Digital Representation and AI-driven Virtual Experience for Historic Houses. The Case Study of Borgo Storico Seghetti Panichi.

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Keywords: Cultural Heritage, Historic Garden, 3D Modeling, Virtual Reality, AI driven.

Abstract

The paper presents the digital representation and virtual experience of Borgo Storico Seghetti Panichi, a cultural site distinguished by the close interplay between architecture and landscape. The project was developed using an integrated approach that brings together 3D survey techniques, immersive technologies, and Artificial Intelligence (AI). Consolidated techniques such as Terrestrial Laser Scanning (TLS) and UAV-based photogrammetry were adopted to generate accurate 3D models of the Villa, the Roccolo, the Church, and the surrounding historic park. Moreover, preliminary tests with 3D Gaussian Splatting (GS) were conducted to evaluate its potential for photorealistic and real-time visualization in Cultural Heritage (CH) contexts. The different digital representations were embedded in a Virtual Reality (VR) application designed to offer an engaging and educational user experience. The immersive environment includes interactive components such as the digital replicas of the buildings and the historic park, audio narration, and a virtual keyboard connected to a Large Language Model (LLM). This system enables users to formulate questions in natural language and receive dynamic, context-specific responses within the VR environment, fostering active learning and customized exploration. The development process included a structured pipeline from survey data to VR implementation, with specific focus on optimization for standalone headsets. User evaluation tests confirmed the effectiveness of the experience in terms of realism, interaction, and accessibility, while also identifying areas for further improvement.

1. Introduction

The digitization of CH has undergone a significant evolution over the past decade, shifting from traditional, well-established methodologies to innovative approaches supported by digital technologies and, more recently, AI. This transformation has opened new perspectives for the documentation, conservation, and dissemination of CH. Among the most widely adopted surveying methods, the integration of TLS and UAV-based photogrammetry represents a well-established practice in the field of CH, capable of delivering highly accurate 3D reconstructions (Tapinaki et al., 2023) (Lo Pilato et al., 2023). However, even these digital techniques present certain limitations (Croce et al., 2024). TLS may encounter difficulties with reflective or transparent surfaces, and it requires careful planning to minimize occlusions. Photogrammetry, while being cost-effective, can result in incomplete or noisy reconstructions in the presence of uniform textures, vegetation, or poor lighting conditions. Moreover, both methods involve post-processing steps such as alignment and noise reduction, which can be highly time-consuming. In response to these challenges, AI-based techniques have emerged, such as Neural Radiance Fields (NeRF) and 3D GS. NeRF introduced an innovative approach to view synthesis by training neural networks to interpolate scene geometry and appearance from a set of calibrated images. Although it enables accurate visualizations and effectively simulates the optical behavior of complex materials, its application in the documentation of Architectural Heritage (AH) is currently limited by high computational demands, which prevent real-time rendering. More recently, GS has emerged as a promising technique, overcoming some of the key limitations of NeRF. Unlike these implicit neural models, the GS method adopts an explicit representation of the scene through a dense cloud of three-dimensional anisotropic Gaussians (splats). Each directly encodes color, opacity, and spatial shape, making the method particularly efficient for real-time rendering and interaction (Fei et al., 2024). This approach allows for precise control over the splats, enabling the generation of highly photorealistic renderings as well as the export of point clouds or mesh-based reconstructions. Experimental comparisons have shown that GS outperforms NeRF in terms of rendering quality and efficiency. Particularly, in the field of AH, the application of GS is still emerging, yet highly promising. Early case studies, including 3D reconstructions of complex interiors using low-cost 360° cameras or drone-based acquisitions, demonstrate its computational efficiency and photorealistic rendering capabilities (Clini et al., 2024). This technology aligns seamlessly with the broader context of CH digitalization, which today extends far beyond mere documentation, serving instead as a vital tool for enhancing accessibility, promoting the value of heritage, and effectively conveying knowledge through engaging and immersive experiences.

