

HERIX: an integrated platform for creating Immersive, Interactive and Liquid eXtended Reality experiences for Cultural Heritage

M.F. Drago¹, E. Marino¹, S. Serratore¹, A. Lagudi¹, L. Barbieri¹, and F. Bruno¹

¹Department of Mechanical, Energy and Management Engineering (DIMEG), University of Calabria, P. Bucci, 46C, Rende, CS 87036, Italy

Abstract

The increasing demand for interactive and immersive experience in the field of cultural heritage (CH) has stimulated the exploration of novel approaches to engage audiences with cultural assets. Extended Reality (XR) technology has emerged as a powerful tool in this domain, offering high-quality, immersive, and interactive experiences that enhance the appreciation of cultural and natural heritage. Despite their potential, the widespread adoption of XR solutions remains limited, primarily due to the technical complexity associated with content creation and the need to ensure compatibility across a broad range of XR devices. To address these challenges, this paper presents HERIX, a scalable and modular platform designed for the creation and deployment of XR scenarios. HERIX provides an integrated environment that enables content creators with limited programming skills to develop interactive XR experiences while allowing visitors to engage with them. The platform consists of three key components: an authoring tool for scenario creation, two XR applications for content consumption, and a web server for data access and management. By streamlining the authoring process, HERIX lowers technical barriers and enhances accessibility. A preliminary evaluation through two user studies highlighted its potential and appeal within cultural contexts.

CCS Concepts

· Computing methodologies → Mixed / augmented reality; Virtual reality · General and reference → Evaluation;

1. Introduction

In recent years, the demand for innovative solutions in CH dissemination has significantly increased [IUMV23, MDG23]. Museums, archaeological sites, and cultural institutions are increasingly adopting digital technologies to enhance visitor engagement and improve accessibility [LBBS23, ATU*21, SRH*20]. The integration of digital tools not only facilitates a more immersive experience but also helps overcome traditional barriers related to physical access and content interpretation [MDG23, BRL*20, KGC*20].

Recent research highlighted the growing role of digital solutions in CH. For instance, Jin et al. [JL22] examined how virtual technologies enhance interactivity and spatial perception in cultural experiences, broadening access to heritage for diverse audiences. Preserving heritage is crucial. Cultural assets face threats from aging and environmental factors. Digital tools, together with traditional and technical methods, help safeguard them. They also enhance public engagement and support knowledge dissemination [TLTP23].

In this evolving landscape, XR technologies offer new opportunities to develop and deploy interactive scenarios that enhance users' cultural immersion, learning and creativity experiences [MGMB22, GBL*22]. The release of numerous applications such as virtual tours [BpAGP22, DIMBD22,

MYT*19], interactive reconstructions of destroyed artifacts [SBKP21], and immersive storytelling experiences in CH sites [YWC*25, SOO*24] demonstrate how XR technologies are transforming CH sector to enhance engagement and support digital preservation [DL24, BBG*22].

Despite the growing interest in XR applications for CH, the development of such experiences remains a challenge due to the technical expertise required and the complexity of content creation [VMN*22, FFD*21]. Moreover, the development process often involves significant financial and time investments, which can limit the scalability and sustainability of these solutions, especially for smaller institutions with limited financial resources [FRA17]. Consequently, despite their high potential, XR applications encounter barriers that limit their widespread adoption and use in CH settings.

Based on these considerations, this paper introduces HERIX, a scalable, flexible, and modular platform designed to support and guide content creators for the development and deployment of liquid XR scenarios. The proposed platform aims to address the technical and financial challenges often associated with the development of XR experiences in the CH domain by providing an integrated environment that lowers the barriers to entry for content creators, especially for those with limited programming skills. More specifically, HERIX streamlines the authoring process,

allowing users to design and implement immersive and interactive XR experiences without requiring extensive technical expertise.

The proposed platform consists of the following three core components. First, an authoring tool enables content creators to develop XR scenarios through an intuitive user interface, by facilitating the integration of multimedia elements, spatial interactions, and user engagement mechanics. Second, XR applications provide an immersive environment for end-users to access and interact with the created content, enhancing their engagement with CH through virtual exploration, interactive storytelling, and real-time data visualization. Third, a web server manages data storage and distribution, ensuring deployment, scalability, and accessibility of XR content across different devices and platforms.

