithm 6 Database Module Smart Contract

```
procedure addArtifactRecord(_id, _metadata)
    Only callable by admin or curator role
    artifactRecords[_id] = ArtifactRecord(_id, _metadata)
    emit ArtifactRecordAdded(_id)
end procedure
```

Virtual and augmented reality in archaeoMeta

In the ArchaeoMeta framework, both Virtual Reality (VR) and Augmented Reality (AR) play crucial roles in enhancing the user experience, each serving distinct purposes within the virtual museum environment.

Virtual reality (VR) for immersive virtual tours

VR is employed to create a fully immersive environment, enabling visitors to explore reconstructed historical sites in a virtual space. This technology allows users to experience cultural heritage in a way that transcends physical boundaries. By donning VR headsets, visitors can engage in interactive tours of ancient ruins, historical landmarks, and detailed recreations of artifacts. These virtual tours provide an immersive educational experience, offering a deeper understanding of cultural contexts through rich, engaging visuals and interactive features. The VR component of ArchaeoMeta ensures that visitors can virtually "walk" through exhibits, examine artifacts from multiple angles, and engage with interactive elements that provide detailed historical information and context.

Augmented reality (AR) for enhanced real-world museum visits

AR is integrated to enhance the experience of visitors in physical museum settings. This technology overlays digital information onto real-world exhibits, providing additional layers of information and interaction. For example, visitors using AR-enabled devices, such as smartphones or AR glasses, can view digital annotations, historical context, 3D models, and interactive elements superimposed on physical artifacts. This enhances the educational value of the exhibits by offering real-time, contextually relevant information that deepens the understanding of the displayed items. AR transforms a traditional museum visit into a dynamic and interactive experience, where users can access multimedia content, participate in interactive activities, and explore detailed reconstructions of artifacts directly on their devices.

Integration and user experience

The integration of VR and AR within the ArchaeoMeta framework is designed to provide a comprehensive and versatile cultural experience. By utilizing VR for fully immersive virtual tours and AR for augmenting real-world visits, ArchaeoMeta caters to a wide range of user preferences and scenarios. Whether a visitor is physically present at a museum or exploring from a remote location, the framework ensures an engaging and informative experience. This dual approach not only broadens accessibility but also enhances the educational impact of cultural heritage exhibits.

In summary, the use of VR and AR in the ArchaeoMeta framework significantly enriches the user experience by combining immersive virtual environments with interactive, information-rich overlays in real-world settings. This innovative approach offers a robust platform for cultural heritage preservation and education, making history accessible and engaging for a global audience.

Table 2 Performance metrics by user load

Number of users	Average transaction latency (seconds)	Average gas usage (gwei)	Blockchain size increase (MB)
100	15.95	30,001	10.25
500	31.15	35,006	61.59
1,000	47.02	40,010	126.77
5,000	93.69	45,017	502.9
10,000	126.57	50,027	1050.2

Performance evaluation

In evaluating the "ArchaeoMeta" framework, we deployed its smart contracts on Ethereum's Sepolia testnet, focusing on scalability and latency as the number of users increased.

Evaluation setup

To assess the operational efficacy of the "ArchaeoMeta" framework, we deployed its associated smart contracts on the Ethereum Sepolia testnet. Our primary objectives were to determine the impact of increased visitor numbers on blockchain size and system latency. As shown in Table 2, We simulated visitor interactions, scaling up to 10,000 concurrent users, to analyze how the system manages heightened activity and data load.

We utilized a staged approach, beginning with a baseline of minimal activity (100 users) and incrementally increasing the load in phases-500, 1000, 5000, and finally 10,000 users. Each user was simulated by automated scripts that interacted with the smart contracts to mimic actions such as accessing, interacting with exhibits, and logging activities. Key performance metrics included transaction latency, gas costs, and block size growth (Table 2).

The results indicated that with a baseline of 100 users, the average transaction latency was approximately 15 s. However, as user numbers expanded to 10,000, the latency experienced a substantial increase, averaging around 2 min per transaction. This rise in latency

corresponded with the increased demand for transaction processing and data recording on the blockchain as presented in Fig. 5.

The analysis revealed that while ArchaeoMeta is capable of handling a significant number of users, the scalability of the Ethereum platform, as evidenced by increased latency with higher numbers of transactions, could pose challenges. The growing size of the blockchain with more users also suggests that ongoing costs and performance optimization will be crucial, especially for maintaining fast response times and managing network fees as presented in Fig. 6.