In this context, eXtended Reality (XR) technologies provide immersive environments that foster new forms of exploration, broadening the audience and redefining the relationship between space, narrative, and cultural knowledge (Chen et al., 2023). A significant evolution is represented by Interactive Virtual Objects (IVOs) and dynamic environments, which enable users to actively contribute to the construction of customized narratives within XR-based museum experiences (Banfi & Mandelli, 2021). In addition to spatial and visual interaction, it is now possible to integrate an intelligent conversational dimension using LLMs and AI-based chatbots. Users can interact with the virtual environment using natural language, formulating questions, and receiving real-time responses. This innovation enables a form of dynamic and active knowledge experience, in which visitors become the protagonists of their own interpretive journey (Suryanto et al., 2023) or is guided through pre-structured inquiries (Cossatin et al., 2025). This type of approach is opening new perspectives in the museum sector, proving to be an effective tool for overcoming cognitive, linguistic, and physical barriers, thus promoting a more inclusive and cross-cutting experience of

CH (Lau et al., 2024), both tangible and intangible, while enhancing emotional engagement (Zhao et al., 2025).

The project presented fits into this scenario, offering an advanced integration of 3D survey and AI-driven interaction in XR. Starting from a high-resolution integrated survey, 3D representations were processed using 3D GS techniques to achieve immersive and real-time navigable visualizations. These digital representations were embedded in an interactive VR environment. A distinctive feature of the project is the implementation of a virtual keyboard connected to an LLM, which allows users to ask questions in natural language directly within the immersive experience. In return, users receive contextual, relevant, and dynamic information, enabling a dialogic mode of engagement. This form of intelligent interaction, user-centered and powered by conversational AI, introduces a new dimension of cultural mediation: heritage is no longer merely represented or narrated, but becomes an experiential space where the visitor can build their own interpretive path through questions, curiosity, and personal reflection. In this way, AI serves as an active bridge between complex content and diverse audiences, fostering accessibility and personalization in the discovery of CH.

2. Methodology

2.1 Case Study

The Borgo Storico Seghetti Panichi (Figure 1), located in Castel di Lama (Italy), represents a significant example of Italian architectural and landscape heritage, and it has recently been involved in project of a restoration, conservation, and enhancement through immersive digital technologies. The origins of this complex date back to the early Middle Ages; historical documents confirm that the castle already existed in the early 1300s as a military outpost. In the mid-1700s, the current noble villa was constructed on the site of the former fortified structure, marking a definitive transformation from a defensive military complex to an aristocratic residence. Adjacent to the villa, several buildings of historical value can be identified, such as the Oratory of San Pancrazio, known for its bell tower, which was adapted from a pre-existing medieval tower, and the Roccolo, an ancient hunting structure that was described as early as the late eighteenth century and later modified. A crucial role in shaping the identity of the Borgo has been played by the Historic Park, designed at the end of the 19th century by the renowned botanist Ludwig Winter. Winter adapted his Franco-Ligurian romantic style to the local landscape, creating a park that combines native and exotic plant species, artificial ponds, and terraced areas for citrus trees and roses.

In recognition of its historical and landscape significance, the Borgo was selected as the focus of a project funded by the Italian National Recovery and Resilience Plan (PNRR), (Next Generation EU - Historic Parks and Gardens, M1C3 Misura 2.3). In addition to the physical restoration and conservation of the park and its buildings, the project included an extensive digitalization of the historical, architectural, and landscape heritage through integrated surveying techniques, enabling the creation of highly accurate digital models. A key goal of the project was to develop an immersive VR application, designed to enable an engaging experience of the Borgo. Through the VR environment, the complex can be virtually explored, allowing interaction with the Villa, the Oratory, and the Roccolo.

The project is presented as a virtuous example of how the conservation of historic gardens can be effectively integrated with digital strategies, where the use of immersive technologies enhances both accessibility and the overall experience of the Borgo Storico Seghetti Panichi.

Figure 1. Aerial panoramic view of Borgo Storico Seghetti Panichi.