By integrating these components into a cohesive ecosystem, HERIX simplifies the entire lifecycle of XR content creation from conceptualization and development to testing and deployment of XR scenarios. This solution not only enhances the accessibility of XR technologies within the CH sector but also supports the scalability and sustainability of digital initiatives, making XR-based experiences more feasible even for institutions with limited financial and skilled human resources.

To assess the effectiveness of the proposed platform, a preliminary evaluation was conducted through two user studies, which provided valuable insights into both the authoring process and the user experience. The findings highlight HERIX's potential to facilitate the prototyping and consumption of XR scenarios, demonstrating its capability to foster engagement, learning, and creativity within CH contexts.

The remainder of the paper is organized as follows. Section 2 presents a comprehensive review of existing research, focusing on key contributions in the field of authoring tools proposed for creating XR experiences. Section 3 introduces the proposed platform and describes its data workflow. Section 4 outlines the design and execution of preliminary experimentation, which adopts subjective metrics to evaluate usability and user experience. Section 5 discusses the results, and Section 6 provides conclusions and future works.

2. Related works

Over the last few years, XR has emerged as a powerful medium for enhancing the accessibility, understanding, and engagement with CH [BBG*22, BFH*23, CLR*22]. Numerous applications have demonstrated the potential of immersive media to provide contextual, narrative-driven, and interactive experiences, such as virtual museum tours, AR-enhanced site visits, and 3D reconstructions of lost or inaccessible artifacts and cultural sites [FHS21, TLM22, GBL*22]. However, the development of XR experiences for CH often entails high technical complexity. Challenges, in fact, include the integration of multimodal content, real-time interaction design, device and platform heterogeneity, and the need for continuous updates and maintenance [DL24, BPF*18, FHS21, BFH*23]. In addition, many heritage institutions lack the internal expertise or financial resources to develop such experiences independently [WDL*25, CB20].

Recent efforts in XR content creation tools have led to a growing divide between authoring platforms intended for expert developers, which offer high flexibility but require coding skills, and those designed for non-programmers, prioritizing accessibility and ease of use. This distinction has been widely acknowledged in comparative reviews of VR/AR authoring environments, which typically categorize tools according to the required technical expertise, the degree of abstraction in the interface, and the type of interaction supported such as scripting, visual programming, natural language, or direct manipulation [CMG*22]. For example, although frameworks such as Unity and Unreal Engine provide a high degree of control and performance, they remain largely inaccessible to CH professionals and educators who lack formal training in programming [BPF*18]. Conversely, a new generation of no-code and low-code tools has emerged to empower broader communities of users, including curators, designers, and artists, to produce rich XR applications [CMG*22, CPS24].

Generally speaking, coding-based authoring environments are still the preferred choice for XR experiences requiring high-performance graphics, real-time interaction, and integration with external data sources or AI-driven behaviors. Platforms like CAVE-AR enable live simulation and debugging of AR applications by visualizing user actions and sensor data in a shared virtual space. These tools rely heavily on standard programming practices and support integration with Unity for runtime customization [CF19]. Similarly, ConnectVR leverages a trigger-action model to let creators build interactive narratives based on cause-effect chains using a visual scripting system. Although designed to minimize code, it still assumes a basic familiarity with interaction design and event-driven logic [CPS24]. In contrast, no-code platforms have gained traction for their ability to simplify the XR development process. AtomXR, for example, combines immersive in-headset authoring with natural language input, allowing users to create spatial logic and interactive elements using speech, gaze, and touch. This hybrid interaction model significantly reduces the cognitive load and enables rapid prototyping even by users without prior XR experience [CAN*23]. Similarly, tools like Narralive and ARTutor propose structured approaches to digital storytelling in heritage through template-based interfaces. These allow non-technical users such as museum educators or archaeologists to compose mobile or AR-based experiences by arranging scenes, linking content, and defining narrative flow without programming [LT18]. A related approach is presented [GZK*20] that enables curators to build interactive experiences through visual scripting and integrates avatars and gesture-based interaction. However, such solutions are often tied to specific hardware and lack unified cloud-based management and narrative modularity.