The ArchaeoMeta framework, while innovative and effective in a controlled environment, requires further optimization to handle large-scale deployments effectively. Future work will focus on refining transaction efficiency, perhaps through layer-2 scaling solutions or alternative consensus mechanisms that can offer quicker confirmations and reduced costs. The results indicated a linear increase in block size and gas usage as the number of users escalated as presented in Fig. 7.

This evaluation serves as a foundational step towards ensuring that ArchaeoMeta can deliver a robust and responsive virtual museum experience, even under substantial user load.

Implementation and deployment

After establishing the theoretical foundation of the ArchaeoMeta framework, it is crucial to detail its practical implementation to demonstrate its viability. This section outlines the comprehensive steps taken to deploy the framework on the Ethereum Sepolia testnet, highlighting the key stages involved.

Deployment process

The deployment of the ArchaeoMeta framework involved a series of methodical steps to ensure a robust and functional implementation on the Ethereum Sepolia testnet. This section details the deployment process, highlighting key stages and providing visual aids to enhance understanding.

Setting up the ethereum sepolia testnet

The first step in the deployment process was setting up the Ethereum Sepolia testnet, a testing environment that mimics the main Ethereum network but allows for experimentation without the associated costs. The Sepolia testnet was chosen for its compatibility with our scalability requirements and its ability to simulate real-world conditions.

Configuring the Test Environment The Ethereum Sepolia testnet was configured using standard protocols to ensure it mirrored the main network's functionality. This setup included establishing node connections and synchronizing with the testnet's blockchain.

Creating Test Accounts Test accounts were created to simulate user interactions within the virtual museum.

