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Adaptive cultural mediation through HBIM and VR: enhancing personalized experiencesvia thematic data structuring

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Abstract:

The mediation of architectural heritage has gained prominence in cultural and historical research, particularly through advancements in technologies like Historic Building Information Modeling (HBIM) and Extended Reality (XR). While these technologies have been extensively explored individually, their combined application for cultural mediation remains under examined. This paper presents a new concept of Adaptive Cultural Mediation (ACM), integrating HBIM and XR to create an interactive, user-specific mediation environment. ACM enables users to filter information based on interests, such as architectural elements or historical context, providing an immersive, personalized experience. Our approach is exemplified through a virtual model of the Mosque Al-Quaraouiyine in Fez, Morocco, where 3D scanning and HBIM modelling capture architectural details and historical annotations. MongoDB, a NoSQL database, supports the integration of multimedia content and user preferences, structured around thematic filters for real-time adaptability. This setup, powered by Unity in a VR environment, facilitates dynamic content retrieval, enhancing user engagement by aligning information display with selected themes. The results demonstrate the effectiveness of combining HBIM with NoSQL databases in XR environments, displaying how adaptive cultural mediation can transform heritage site exploration into an engaging, context-rich experience.

1. Introduction

Architectural heritage mediation is gaining more attention for cultural conservation and valorization, especially in a context where digital technologies are transforming the way we interact with history and heritage sites. Cultural mediation plays a crucial role in bringing the public closer to history and culture while preserving information flow among generations. In this context, Historic Building Information Modeling (HBIM) and Extended Reality (XR) emerge as new technologies for digital modeling, documentation, and immersive visualisation, allowing rich mediation and interactive digital learning experiences (Nofal, 2023; González-Avilés et al., 2018; Fai & Rafeiro, 2014; Bruno & Roncella, 2019).

Before the advent of new technologies, cultural mediation relied primarily on traditional methods such as guided tours, explanatory panels, and printed guides. These approaches, although effective in certain contexts, often lacked personalization and interactivity (Masciotta et al., 2021). The experience offered to visitors is generally linear, with no possibility to choose themes or explore specific elements according to their own interests, making the experience less engaging and more uniform (De Luca et al., 2021; Fai & Rafeiro, 2014). With the arrival of digital technologies such as HBIM, and Extended Reality, cultural mediation has evolved into more interactive and adaptive forms (Dore & Murphy, 2020). These new methods allow for more immersive experiences, giving visitors the opportunity to personalize their exploration of cultural heritage according to their specific interests (Nofal, 2023). The use of HBIM, which centralizes geometric and semantic information of heritage structures into a rich 3D model, facilitates detailed heritage documentation adaptable to different levels of architectural and historical data granularity (Banfi et al., 2023; Paladini et al., 2019). In parallel, XR technologies, such as Virtual Reality (VR) and Augmented Reality (AR), enable the interactive exploration of these models, simulating physical presence at the site, thus enhancing user engagement (Nofal et al., 2020; Banfi et al., 2023).

Previous studies have shown that HBIM is effective in creating highly detailed digital models of heritage sites, which plays a crucial role in conservation and documentation efforts (Masciotta et al., 2021; Bevilacqua et al., 2020). Similarly, XR has been explored to provide immersive experiences that increase accessibility and interaction, especially for physically inaccessible heritage sites (Paladini et al., 2019; Nofal et al., 2020). Both technologies have paved the way for more informative and engaging cultural experiences. However, while significant research has focused on the individual use of HBIM and XR, their combined application remains largely underexplored, particularly in developing truly adaptive and personalized media experiences (Carvajal et al., 2017;

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Fernández-Palacios et al., 2023; Parisi et al., 2024). In this paper, we introduce the concept of Adaptive Cultural Mediation (ACM), an innovative approach that integrates HBIM and XR/VR technologies to create an interactive and personalized mediation environment.

The main objective of this paper is to implement the concept of ACM by proposing a framework for cultural mediation based on the integration of HBIM and VR technologies .

The contributions of our study are twofold. Firstly, we propose an innovative approach based on the concept of "Adaptive Cultural Mediation" (ACM), which surpasses traditional methods by incorporating interactive and personalized user experiences. Secondly, we develop an HBIM model enriched with semantic and historical data, structured specifically to serve the purposes of ACM. Additionally, we utilized MongoDB for real-time data management, ensuring responsive and seamless access to user-specified information.