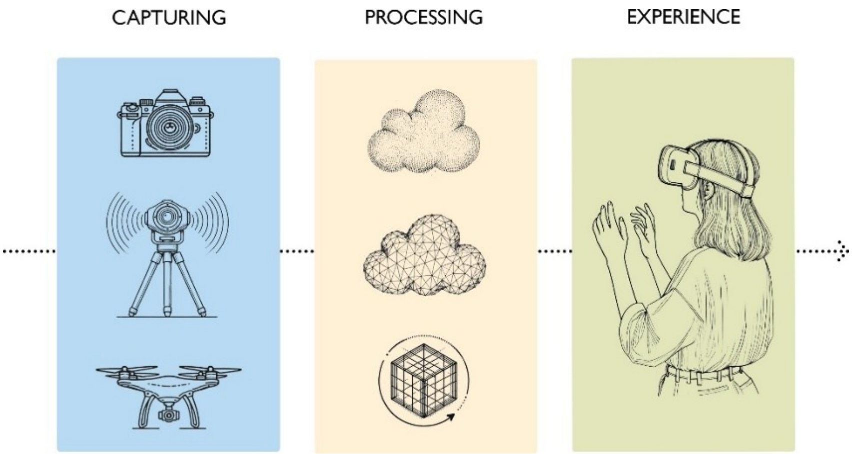

Figure 2. Presented workflow. Data capturing and processing for the experience of architectural and landscape heritage.

2.2 Data collection and processing

The first step of the project focused on documenting the case study through an integrated digital survey, combining image-based and range-based techniques to achieve a comprehensive and accurate representation of Borgo Storico Seghetti Panichi, including the Villa, the Historic Garden, the Roccolo, and the Oratory of San Pancrazio. This represents the first systematic survey of the Borgo conducted using these technologies, and it served as the essential foundation for the subsequent development of virtual experience (Figure 2). The data acquisition process was carried out using three different tools, each contributing to the comprehensive documentation of the site. Firstly, a terrestrial laser scanning campaign was conducted using a Leica RTC360 scanner, performing 180 scans to cover the entire park and the interiors of the historic buildings. This allowed for the generation of a dense point cloud, capturing the geometry of the site and its architectural features with a high level of detail. Concurrently, an aerial photogrammetric survey was carried out using a DJI Mavic 3 Classic drone. The flight mission was planned to ensure complete coverage of the park and close-up captures of the three main architectural elements (the Villa, the Roccolo, and the Church), resulting in approximately 1,900 images. To ensure the georeferencing of the TLS and the photogrammetric data, GCPs were surveyed using a GNSS-RTK HiPer HR. This enabled absolute scaling and the correct merging of the different data sources into a unified 3D model of the Borgo and its surrounding landscape. Figure 3 shows an orthoimage of the surveyed area, that provides a complete, detailed, and up-to-date plan of the Borgo. This orthoimage also supported the narrative and design choices of the VR experience, offering a coherent spatial reference for virtual navigation. Subsequently, four main elements were segmented and extracted from the complete model for integration into the immersive application: the model of the Historic Villa, the Roccolo, the Church, and the surrounding terrain. The latter was simplified to optimize performance within the virtual environment, without compromising its morphological recognizability.

The three buildings were also reconstructed using GS techniques (Figure 4). Starting from the photogrammetric alignment of images performed in RealityCapture, the GS representations were generated using the Postshots software. These were subsequently refined through the online platform Supersplat to remove elements outside the target structures.

Figure 3. Orthoimage of Borgo Storico Seghetti Panichi.

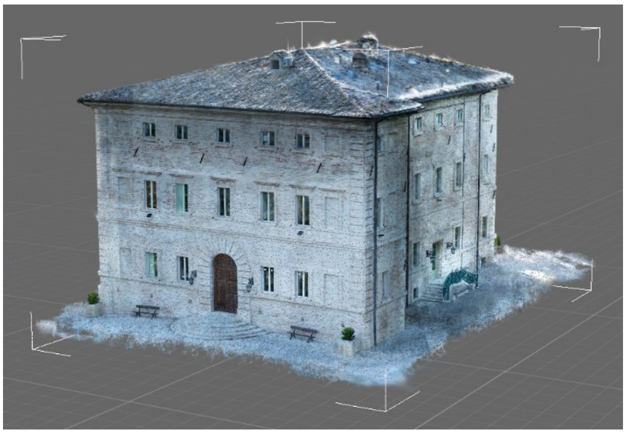

Figure 4. Visualization of the GS representation of the Historic Villa at Borgo Storico Seghetti Panichi.