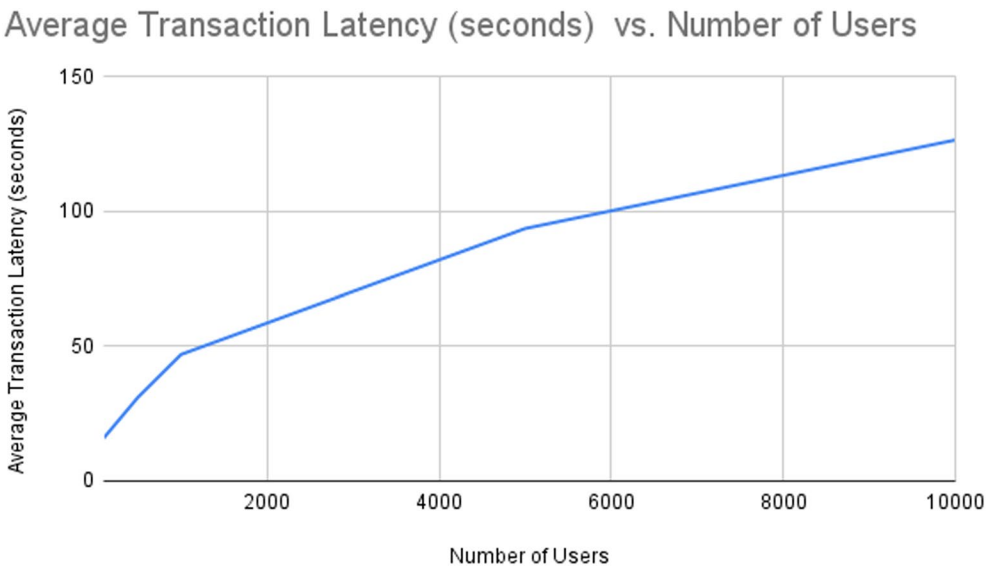

Fig. 5 Average Transaction Latency (seconds) vs. Number of Users

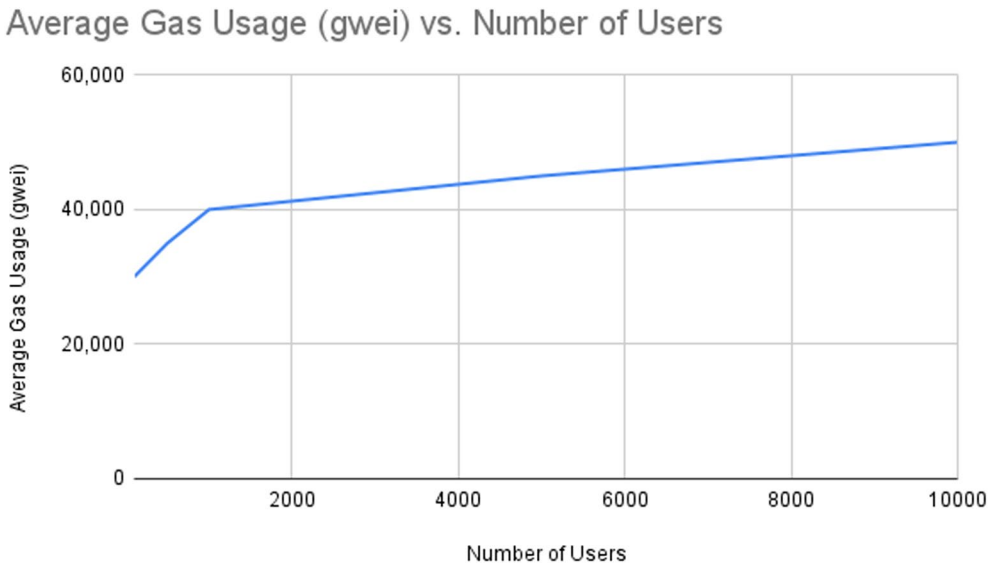

Fig. 6 Average Gas Usage (gwei) vs. Number of Users

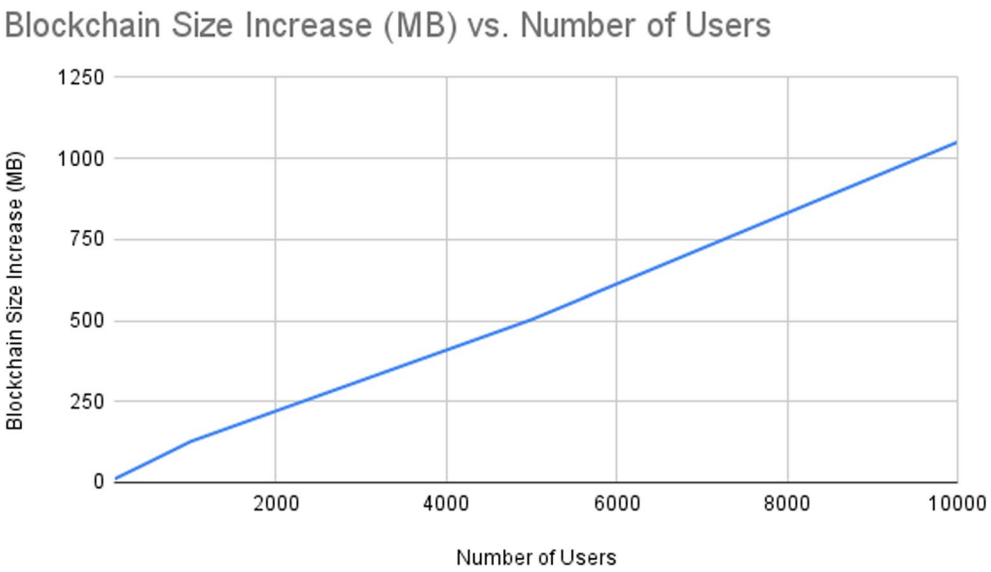

Fig. 7 Blockchain size (MB) vs. Number of Users

These accounts were funded with test Ether to facilitate transactions without incurring real costs.

Deploying smart contracts

The next phase involved deploying smart contracts on the Sepolia testnet to manage visitor interactions and secure digital artifacts.

Smart Contract Development Smart contracts were developed using Solidity, focusing on functionalities such as user authentication, transaction processing, and digital artifact management.

Deployment on Sepolia The smart contracts were deployed on the Sepolia testnet using the Remix IDE, ensuring smooth integration with the blockchain. This step involved compiling the contracts, deploying them to the testnet, and verifying their functionality through initial tests.

Smart Contract Execution Flow Fig. 2 provides a visual representation of the smart contract execution flow, illustrating how user interactions are

Fig. 8 Navigational Interface of the ArchaeoMeta Virtual Museum

Fig. 9 Artifacts Shelves in ArchaeoMeta

processed and how digital artifacts are managed on the blockchain.

Conducting user simulations

To evaluate the framework's performance, user simulations were conducted, scaling up to ten thousand concurrent users.

Simulation Setup A simulation environment was created to mimic real-world user interactions with the virtual museum. This involved scripting user actions such as logging in, viewing exhibits, and interacting with digital artifacts.