This article is organized as follows: Section 2 describes the adopted methodology, detailing HBIM modelling techniques and the integration with MongoDB and Unity. Section 3 discusses the results of our study applied to the digital model of the Al-Quaraouiyine Mosque and identifies the technical challenges encountered in applying our approach. Finally, we conclude with future research perspectives, emphasizing opportunities to extend our methodology to other heritage sites.

2. Method

Our ACM method is designed to adapt to individual user preferences through thematic filters, enabling targeted exploration of heritage data. These filters, focus on elements such as architectural features, historical context, or cultural significance, address challenges related to information overload often present at large-scale sites, while considering the diverse needs of users. By placing the user at the center of the process, ACM provides a mediation experience that is not only informative but also engaging and immersive, thus meeting the growing expectations for a modern and adaptive cultural mediation experience.

Our method illustrated in figure 1, is applied to the mosquee of Al Quariwiyine in Fes-Morocco. First, we seek to establish a synergy between HBIM and VR by creating an enriched digital model that allows users to interact with historical and architectural data in an immersive setting. Second, we propose structuring multimedia data using MongoDB, a NoSQL database (MongoDB) system, to organize information according to thematic filters defined to meet users' specific interests. Finally, we develop an immersive VR experience that recreates the environment of the site, facilitating in-depth and contextualized exploration.

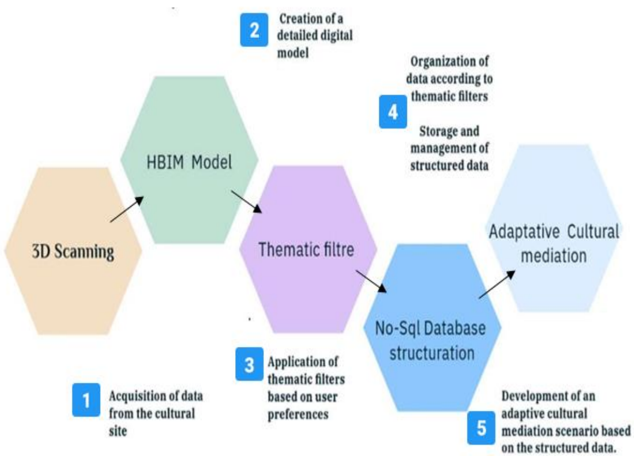

Figure 1. General workflow for ACM

The first step of our methodology is the creation of a HBIM model of the Al-Quaraouiyine Mosque. To achieve this, we employed a 3D terrestrial scanning method, which accurately captures the architectural specifics of the historic site. Enriched semantic data associated to architectural elements are then integrated to the geometric model to allow a rich cultural mediation experience.

For data storage, we selected MongoDB, a NoSQL database, due to its capability to manage diverse data types, including multimedia content such as images, videos, and textual descriptions. This flexibility enables the organization of data based on thematic filters, allowing for efficient real-time retrieval during users' virtual explorations. This structure further supports the customization of information to match each visitor's specific interests, thereby enhancing their overall experience.

Finally, Unity is used as a development engine to create an immersive virtual reality environment. This platform allows for the development of an intuitive user interface, where visitors can interact with the HBIM model of the mosque while selecting thematic filters that personalize their experience. Real-time interaction between the user and content is made possible by MongoDB's capability to provide instant data, transforming cultural heritage exploration into an experience that is both informative and engaging (Figure 2).