Alongside the production of the geometric model, ground-based panoramic photographic documentation was also acquired, aimed at the creation of a navigable Virtual Tour. This alternative mode of access to immersive experience allows for a guided and interactive exploration of the park and villa spaces, maintaining high perceptual quality and enhancing content accessibility. The entire process of surveying, processing, and segmenting the data provided the essential technical foundation for the development of immersive experience, while also representing an asset in terms of digital preservation and informed heritage management. The ability to obtain an accurate and navigable digital replica of the Borgo enables the implementation of strategies for valorization, documentation, and long-term monitoring, laying the groundwork for future applications not only in the cultural field but also in tourism and education.

2.3 Development of the XR Experience

The immersive experience was developed in XR as part of the project dedicated to the Borgo Storico Seghetti Panichi was conceived as an interactive virtual environment designed to foster active learning and informed user engagement. The project was structured into three main operational phases, pre-production, production, and post-production, based on a methodological framework derived from the processes typical of the audiovisual sector and interactive immersive experiences. (Buccheri, 2003).

The first phase was dedicated to identifying the narrative content to be transposed into the virtual environment, with particular focus on the historical, architectural, and landscape features of Villa Seghetti Panichi, the Chapel of San Pancrazio, and the Roccolo. Thematic texts were drafted for voice generation via AI, narrative trigger points were defined, and a storyboard was created to visualize the logical flow of the experience. This document played a key role in structuring the immersive journey, enabling a balance between user-driven interaction and narrative coherence, by defining how each action would activate specific visual and auditory content. (Figure 5).

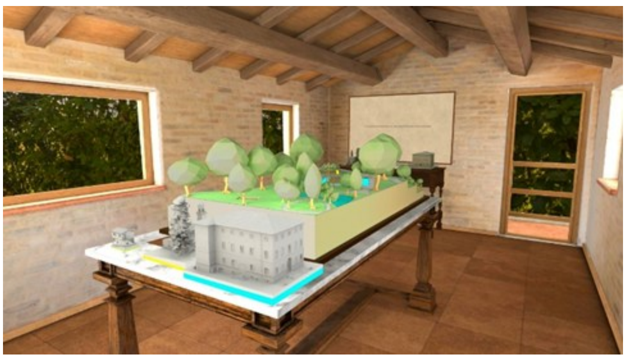

Figure 5. Image captured within the XR headset, providing a view of the virtual environment as experienced by the user.

As part of this phase, the dual structure of the interaction was also designed, articulated in two distinct yet complementary moments. The first, more traditional, involves the user placing 3D models of the buildings within a physical model of the Borgo. The correct placement of each object is triggered by an AI-generated voice narration, created with Murf.AI, which tells the history and key features of the selected building. In parallel, the system manages a change in the visual environment outside the windows, revealing different scenarios consistent with the selected content. This creates a multi-layered immersive environment in which narration, manipulation, and perception are closely interwoven. This component is intended to serve an introductory and orientational function, designed to facilitate user familiarization with the virtual environment, namely the Roccolo, and with the topics being addressed. Secondly, a separate table is equipped with an interactive marble slab. When one of the three buildings is placed on it, a virtual drawer opens, revealing a digital keyboard that is used to enable the user to initiate a natural language dialogue with a conversational system based on a LLM (Figure 6).