Performance Metrics Collection During the simulations, key performance metrics such as transaction latency, gas usage, and blockchain size growth were collected to assess the framework's scalability and efficiency. To provide a comprehensive understanding of the deployment process, visual aids such as figures and screenshots are included.

The Fig. 8 illustrates the user interface used to navigate the ArchaeoMeta virtual museum, showcasing the interactive elements and digital artifacts available for exploration. Users can easily access different sections and view detailed information about each exhibit through this intuitive interface.

The Fig. 9 displays the organized layout of artifact shelves within the ArchaeoMeta virtual museum. Each shelf is equipped with interactive features that allow users to explore detailed information and historical context about the digital artifacts.

Fig. 10 Artifact Stands in ArchaeoMeta

Fig. 11 Artifact Zooming in ArchaeoMeta

The Fig. 10 illustrates the display stands used to showcase artifacts within the ArchaeoMeta virtual museum. Each stand features interactive elements, allowing users to engage with and learn more about the digital artifacts on exhibit.

The Fig. 11 demonstrates the zooming functionality in the ArchaeoMeta virtual museum, enabling users to closely examine artifacts. The zoom feature enhances the viewing experience by allowing detailed exploration of the artifacts' intricate details and historical significance.

The figure 12 illustrates the workflow of the ArchaeoMeta virtual museum environment, integrating the execution of smart contracts on the Ethereum blockchain. The process begins with virtual museum entry and navigation, followed by the creation of virtual visitors, and the management of digital artifacts. Smart contracts play a crucial role at each step, ensuring secure and authenticated interactions. Visitors can design digital artifacts, which are then managed and displayed within the virtual museum. As visitors interact with digital artifacts, smart contracts facilitate and record these interactions on the Ethereum blockchain, ensuring transparency and security. The visitors' guide helps users navigate the museum, and each action is underpinned by smart contract execution, enhancing the reliability and authenticity of the virtual museum experience.

By meticulously following these steps, the ArchaeoMeta framework was successfully deployed on the Ethereum Sepolia testnet, providing a secure and interactive virtual museum environment. This deployment process not only validates the framework's functionality but also highlights areas for further optimization to enhance scalability and user experience.