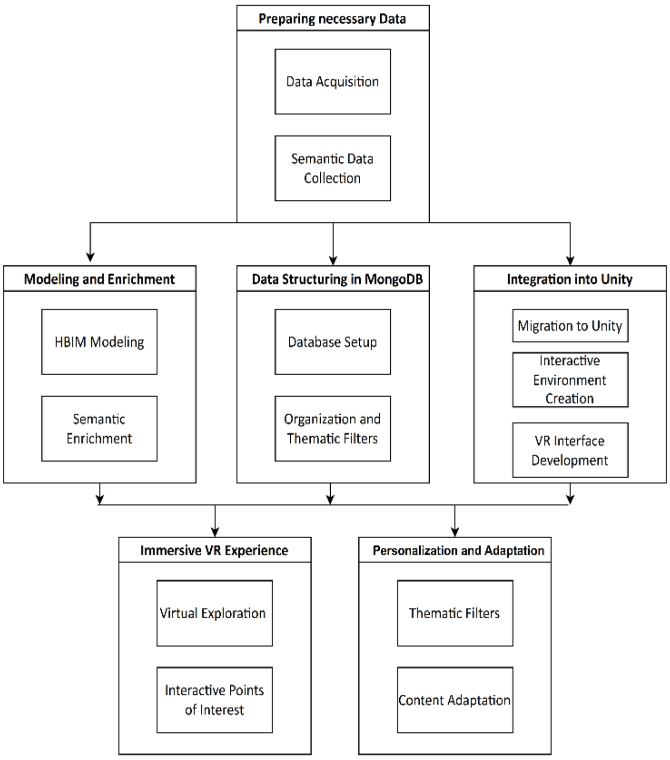

Figure 2. Adaptive Cultural Mediation Workflow: From Data Acquisition to Immersive User Experience

3. Case study

Our method has been applied to the Al-Quaraouiyine Mosque, located in Fez, Morocco (Figure 3). Founded in 859 by Fátima al-Fihriya, the mosque is one of the oldest institutions of higher learning in the world. It features Islamic architecture from the Almoravid and Almohad periods and remains a major center of Islamic culture in the Maghreb. Named after refugees from Kairouan, the mosque can accommodate up to 20,000 worshippers. The courtyard, decorated with blue and white tiles, includes an original Almohad fountain from the 12th century, showcasing intricate Moorish floral and geometric designs. This case study is particularly relevant for testing our adaptive cultural mediation approach due to the diversity of its architectural elements and its historical richness. It allows users to virtually explore the mosque according to specific themes, such as architecture, history, or religious significance, thus providing an immersive and personalized experience.

We conducted an in-depth historical study of the mosque, using archives and architectural surveys to document its history and enrich our HBIM model with historical and semantic data.

Figure 3. Al Quaraouiyine Mosque "Sahn Al Quaraouiyine"

3.1 Data acquisition and hbim modelling

For the HBIM modeling of the Al-Quaraouiyine Mosque, 3D geometric data were acquired using a terrestrial laser scanner with 21 stations deployed on-site to ensure complete coverage of the courtyard and main prayer hall. The scan resolution was set to 5 mm, ensuring a high level of detail for architectural features. The raw data were imported into Cyclone preprocessing software for noise cleaning and scan registration, resulting in a high-quality point cloud for HBIM construction. (Figure 4)

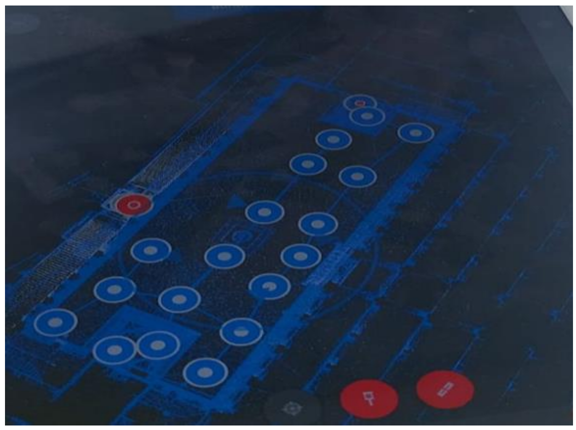

Figure 4. Distribution of 3D Scan Station Points

Semantic information was gathered from site managers in the form of documents and historical multimedia files. These data were integrated into the HBIM model, enriching it with metadata linked to specific architectural elements. Multiple on-site visits were also conducted to capture additional photos and videos, further documenting materials, ornamental details, and their cultural context.

The point cloud was employed to create an accurate 3D model of the Sahn Al-Quaraouiyine (Figure 3). Structural elements were meticulously modelled to replicate the courtyard's fundamental structure, including the geometry, dimensions, and spatial arrangement of each component. This comprehensive digital base, enriched with contextual information, provides a faithful representation for subsequent project phases. Architectural features, ornamental details, and historical elements were modeled using parametric families in Autodesk Revit, resulting in a complete HBIM representation. Each ornament, sculpture, and construction material was incorporated to create an accurate digital archive that virtually preserves the site's cultural and heritage richness.

To enhance visual quality, SIMLAB Composer was utilized to apply realistic textures and fine-tune lighting parameters. The resulting model, illustrating these improvements, is presented in Figure 5.