A number of platforms aim to integrate authoring, visualization, and user interaction often including features like avatars, real-time collaboration, or conversational interfaces. ATON, for example, is an open-source framework for building liquid web applications that are responsive across devices and support both immersive presentation and collaborative annotation. Designed specifically for CH sector, it provides modular tools for 3D content

management, storytelling, and real-time collaboration through web technologies [FFD*21].

While numerous authoring tools and platforms have been proposed to facilitate the development of XR experiences in CH, most existing solutions still suffer from critical limitations that constrain their adoption, flexibility, and scalability in real-world CH scenarios. For example, the high fragmentation of the development pipeline as they focus on specific parts of this process without offering a coherent and unified environment for development. Furthermore, experiences are tightly bound to specific hardware or deployment environments, limiting their long-term sustainability and broad accessibility.

To overcome these constraints, this paper introduces HERIX, an innovative platform specifically designed for the CH domain. HERIX provides a modular, scalable, and user-friendly environment that streamlines the entire development workflow, making it accessible to non-technical users. It enables the creation and deployment of liquid XR experiences across multiple platforms, supporting broader adoption and reusability.

3. The proposed platform

HERIX is an innovative platform designed to streamline the creation, distribution, and delivery of immersive, interactive, and liquid XR experiences in CH contexts. Developed in Unity® environment for its cross-platform capabilities [MBBM24], the system supports scalable deployment across both AR and VR environments. Importantly, to ensure flexibility and scalability, HERIX adopts a modular architecture structured around three main components: the authoring tool, XR applications, and a web server (Figure 2). These components communicate via well-defined APIs and structured data protocols, enabling interoperability and a clear separation between content preparation and consumption. This allows each module to evolve independently and be reused across multiple XR experiences. In addition, HERIX enables non-technical users to author XR scenarios through a guided, no-code interface, defining key elements such as environments, media assets, and interaction rules. The authored content is then rendered through AR/VR applications, which retrieve and display the data from the centralized server, adapting to the capabilities of the target device.

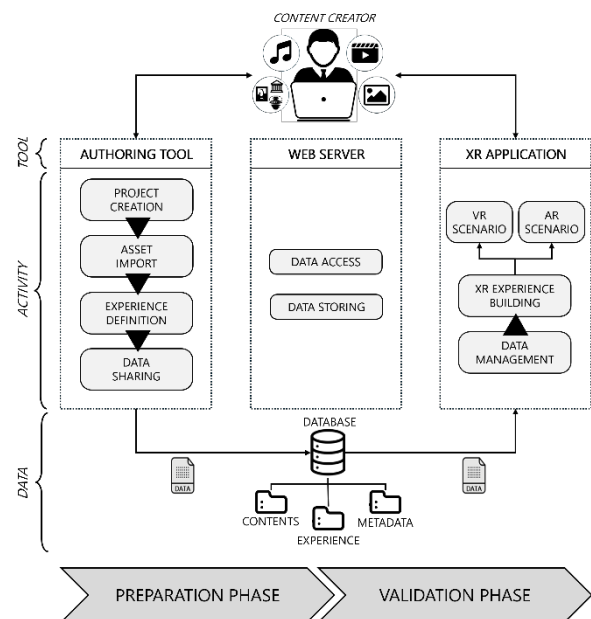


Figure 2: Workflow of the HERIX platform.

As illustrated in Figure 2, the preparation phase centers around the authoring tool, which enables content creators, even those with limited technical expertise, to design XR experiences effectively. Authoring tool's architecture adopts a component-based design, where core functionalities such as asset management, narrative block configuration, and interaction design are developed as reusable modules. This structure supports customization, facilitates future extensions, and ensures scalability across different experience types (AR or VR).

In general, project creation is the initial step in the XR content development workflow, in which content creators define essential metadata and key parameters shaping the XR experience. These include the experience type (AR or VR), associated cultural site, intended audience profile, localization settings (supported languages), and target devices (smartphones, tablets, or VR headsets), along with hardware specifications. The structured configuration of these parameters guarantees an immersive and consistent user experience, while offering flexibility to adapt content to diverse and evolving needs.

The second step, i.e. asset import, involves uploading and managing the digital resources that will populate the XR experience. The authoring tool supports a wide range of media formats, including 3D models, images, videos, and audio contents. Once imported, assets are processed and optimized to ensure smooth rendering across different devices. Additionally, the system provides built-in asset categorization, organizing resources into a structured library with predefined categories for easier management and retrieval.