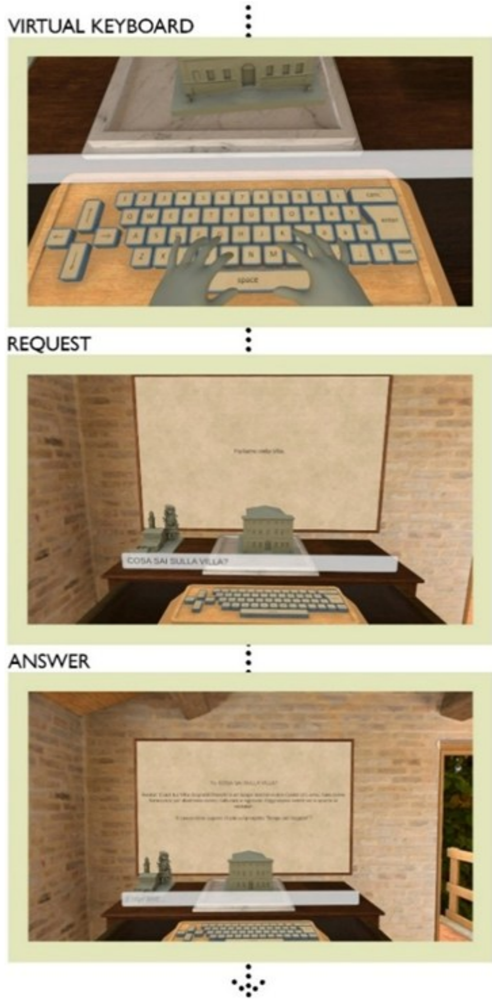

Figure 6. Virtual keyboard interface, with a user-typed question and the corresponding AI-generated response displayed in the immersive environment.

This interactive phase was designed to offer users the opportunity to independently and personally explore the content previously introduced during the initial stage of the experience, thus providing on-demand informational depth. The artificial intelligence system is powered by the Gemini APIs, the interface for accessing Google's latest-generation language models, which enables the generation of coherent, relevant, and context-aware responses tailored to user queries. From a development standpoint, the interaction is based on a system prompt, an invisible instruction provided to the model at the beginning of each session, that is used to guide the behavior of the LLM. The system prompt is established to define essential semantic and stylistic constraints, instructing the model to respond exclusively based on the provided context or prior questions, to respect a predefined character limit for readability, and to consistently adopt a courteous tone aligned with the educational purpose of the experience. Additionally, the prompt is designed to direct the model to suggest related topics whenever possible, and, in cases where no specific information is available for a user's query, to

offer alternative insights related to the general theme, in order to avoid the generation of irrelevant or out-of-scope content.
The model’s contextual knowledge is dynamically loaded based on the user’s interaction. The system distinguishes three main thematic domains, each corresponding to one of the buildings selectable by the user. Each domain is linked to a curated and optimized corpus of texts, including historical data, architectural descriptions, landscape analysis, and information derived from on-site surveys. When the user places a model on the marble slab, the system loads the corresponding context and restricts content generation to that domain, thereby ensuring thematic coherence and informational relevance. The generated responses are displayed in real time on a virtual board placed in front of the user, creating an active learning experience in which knowledge is built through a combination of interaction, curiosity, and personalized feedback.

During the second phase, the 3D representations of the buildings and scene objects were integrated within the virtual environment. However, the integration of GS into standalone VR headsets proved challenging due to their intensive computational requirements and high data complexity. These models required resources exceeding the hardware capabilities of standalone devices, causing slowdowns, latency, and unstable real-time rendering. Therefore, Gaussian-based models were excluded from the standalone VR experience in favor of mesh-based 3D models, which were refined through a careful retopology process, aimed at reducing polygonal complexity while preserving architectural accuracy and ensuring compatibility with standalone VR devices (Gonizzi Barsanti et al., 2022). From a methodological standpoint, a distinction was made between different modelling approaches. Specifically, the Roccolo environment and the other buildings models were reconstructed using a reality-based approach, directly derived from 3D survey data, and subsequently simplified and optimized for real-time use (Figure 7). Conversely, the remaining environmental and scenographic elements were created through direct modelling, following historically and functionally consistent design criteria. These assets were then textured using Adobe Substance 3D Painter to ensure accurate material rendering and visual coherence within the scene. Architectural details were refined through close comparison with the existing built elements, and the entire modelling process was guided by the aim of achieving a high level of visual fidelity without compromising the performance standards required for smooth VR experiences.