Figure 5**.** The HBIM of Al Quaraouiyine Mosque

3.2 Data structuring

Data structuring was carried out using MongoDB, a NoSQL and open source document-oriented database, to enable flexible management tailored to the needs of ACM. Each element of the HBIM model was represented as a JSON document, integrating geometric and semantic attributes, organized into different collections.The data were first exported from the HBIM model as BSON (Binary JSON) files, a MongoDB-specific format that ensures optimized and efficient management. Architectural elements such as arches, doors, and columns were modeled as JSON documents, with each document containing fields describing geometric characteristics (dimensions, material) and contextual attributes (function, history, significance). These documents were structured into thematic collections such as "Architecture," "History," and "Ornaments." This organization into collections allows for efficient management and retrieval of relevant information during mediation (Figure 6).

Each document contains a "culturalSpace" field specifying which part of the mosque the element belongs to (e.g., "Main Courtyard" or "Prayer Area"). These fields were used to assign elements to different cultural spaces, facilitating navigation by zones during immersive exploration. To optimize queries and enable fast and efficient searches, we also created indexes on key fields such as "elementType" and "thematicTag," using MongoDB's native indexing features.

The database structuring was automated using Python scripts with the PyMongo library. These scripts enabled the import of JSON documents, the creation of indexes on relevant attributes, and the enrichment of data with metadata collected from historical research. Python scripts were also used to integrate multimedia information (images, videos, PDF files) into each document by adding links to these files in the appropriate document fields.

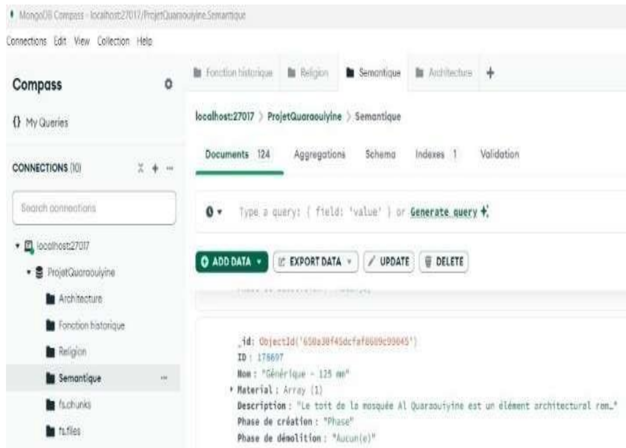

Figure 6**.** Semantic Thematic Filters in MongoDB Compass

To meet the requirements ACM, we used the MongoDB Aggregation Framework to enable advanced aggregations and filtering based on user preferences. Each user can select thematic filters (e.g., "Architectural Elements," "Religious Functions"), and the aggregation framework groups documents according to these filters, presenting information in a coherent and relevant manner.

Integration of MongoDB into the Unity environment was achieved through a Flask API, which serves as a data access point for the C# scripts used in Unity. The API receives user requests, queries MongoDB based on the selected criteria, and returns relevant information to Unity. These data are then displayed in real time in the VR environment, providing an interactive and personalized experience.

This approach to database structuring, which combines MongoDB, Python scripts, a Flask API, and C# scripts in Unity, allows for efficient management of the complexity of heritage data while offering interactive mediation that adapts to each user's specific preferences (Figure 7).

```python
#  Python script using PyMongo to structure data in MongoDB

from pymongo import MongoClient, ASCENDING
import json

# Connect to MongoDB
client = MongoClient("mongodb://localhost:27017/")
db = client["mosquee_al_quaraouiyine"]

# MongoDB Collections
thematic_collections = ["Architecture", "History", "Ornaments"]

# Function to insert JSON documents into a collection
def insert_documents(collection_name, json_file):
    collection = db[collection_name]
    with open(json_file, "r", encoding="utf-8") as file:
        data = json.load(file)
        if isinstance(data, list):
            collection.insert_many(data)
        else:
            collection.insert_one(data)
```

a

```python
#  query to retrieve elements based on thematic filters and user preferences
filters = {
    "tagThematic": "architecture",
    "culturalSpace": "Main Courtyard",
    "userPreferences.details": True
}
results = db["Architecture"].find(filters)

print("Filtered results:")
for result in results:
    print(result)
```

b

Figure 7. Thematic Filters in MongoDB using PyMongo: (a) Data Structuring Script, (b) Query for Thematic Filters

3.3 Data integration into unity

Data integration into the Unity environment is a crucial step for creating an immersive and interactive experience using the HBIM model enriched with data from MongoDB. This integration uses a technical architecture combining a REST API, C# scripts, and optimization techniques to ensure a smooth virtual exploration of the Al-Quaraouiyine Mosque.