The third step, experience definition, represents the core phase within the entire workflow, focusing on structuring the immersive user journey. At this stage, a detailed storyline is generated to define the narrative structure of the experience, encompassing accessible content, interaction rules, and conditions of engagement. A key initial functionality involves the definition and customization of the virtual environment. For instance, content creators can import 2D or 3D scenarios, also georeferenced maps, representing archaeological sites, museums, monuments, and artifacts. These scenarios provide a spatial reference framework, facilitating the subsequent integration of various multimedia and interactive elements within the immersive environment. The experience is organized into a structured set of narrative blocks, which are fundamental entities characterizing the immersive scenario. Different types of blocks have been implemented that can be categorized as follows:

- **Content Block:** this includes diverse multimedia elements such as videos, images, 3D models, texts, and audio;
- **Logic Block:** this defines the user's interaction logic within the virtual environment through an event-action mechanism;
- **Virtual Assistant Block:** this leverages artificial intelligence (AI) technology to provide contextually relevant information about cultural artifacts, enriching the overall immersive experience.

For example, a content creator may use a content block to insert a 3D virtual replica of an archaeological artifact, then add a logic block to define a set of user interactions, allowing users to manipulate the artifact (e.g. grasp, rotate, scale, move) to closely examine its artistic details from multiple perspectives.

At this stage, content creators also establish the spatial arrangement of these narrative blocks, specifying their precise positioning within the virtual environment. Therefore, the immersive experience follows a graph-oriented logic, where nodes represent narrative blocks, and arcs define activation logics and conditions for progression within the experience. This structure enables the flexible authoring of non-linear and adaptive experiences.

The fourth step, data sharing, produces a structured data package containing all components defined during the authoring process, including project settings, assets, interaction logic, and metadata. This package is designed to ensure consistency, integrity, and reusability of the experience over time. Once the data package is generated, the web server handles its upload to a centralized cloud repository, where the information is stored and organized into logical entities such as *Experience*, *Contents*, and *Metadata*. To support accessibility and integration, the web server also provides a set of services that allow the authoring tool and XR applications to query, retrieve, and update the stored content. This infrastructure

enables synchronization between the preparation and validation phases, while ensuring scalable, secure, and interoperable deployment of XR experiences across heterogeneous devices.

The second phase, validation, allows content creators to preview and evaluate the XR experience before final deployment. This step is essential to ensure accuracy, usability, and overall content quality. Through the XR applications, in fact, creators can simulate the AR or VR experience on different target devices, verifying spatial arrangements, interaction flows, and UI elements in realistic runtime conditions. By testing the experience from the end-user's perspective, creators can identify inconsistencies, refine interactions, and apply data-driven improvements. This phase supports both technical validation and iterative content refinement based on usability testing.

Specifically, the first step, data management, involves retrieving and handling the XR experience previously authored and stored in the centralized cloud repository. This process is carried out by querying the database through the dedicated web services exposed by the web server, which enable secure and efficient access to the structured data. Therefore, the structured data are retrieved and made available for the subsequent and final step, the experience building phase.

In this concluding phase, all aspects of the XR experience lifecycle are managed, including asset loading, interaction logic configuration, content adaptation to the capabilities of the target device, and preparation of the immersive environment for user interaction. This phase ensures that each component is correctly interpreted and rendered, maintaining the coherence and integrity defined during the authoring process.

Once the XR experience is finalized, it can be accessed by users through two different modes. The AR scenario, specifically designed for mobile devices such as smartphones and tablets, overlays digital content onto the real-world environment, enhancing user interaction with physical contexts. Conversely, the VR scenario, optimized for HMDs (Head-Mounted Displays), immerses users in fully virtual environments, enabling them to explore CH content entirely within digitally recreated spaces.

An additional feature of the proposed platform is the integration of an AI-powered virtual assistant that provides context-aware information on cultural assets throughout the XR experience. Configurable by content creators, it adapts responses based on user location, actions, and preferences. Technically, it leverages a common ChatGPT-based service [SbPnPr25], enabling multi-turn dialogues and real-time, context-sensitive responses. The assistant is accessible via dedicated APIs and integrates into both AR and VR environments.