In the third phase, the complete experience was implemented through C# scripting within the Unity development engine. This phase included the coordination of object interactions, voice content management, scene transitions, and AI-driven response activation. Each step of the immersive pathway was designed to support a fluid narrative structure, allowing users to engage in active and personalized learning through exploratory behaviour.

Figure 7. Optimized mesh models obtained from photogrammetric processing and laser scanning survey. From top to bottom: Villa, Oratory of San Pancrazio, Roccolo.

The integration of immersive storytelling, gestural interaction, and intelligent dialogue fosters a dynamic, situated learning environment in which the user plays a central role in the construction of meaning. The system, both adaptable and scalable, serves as an innovative model for cultural engagement in XR, opening up meaningful opportunities for application in museum settings, education, and public dissemination (Figure 8).

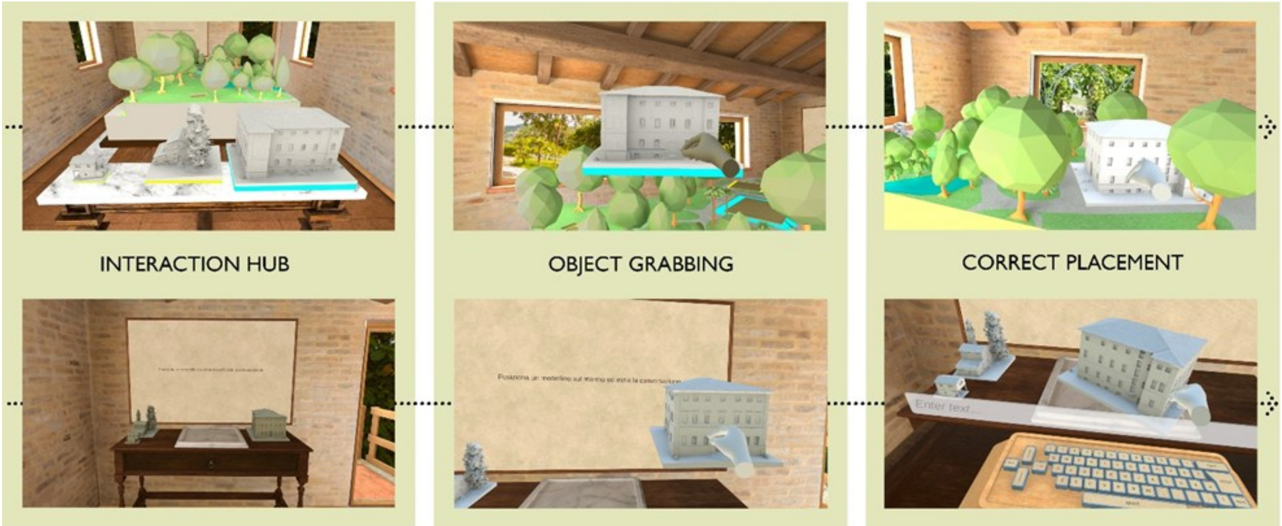

Figure 8. Interaction sequence within the virtual environment: above, the user selects and grabs a building model from the table, places it correctly within the model of the historic park and activates an automatic storytelling. In the second phase, the user selects a model and places it on the pedestal at the center of the table to trigger interaction with the LLM.

3. User evaluation

In line with a conscious methodological approach (Clini et al., 2021), a usability and satisfaction test were conducted with students from the Building Engineering-Architecture program at the Polytechnic University of Marche (Italy). The objective was to assess the communicative and immersive effectiveness of the virtual experience developed for the Borgo, analyzing five key dimensions: authenticity, interaction, navigation, learning, and audience broadening (Angeloni, 2022) (Figure 9).