To enable communication between MongoDB and Unity, a REST API was developed using Flask. This API retrieves relevant information in real time based on user preferences set in the immersive environment. Unity sends requests to the API, which queries MongoDB using specific filters and returns the data in JSON format, enabling seamless interaction between the database and the immersive experience.

In Unity, scripts manage user interactions by sending requests to the server whenever users choose a theme or interact with elements in the environment. The server then provides the needed information, which is displayed instantly, allowing for dynamic updates like showing relevant images, videos, or information, making the experience more engaging and personalized.

To enhance performance, a caching mechanism was added to the Flask API. The cache temporarily stores responses to frequent requests, reducing latency and avoiding redundant database queries. If data is found in the cache, it is returned immediately; otherwise, a request is made to MongoDB, and the response is cached for future use.

Additionally, asynchronous requests are used in Unity to ensure smooth, uninterrupted interaction. Data is loaded in the background, allowing the user to continue exploring without delays, ensuring an uninterrupted and engaging experience.

This integration of data into Unity, combining the use of a REST API, C# scripts, and optimization mechanisms, transforms the HBIM model into an interactive and personalized experience. Users can virtually explore the Al-Quaraouiyine Mosque while accessing enriched contextual information that adapts to their preferences, offering a more immersive and dynamic cultural mediation.

3.4 VR implementation

After integrating the data into Unity, the next step was to set up VR integration to make the cultural mediation experience fully immersive. This phase leveraged Unity's capabilities to create an interactive virtual environment, combined with the use of VR equipment.

For this integration, VR equipment was configured to allow users to fully immerse themselves in the virtual environment. Integrated with Unity, this setup enables smooth and natural interaction with elements of the HBIM model, enhancing the engagement and intuitiveness of the experience. (Figure 8)

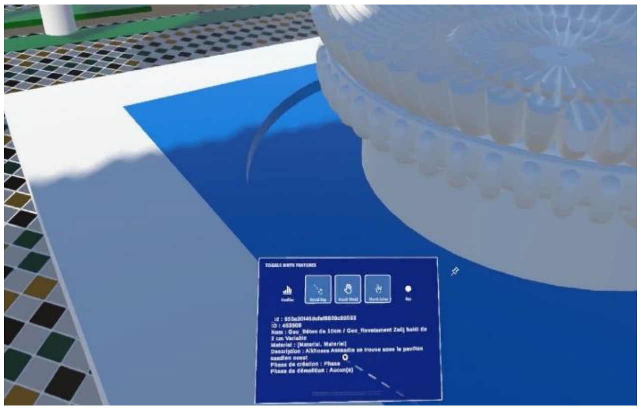

Figure 8. Visualisation of Semantic Data for HBIM Objects

We developed a VR user interface in Unity to facilitate user navigation and interaction within the virtual space. This interface allows users to select elements of the HBIM model, activate thematic filters, and explore cultural spaces immersively (figure 9). VR controllers were configured to allow actions such as zooming, rotating, and selecting elements. Interactive points of interest were integrated into the model, allowing users to receive detailed contextual information, such as historical descriptions, when interacting with specific architectural elements.

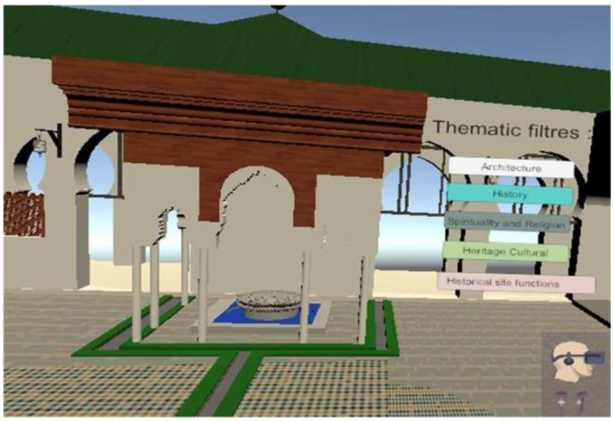

Figure 9. ACM in Unity environment (VR Mode)

To ensure optimal performance in VR, specific optimizations were applied, such as optimizing the existing 3D meshes (Level of Detail - LoD) and adjusting textures to minimize graphic load. Tools like Unity Profiler were used to test performance, adjust graphic settings, and ensure that the VR model remains performant on the VR hardware used, providing a smooth experience without latency.