4. Preliminary experimentation

A preliminary evaluation was conducted to assess the overall effectiveness and usability of the HERIX platform in a realistic context. The study aimed to validate the complete workflow, from

the creation of XR experiences using the authoring tool to their deployment and interaction through both AR and VR applications. The evaluation pursued three main objectives:

- to assess the usability of the platform in designing and delivering immersive CH experiences;
- to evaluate the quality of the user experience and the level of satisfaction when interacting with both AR and VR scenarios;
- to collect qualitative feedback to support the initial validation of the platform's potential within the CH domain.

The experimentation involved three participants (one male, two females; average age: 33) with academic and professional backgrounds in archaeology. While they had no prior experience with XR authoring tools, all had previously interacted with AR and VR applications in CH settings. Their domain expertise enabled them to provide context-aware insights into both the content creation process and the immersive experience.

This first-stage study was intentionally designed as a preliminary internal evaluation involving CH professionals as content creators. Their domain expertise enabled them to provide context-aware insights into both the authoring process and the resulting immersive experiences. Although they evaluated scenarios they had created themselves, this setup allowed for a full-cycle assessment of the HERIX platform and helped identify key areas for improvement before broader testing with final users.

4.1. Procedure

The experimental procedure was designed to preliminarily validate the HERIX platform by testing its workflow, involving participants in both phases of the process. Initially, they used the HERIX authoring tool to create two XR scenarios, and subsequently experienced the resulting applications.

The experimentation was conducted over the course of two separate days. On the first day, following a brief introduction outlining the objectives of the study and the tasks to be performed, the participants attended a training session of approximately 20 minutes to familiarize themselves with the functionalities of the HERIX authoring tool. After the training, participants were guided by the experimenter in the development of two XR scenarios using the various types of narrative blocks available in the platform. Specifically, they were asked to reproduce a predefined scenario, as described by the experimenter. The content creation phase lasted approximately 45 minutes per scenario. Upon completion, participants completed a structured questionnaire and provided qualitative feedback on the authoring functionalities and the usability of the platform.

On the second day, participants interacted with the XR scenarios they had previously created using the HERIX authoring tool. As in

the first session, an introductory briefing was provided to present the main functionalities of the XR applications. This was followed by a short demo session of approximately 5 minutes, allowing participants to become familiar with the application interfaces. They then explored both the AR and VR scenarios, each lasting approximately 30 minutes. At the end of the session, participants completed a structured questionnaire aimed at assessing both the usability of the XR applications and their overall user experience, also providing comments and feedback.

4.2. Metrics

Regarding the metrics adopted for the preliminary evaluation, the testing phase relied on quantitative instruments deemed effective for providing measurable insights into the usability and user experience of both the authoring tool and the XR applications.

To assess usability, the System Usability Scale (SUS) was administered in two distinct phases: following the use of the HERIX authoring tool and after the exploration of the XR applications in both AR and VR modalities. The standard SUS questionnaire consists of 10 statements rated on a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree" [MBSB24, LS18]. The resulting score, which ranges from 0 to 100, offers a clear and interpretable indicator of overall usability. Some items are specifically designed to evaluate learnability (e.g., items 4, 7, and 10), while the remaining items focus on general usability aspects [WZB*19].

As for user experience and satisfaction, the User Experience Questionnaire (UEQ) was employed to collect participants' impressions. This standardized tool includes 26 items grouped into six dimensions: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Responses are recorded on a scale from -3 (most negative) to +3 (most positive) [SAY22, IL24].

Additional qualitative data were collected through participants' comments and feedback provided throughout the sessions, offering further insights to support the preliminary evaluation of the platform.

4.3. Case studies

The preliminary evaluation was structured around two distinct case studies, reflecting the dual nature of the HERIX platform, namely its ability to support both in-situ and fully virtual CH experiences. In both scenarios, participants engaged in a guided tour developed using the HERIX authoring tool. The AR experience was conducted on-site at the archaeological park of Timpone della Motta in Francavilla Marittima, a cultural area located in the Calabria region of southern Italy. Users were guided through key areas of the site, where digital reconstructions of selected artifacts were spatially anchored to their original locations, allowing participants to contextualize the material culture within its

authentic setting. Conversely, the VR experience took place in a controlled indoor environment simulating a museum context. In this setting, participants explored a virtual exhibition specifically designed to present the same artifacts discovered at the archaeological site, offering an immersive interpretive experience independent of physical constraints.