In the authenticity dimension, users expressed a high level of appreciation for the visual realism of the environment and digital objects: over 80% reported perceiving the Roccolo as a coherent and immersive space, experiencing a strong sense of presence. This outcome confirms the effectiveness of the integrated survey, and the reality-based modeling process employed. Regarding interaction, the experience was considered intuitive during the manipulation of 3D models on the interactive table. However, the use of the virtual keyboard received more mixed feedback: although several users found it functional, only 43.5% considered it immediately simple, suggesting the need to include orientation tools such as short tutorials or visual guides. In terms of navigation, most users reported a clear perception of their position and the interactive elements within the virtual space. Nonetheless, around 20% experienced moments of disorientation, especially when searching for interaction points, indicating the opportunity to introduce more explicit visual cues. For the audience broadening dimension, the results were encouraging because over 75% of participants stated they would recommend the experience to others and developed a renewed interest in visiting the real site after the immersive exploration. This highlights the potential of VR as a tool for cultural enhancement and tourism promotion.

To confirm the robustness of the evaluation instrument, the internal reliability of the questionnaire was assessed using Cronbach's alpha model. This coefficient is used to measure the internal consistency of items within each dimension, evaluating how well they reflect the same construct. With values above the 0.7 threshold, the test showed good internal consistency across all dimensions, confirming the reliability of the instrument used.

DIMENSION	QUESTIONS
Authenticity	1) The perception of the virtual environment is very realistic.
	2) The perception of the objects in the scene is very realistic.
	3) I felt as if I were physically visiting the Roccolo.
Interaction	4) Interaction with the virtual environment was natural.
	5) Interaction with the virtual table was easy.
	6) Interaction with the virtual keyboard was easy.
Navigation	7) I always knew where I was within the virtual environment.
	8) I moved easily within the virtual environment.
	9) I always knew where to go to interact with the objects in the scene.
Learning	10) The information provided is sufficient.
	11) The information provided is clear.
	12) The information provided is interesting.
Audience broadening	13) I would recommend this experience to others.
	14) I am interested in further virtual visit experiences.
	15) I would like to visit Borgo Seghetti-Panichi in person.

Figure 9. The questionnaire designed to investigate the overall user experience across five key dimensions.

Additional specific questions were focused on the virtual keyboard and the functioning of the AI conversational system, within the learning dimension. Results confirmed a general interest in this mode of interaction: about 70% of users reported that the textual dialogue made the experience more engaging and personalized, facilitating a stronger connection with the site's historical and architectural content.

4. Conclusions and Future works

The contribution, focused on the case study of Borgo Storico Seghetti Panichi, highlighted the potential of integrating digital surveying techniques, 3D modeling, and XR environments for CH experience. The introduction of a conversational system based on a LLM was found to significantly enhance the user experience, making the access of CH more personalized and interactive.

The adopted approach combines consolidated methods, such as TLS and UAV photogrammetry, with emerging techniques like 3D GS, enabling the generation of lightweight yet visually realistic models, particularly suitable for real-time immersive applications. In this context, one of the main future developments will involve the integration of GS-based models within the VR environment, with the goal of further optimizing performance and visual quality.

The usability tests confirmed the communicative effectiveness of the system but also revealed certain aspects in need of refinement. Based on this feedback, new development directions are currently being explored to make the interaction even more intuitive and accessible. In particular, the implementation of a voice recognition system is being considered, which would allow users to ask questions naturally and receive personalized answers in multiple languages, delivered through textual, audio, or visual content. At the same time, the knowledge base used by the AI system is expected to be expanded, to provide more detailed, relevant, and articulated responses. This enhancement is crucial to improve the quality of the conversation and to better address the needs of users with varying levels of knowledge and interest. From this perspective, the project represents a replicable model for the digital enhancement of CH, where emerging technologies and AI converge to offer immersive, accessible, and user-centered experiences.

Acknowledgements

The authors would like to thank the owners of the Borgo Storico Seghetti Panichi for their availability and for granting access to the villa and garden, which was essential for the development of this study.

This work was carried out within the framework of the project funded by the Italian National Recovery and Resilience Plan (PNRR), Next Generation EU – Historic Parks and Gardens, M1C3, Measure 2.3.

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