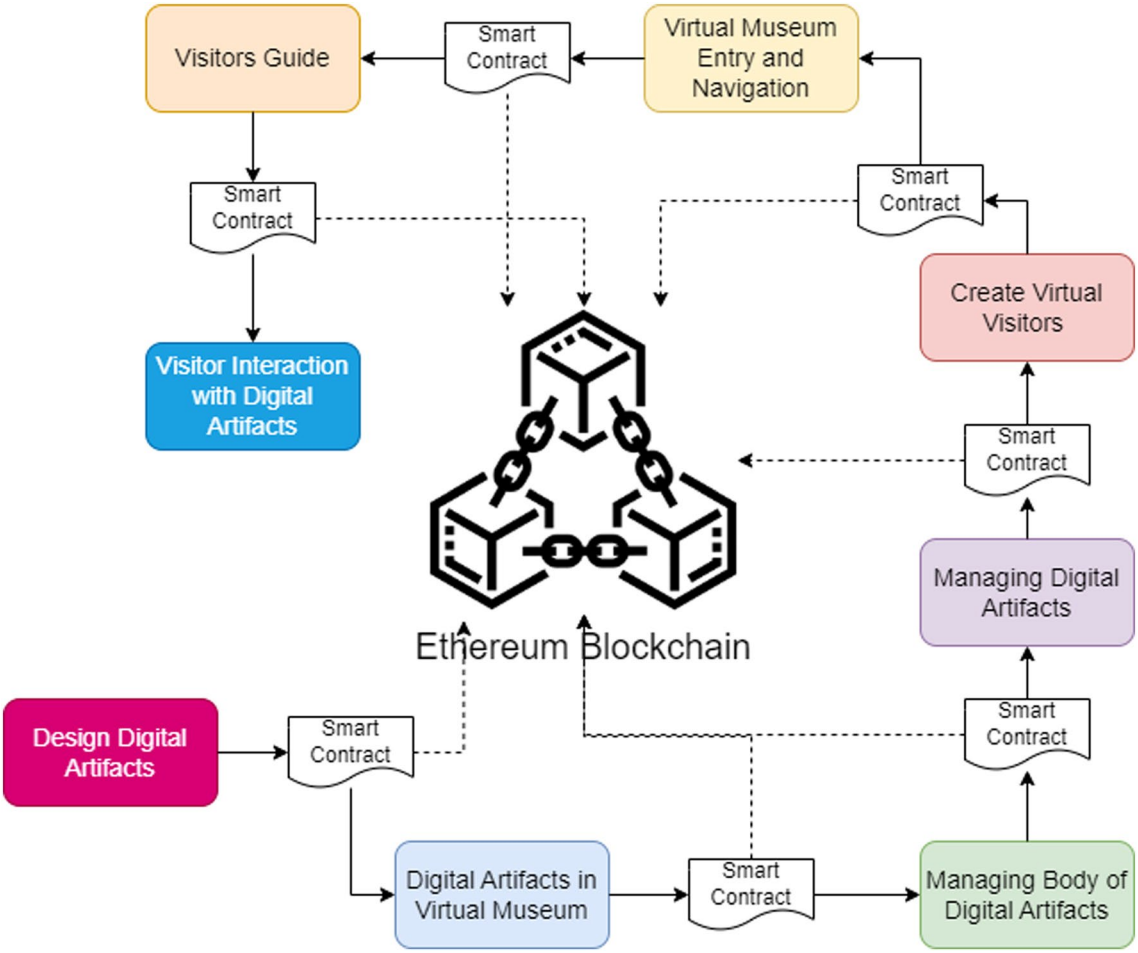

Fig. 12 Workflow of the ArchaeoMeta Virtual Museum Environment Integrated with Smart Contracts

Evaluation

The performance of the ArchaeoMeta framework was rigorously evaluated to determine its scalability and efficiency in a virtual museum setting. This section presents the evaluation process, starting with the introduction to the Sepolia testnet and analyzing key performance metrics.

Introduction to sepolia testnet

The Ethereum Sepolia testnet, a testing environment for Ethereum applications, was chosen for this study due to its robust infrastructure and compatibility with our scalability requirements. Sepolia provides a realistic testing ground for blockchain-based applications, allowing developers to simulate real-world conditions without the financial cost associated with the mainnet. This testnet enables the deployment and interaction with smart contracts in a controlled environment, ensuring that the ArchaeoMeta framework can be evaluated for performance and scalability under varying loads.

Performance metrics

The performance evaluation of the ArchaeoMeta framework focused on several key metrics: transaction latency, gas usage, and blockchain size growth. These metrics were assessed by simulating user interactions, scaling up to ten thousand concurrent users to understand the impact on the Ethereum blockchain.

Transaction latency

The time taken for a transaction to be confirmed on the blockchain. As the number of concurrent users increased, transaction latency also increased, highlighting the need for optimization to handle high user traffic efficiently.

Gas usage

The amount of computational effort required to execute smart contracts. Higher gas usage was observed with an increase in user interactions, which directly affects the cost and performance of the blockchain.

Blockchain size growth

The increase in the size of the blockchain as more transactions are recorded. The rapid growth in blockchain size with higher user volumes underscores the importance of managing data storage and retrieval efficiently.

Discussion

While our quantitative metrics such as transaction latency and gas usage indicate significant scalability challenges, qualitative assessments provide a more holistic view of the framework's effectiveness. User satisfaction surveys revealed that users appreciated the enhanced interaction and security provided by the ArchaeoMeta framework. The immersive experience enabled by VR and the informative overlays provided by AR were particularly well-received, contributing to higher engagement levels.

However, the scalability issues identified through our performance metrics suggest that further optimizations are necessary. Implementing layer-2 solutions or exploring alternative blockchain platforms could alleviate some of the scalability constraints, ensuring a seamless user experience even under high traffic conditions. Additionally, qualitative feedback highlighted areas for improvement in the user interface and interaction design, which will be addressed in future iterations of the framework.

The evaluation of the "ArchaeoMeta" framework on Ethereum's Sepolia testnet has provided valuable insights into the scalability and operational viability of using blockchain technology in virtual museums. The integration of smart contracts to manage interactions and secure artifact data demonstrates the potential for blockchain to enhance visitor experiences and administrative efficiency in cultural heritage applications.

Scalability Challenges The performance tests highlighted significant scalability challenges, particularly in transaction latency and blockchain size as user numbers increased. While the framework could handle smaller user groups efficiently, the latency issues at 10,000 concurrent users indicate that current blockchain infrastructure may need enhancements to support large-scale deployments effectively. This scalability concern is critical as it affects the real-time interaction quality within the Metaverse, which is essential for maintaining user engagement and satisfaction.