All media assets employed in the AR and VR scenarios, such as 3D reconstructions, images, and descriptive texts, were previously selected by the archaeologists involved in the study. These assets were imported during the initial phase of the authoring process, allowing each participant to structure personalized experiences starting from a shared dataset.

The first case study focused on an AR scenario developed using the HERIX authoring tool and experienced directly on-site. The selected archaeological site offered a relevant context for testing due to its combination of cultural and environmental features, making it particularly suited to location-based AR applications.

Participants used the authoring tool to import and organize 2D and 3D assets, define interaction flows, and integrate multimedia content such as textual descriptions, images, and audio. The AR experience was then deployed on a tablet device (Samsung Galaxy Tab S8) and tested on location.

Digital content was anchored in the physical environment using a hybrid approach that combined GPS-based geolocation with physical markers placed throughout the site. This ensured accurate spatial alignment and effective contextualization of the augmented information. The case study enabled the evaluation of the authoring tool's ability to support the creation of geolocated and context-aware content, as well as the overall usability and clarity of the AR experience in a real-world CH setting.

Specifically, the AR scenario consisted of a structured experience as a guided tour across two key areas, i.e., Area 1 and 2, of the archaeological site. As illustrated in Figure 3, a georeferenced map of the site was used to anchor digital content in the physical space, supporting spatial awareness and thematic progression.

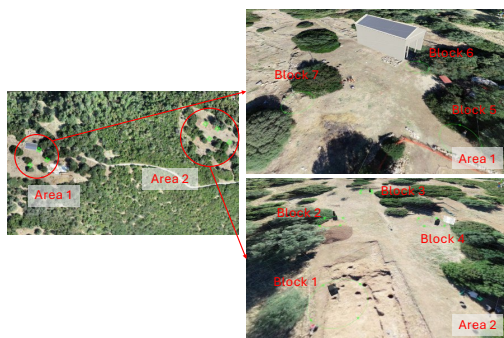


Figure 3: A top-down view of the Timpone della Motta archaeological site: the selected two key areas (left) and the corresponding block elements (right).

As depicted in the Figure 3, each area was associated with a set of narrative blocks, carefully designed to convey different aspects of the site's historical and cultural relevance. Various types of content were deployed, including 3D artifacts, contextual texts, images, and audio elements. This inclusion aimed to simulated realistic and engaging visit, while testing the flexibility of the HERIX platform. Figure 4 shows a participant while adopting the authoring tool to prepare the augmented scenario.



Figure 4: A participant while using the authoring tool (a), and close-up of the virtual scenario being edited (b).

Conversely, Figure 5 shows the user in the archeological site (Fig.5a) while experiencing the augmented scenario (Fig.5b).

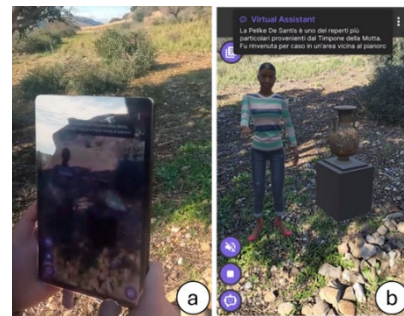


Figure 5: A participant while experiencing the AR scenario in the archeological site (a), and a view of the augmented scenario (b).

The second case study focused on a VR scenario developed using the HERIX authoring tool and experienced within a fully digital environment. In contrast to the AR experience, which was linked to a real-world location, this scenario was designed to simulate a virtual museum setting where cultural content could be accessed virtually. Participants used the HERIX tool to configure the virtual environment by importing 3D assets, organizing exhibition areas, and embedding descriptive and multimedia materials such as texts, images, and audio guides. The resulting VR experience was deployed to an Oculus Quest 3 headset and tested in a controlled indoor space.

The interaction design replicated a guided museum visit, enabling users to freely navigate the virtual environment, explore 3D reconstructions of archaeological artifacts, and receive contextual information via the virtual assistant. Unlike the AR scenario,

navigation in this case was fully immersive and independent of physical constraints, allowing users to focus entirely on content exploration and overall usability.