Data from MongoDB, such as descriptions, images, and videos of architectural elements, were dynamically integrated into the VR environment via the Flask API. When users interact with an object in the virtual environment, relevant information is retrieved in real time and displayed contextually. Thematic filters allow users to customize their exploration, displaying only elements corresponding to the selected themes, such as architecture or religious functions. Users can move through virtual spaces, explore architectural details, and interact with elements of the HBIM model using VR controllers. Interactive elements provide contextual information, allowing immersive and informative exploration.

This phase of VR integration in Unity transformed cultural mediation into an interactive and immersive experience, allowing users to immerse themselves in the Al-Quaraouiyine Mosque while discovering its architectural and historical elements in an enriched manner. By combining VR technologies with HBIM and MongoDB data, this experience offers adaptative cultural mediation, fostering a deeper connection with architectural heritage.

3. Discussion

The use of advanced technologies such as virtual reality and HBIM modeling has shown how digital tools can enrich and modernize cultural mediation, offering a more dynamic and interactive approach. The adaptive nature of the system meets user expectations for accessibility and interactivity, while respecting the site's historical and architectural integrity. The ability to choose specific themes and navigate freely within the virtual environment ensures an engaging and customized experience.

The results obtained clearly demonstrate the effectiveness of integrating the HBIM model with MongoDB and Unity technologies for the implementation of ACM. The developed system allows for interactive and immersive exploration of the Al-Quaraouiyine Mosque, providing users with the ability to personalize their experience based on thematic preferences. This adaptability is central to the concept of ACM, enabling more engaging and accessible cultural mediation for diverse audiences.

The use of MongoDB as a NoSQL database played a crucial role in structuring multimedia and semantic data. Thanks to its flexibility, MongoDB enabled the storage of complex information, such as architectural descriptions and multimedia files, while ensuring fast and optimized real-time data retrieval. Thematic filters were essential in organizing and structuring this data according to user preferences, facilitating access to targeted and relevant information during virtual exploration. This structuring allowed for dynamic adaptation of content based on each user's choices, making the mediation experience much more interactive.

The integration of the HBIM model into Unity also significantly contributed to the success of the ACM project. Unity, with its advanced capabilities for creating immersive environments, transformed the HBIM model into an interactive virtual space where users can explore the mosque using VR headsets. The integration of interactive points of interest and thematic filters in the Unity environment facilitated the personalization of the experience based on each user's interests, enhancing engagement and immersion. The VR experience created a deeper connection with architectural heritage, offering a new dimension to cultural mediation

Finally, the concept of ACM, realized through the combined use of HBIM, MongoDB, and Unity, has demonstrated its potential to transform how cultural heritage is perceived and explored. By enabling personalized and immersive exploration, the system provides an experience tailored to individual preferences and educational needs, representing a significant advancement over traditional, linear mediation methods. The immersive environment enhances understanding of architectural and historical elements while actively engaging users. The results indicate that the ACM approach, supported by HBIM, MongoDB, and Unity, is not only effective but also scalable, paving the way for future applications to other heritage sites.

However, several challenges were encountered during the implementation of this work. One significant challenge was optimizing the 3D models for VR, which required balancing visual quality with performance to ensure a smooth user experience. Another challenge involved integrating different data types from HBIM into MongoDB for efficient retrieval and interaction in real time. Additionally, developing a user-friendly VR interface that could accommodate different levels of user familiarity with technology posed a design and usability challenge.

4. Conclusion

The work presented in this paper has demonstrated the potential of ACM to transform heritage mediation into an immersive and interactive experience. By combining HBIM, MongoDB, and Unity, this approach paves the way for more personalized cultural experiences that adapt to users' preferences.

The results showed that ACM can effectively enhance user engagement and accessibility in cultural heritage contexts. Future research should focus on expanding this approach to other heritage sites and integrating emerging technologies to further improve personalization and interactivity.

. We intend not only to diversify the applications of ACM but also to refine the VR interface by optimizing user interaction features, reducing latency, and enhancing visual quality through advanced rendering techniques. These refinements aim to provide an even
smoother and more captivating immersion, making cultural heritage exploration more accessible and enriching for all audiences.

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