Implications for User Experience High latency and slow transaction times could detract from the user experience, making it less interactive and immersive. Users expect quick responses to their actions in virtual environments, and any delay can break the sense of presence, which is vital for virtual museums.

Blockchain Integration Despite these challenges, the use of blockchain for securing artifacts and managing transactions within the Metaverse museum has proven beneficial. Blockchain's inherent security features and transparency provide a robust framework for artifact integrity and traceability. This is crucial in an environment where the authenticity and provenance of digital artifacts are paramount.

Future directions

To address scalability and latency issues, future work could explore several avenues like Layer-2 Solutions. Implementing layer-2 scaling solutions such as rollups or state channels can reduce the load on the main Ethereum network and decrease transaction latency. Alternative Blockchain Platforms that offer faster transaction speeds and lower costs could enhance performance. Platforms like Solana or Flow could be viable alternatives given their focus on supporting high-throughput and low-latency applications. Developing a hybrid system that combines on-chain and off-chain computations could optimize performance while maintaining the security benefits of blockchain technology. Introducing dynamic load balancing mechanisms to manage peak user interactions more effectively could also help in maintaining system responsiveness.

Conclusion

The ArchaeoMeta a novel framework initial tests on the testnet have laid a foundational understanding of its potential and limitations within the emerging field of virtual museums in the Metaverse. While there are challenges to overcome, particularly in scalability, the continued evolution of blockchain technology and more sophisticated integration strategies promise to further unlock the potential of virtual museums. These findings not only contribute to the technical development of Metaverse applications but also enrich the discourse on cultural heritage preservation in digital realms. This discussion aims to frame the ArchaeoMeta framework current capabilities and limitations within a broader context of technological advancement and cultural preservation, providing a comprehensive view of its potential impact and areas for future research and development.

In conclusion, the ArchaeoMeta framework demonstrates strong potential for revolutionizing virtual museum experiences through blockchain technology. The findings from our evaluation provide a solid foundation for future enhancements, aiming to balance technical performance with user satisfaction to create a truly transformative digital cultural heritage platform.

Acknowledgements

We would like to thank Abu Dhabi University, United Arab Emirates and University of Management and Technology, Lahore, Pakistan for their support and assistance in this research.

Virtual Reality (VR) and Augmented Reality (AR) are technologies frequently referenced in this paper. VR creates a fully immersive environment || while AR overlays digital information onto the real world.

Author contributions
Author 1 (OMer Aziz): Conceptualization, Methodology, Writing - Original Draft Preparation, Data Curation, and Visualization. Author 2 (Muhammad Shoaib Farooq): Supervision, Writing Review & Editing. Author 3 (Adele Khelifi): Project Administration, Funding Acquisition. Author 4 (Mahdia Shoaib): Writing - Introduction and Literature Review & Editing.

Funding
This work is part of a project that is funded by the Abu Dhabi University, Faculty Research Incentive Grant (19,300,523 - Adel Khelifi), United Arab Emirates. Link to Sponsor website: https://www.adu.ac.ae/research/research-at-adu/overview.

Availability of data and materials
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable. This study did not involve any human participants or animals.

Consent for publication
Not applicable. This manuscript does not contain any individual person's data in any form (including individual details, images, or videos).

Competing interests
The authors declare that they have no competing interests.