In contrast to the AR scenario, which was organized around three spatial areas of the site, the VR environment was structured as a curated exhibition featuring five main point of interests (POIs). Each point was dedicated to one of the five most representative artifacts from the archaeological site of Timpone della Motta, ensuring their accessibility and interpretability within a coherent digital layout. Figure 6 shows a perspective view of the virtual scenario, illustrating the spatial layout and distribution of the narrative blocks within the exhibition space.

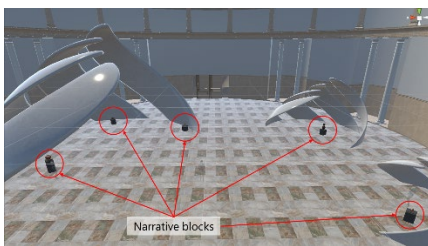


Figure 6: Virtual environment with integrated narrative blocks.

This case study allowed for the evaluation of the HERIX platform's potential to support virtual exhibition design, multimodal content integration, and intuitive navigation within a 3D environment. It also provided insights into how virtual settings can enhance the accessibility of CH materials for remote audiences. The virtual scenario was designed to mirror, in part, the structure of the AR experience, maintaining thematic continuity while exploring the affordances of VR.

Figure 7 shows one participant while preparing the VR scenario, integrating a narrative block within the virtual museum.

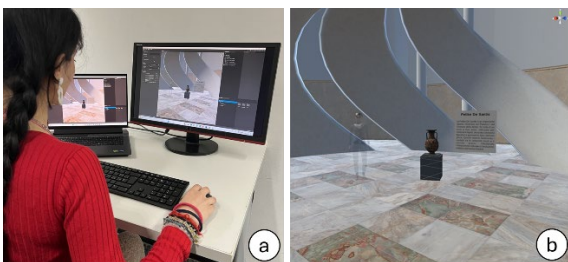


Figure 7: A participant using the HERIX authoring tool to prepare the VR scenario (a), and a view of the resulting virtual environment with an integrated narrative block (b).

Figure 8 shows participants exploring the virtual scenario using a VR headset, navigating within the space and interacting with 3D contents.



Figure 8: A participant experiencing the VR scenario using a headset (a), and corresponding in-environment view from the user's perspective (b).

5. Results and experimentation

The collected data were analyzed using descriptive statistical methods in Microsoft Excel. Graphs include error bars representing the 95% confidence interval, offering a clearer visual indication of data variability and reliability.

The results of the SUS questionnaire show an overall positive perception of usability across the two components of the HERIX platform, i.e., the authoring tool and the XR applications. In particular, the authoring tool achieved an average SUS score of 70.83, while the VR and AR applications scored 77.50 and 75.00, respectively. These scores suggest that participants evaluated the platform as usable and effective in supporting both content creation and immersive experience delivery. According to standard SUS interpretation benchmarks, the tested components fall within the "Good" usability range [Bro13].

Furthermore, Figure 9 illustrates the SUS results at the item level for the authoring tool and the two XR applications. Each item is labeled from Q1 to Q10 and corresponds to a specific aspect of usability: Use Frequency (Q1), Simplicity (Q2), Ease-of-use (Q3), Independence (Q4), Integration (Q5), Consistency (Q6), Learning Curve (Q7), Efficiency (Q8), Self-Confidence (Q9), and Prior Knowledge (Q10). To improve clarity and allow for consistent interpretation, the scores for the negatively worded items (Q2, Q4, Q6, Q8, and Q10) have been inverted, ensuring that higher values uniformly reflect more positive evaluations.

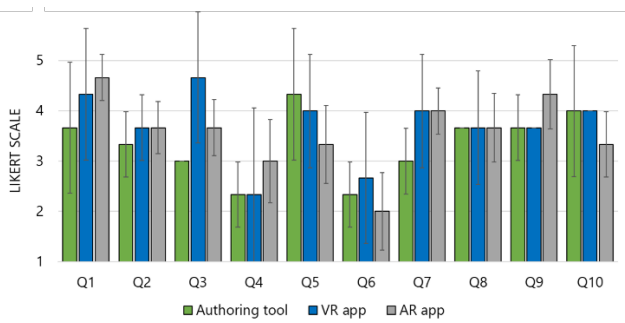


Figure 9: Average Likert scale rating results of SUS for the authoring tool and XR applications.