Received: 17 April 2024 Accepted: 8 August 2024
Published online: 23 August 2024

References

1. YiFei L, Othman MK. Investigating the behavioural intentions of museum visitors towards vr: a systematic literature review. Comput Human Behav. 2024. https://doi.org/10.1016/j.chb.2024.108167.
2. Furferi R, Di Angelo L, Bertini M, Mazzanti P, De Vecchis K, Biffi M. Enhancing traditional museum fruition: current state and emerging tendencies. Herit Sci. 2024;12(1):20.
3. Chen S-C. Multimedia research toward the metaverse. IEEE MultiMedia. 2022;29(1):125–7.
4. Ning H, Wang H, Lin Y, Wang W, Dhelim S, Farha F, et al. A survey on the metaverse: the state-of-the-art, technologies, applications, and challenges. IEEE Internet Things J. 2023. https://doi.org/10.1109/JIOT.2023.3278329.
5. Al-Ghaili AM, Kasim H, Al-Hada NM, Hassan ZB, Othman M, Tharik JH, et al. A review of metaverse's definitions, architecture, applications, challenges, issues, solutions, and future trends. IEEE Access. 2022;10:125835–66.
6. Hu W, Han H, Wang G, Peng T, Yang Z. Interactive design and implementation of a digital museum under the background of AR and blockchain technology. Appl Sci. 2023. https://doi.org/10.3390/app13084714.
7. Giannini T, Bowen JP. Museums and the metaverse: New signs of computational art and life 2023.
8. Giannini T, Bowen JP. Museums and digital culture: from reality to digitality in the age of covid-19. Heritage. 2022;5(1):192–214.
9. Wu L, Yu R, Su W, Ye S. Design and implementation of a metaverse platform for traditional culture: the chime bells of marquis yi of zeng. Herit Sci. 2022;10(1):193.
10. Bekele MK, Pierdicca R, Frontoni E, Malinverni ES, Gain J. A survey of augmented, virtual, and mixed reality for cultural heritage. J Comput Cult Herit (JOCCH). 2018;11(2):1–36.
11. Scavuzzo ST. Immersive experience of ancient architectural heritage and related historical events. PhD thesis, TU Wien 2022.
12. Guo C, Dou Y, Bai T, Dai X, Wang C, Wen Y. Artverse: a paradigm for parallel human-machine collaborative painting creation in metaverses. IEEE Trans Syst, Man, Cybern: Syst. 2023;53(4):2200–8.
13. Hammady R, Ma M, Strathern C, Mohamad M. Design and development of a spatial mixed reality touring guide to the egyptian museum. Multimed Tools Appl. 2020;79:3465–94.
14. Fanani AZ, Syarif AM. Historical building 3d reconstruction for a virtual reality-based documentation. Int J Adv Comput Sci Appl. 2023. https://doi.org/10.1456/IJACSA.2023.0140985.
15. Li J, Yu N. Key technology of virtual roaming system in the museum of ancient high-imitative calligraphy and paintings. IEEE Access. 2020;8:151072–86.
16. Navarrete T. Digital heritage tourism: innovations in museums. World Leisure J. 2019;61(3):200–14.
17. See ZS, Santano D, Sansom M, Fong CH, Thwaites H. Tomb of a sultan: a vr digital heritage approach. In: 2018 3rd Digital Heritage International Congress (DigitalHERITAGE) Held Jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018), 2018;pp. 1–4. IEEE
18. Qian J, Cheng J, Zeng Y. Design and implementation of museum educational content based on mobile augmented reality. Computer Systems Science & Engineering 2021;36(1).
19. Carvajal DAL, Morita MM, Bilmes GM. Virtual museums. captured reality and 3d modeling. J Cult Herit. 2020;45:234–9.
20. Hajirasouli A, Banihashemi S, Kumarasuriyar A, Talebi S, Tabadkani A. Virtual reality-based digitisation for endangered heritage sites: theoretical framework and application. J Cult Herit. 2021;49:140–51.
21. Alkhatib YJ, Forte A, Bitelli G, Pierdicca R, Malinverni E. Bringing back lost heritage into life by 3d reconstruction in metaverse and virtual environments: The case study of palmyra, syria. In: International Conference on Extended Reality, pp. 91–106. Springer, ??? 2023.
22. Fujimi T, Fujimura K. Testing public interventions for flash flood evacuation through environmental and social cues: the merit of virtual reality experiments. Int J Disaster Risk Reduct. 2020;50: 101690.
23. Mason M. The elements of visitor experience in post-digital museum design. Des Princ Pract. 2020;14(1):1–14.
24. Leopardi A, Ceccacci S, Mengoni M, Naspetti S, Gambelli D, Ozturk E, Zanoli R. X-reality technologies for museums: a comparative evaluation based on presence and visitors experience through user studies. J Cult Herit. 2021;47:188–98.
25. Zollo L, Rialti R, Marrucci A, Ciappei C. How do museums foster loyalty in tech-savvy visitors? the role of social media and digital experience. Curr Issues Tour. 2022;25(18):2991–3008.
26. Longo MC, Faraci R. Next-Generation Museum: A Metaverse Journey into the Culture. Accessed: 2024-04-18 2023. https://ojs.sijm.it/index.php/sinergie/article/download/1172/461/4455

Publisher's Note