The AR app received the highest score for Use Frequency ($M = 4.67$, $SD = 0.58$), indicating a strong intention to reuse the tool. It was also positively rated for Self-Confidence ($M = 4.33$, $SD = 1.15$) and Learning Curve ($M = 4.00$, $SD = 0.00$), suggesting that users felt confident and found the app easy to learn. However, it showed the lowest rating among all tools for Consistency ($M = 2.00$, $SD = 0.58$), pointing to perceived inconsistencies in the interface or behavior. The VR app also performed well in key usability aspects. It scored highly in Ease-of-use ($M = 4.67$, $SD = 1.15$), Use Frequency ($M = 4.33$, $SD = 1.15$), and Learning Curve ($M = 4.00$, $SD = 1.00$), indicating that users found it intuitive and quick to become familiar with. As with the AR app, however, lower ratings were reported in Consistency ($M = 2.67$, $SD = 1.15$) and Independence ($M = 2.33$, $SD = 1.53$), suggesting a need for improvements in interface coherence and user autonomy. The authoring tool was particularly appreciated for Integration ($M = 4.33$, $SD = 1.15$) and Prior Knowledge ($M = 4.00$, $SD = 1.15$), indicating that users felt well-prepared to interact with it and recognized a strong cohesion of its features. It also scored positively on Efficiency ($M = 3.67$, $SD = 0.00$) and Self-Confidence ($M = 3.67$, $SD = 0.58$). Nonetheless, like the other tools, it exhibited lower ratings in Consistency ($M = 2.33$, $SD = 0.58$) and Independence ($M = 2.33$, $SD = 0.58$), revealing challenges in providing a predictable user experience and sufficient user autonomy. Across all tools, Efficiency was rated consistently ($M = 3.67$), reflecting general satisfaction with task completion speed and effort, as interpreted within the SUS framework. Simplicity showed moderate and similar ratings across tools, with slightly better scores for the VR and AR apps ($M = 3.67$) compared to the authoring tool ($M = 3.33$). Notably, Independence and Consistency emerged as recurring issues, particularly for the authoring tool and the AR app.

Table 1 reports the mean scores for each individual SUS item.

Table 1: Likert scale ratings for each individual SUS item across all evaluated tools.

Item	Authoring tool		VR app		AR app	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Q1	3.67	1.15	4.33	1.15	4.67	0.58
Q2	3.33	0.58	3.67	0.58	3.67	0.58

Q3	3	0	4.67	1.15	3.67	0.58
Q4	2.33	0.58	2.33	1.53	3	1
Q5	4.33	1.15	4	1	3.33	0.58
Q6	2.33	0.58	2.67	1.15	2	0.58
Q7	3	0.58	4	1	4	0
Q8	3.67	0	3.67	0.58	3.67	0.58
Q9	3.67	0.58	3.67	0.58	4.33	1.15
Q10	4	1.15	4	0	3.33	0.58

Note: Q1: Use Frequency, Q2: Simplicity, Q3: Ease-of-Use, Q4: Independence, Q5: Integration, Q6: Consistency, Q7: Learning Curve, Q8: Efficiency, Q9: Self-Confidence, Q10: Prior Knowledge.

In summary, the results indicate good usability across all three tools, though attention may be needed to enhance perceived Consistency (Q6) and Independence (Q4), particularly in the AR app and authoring tool, respectively.

Furthermore, the collected data were analyzed using the UEQ questionnaire to assess the user experience across both the VR and AR scenarios. Figure 10 presents a bar chart showing the mean values for each of the six UEQ scales separately for the two modalities.

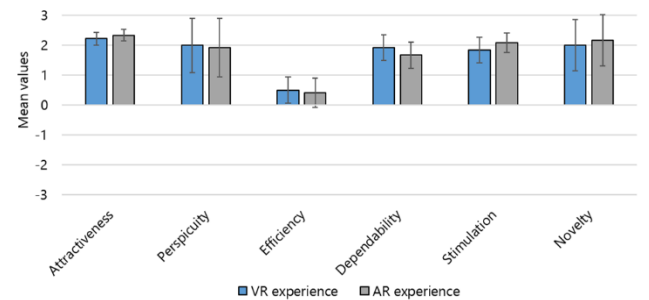


Figure 10: UEQ results of the study for both VR and AR scenarios.

The analysis revealed generally positive perceptions across all six dimensions. Attractiveness was rated highly in both conditions, with slightly higher values in the AR scenario ($M = 2.33$, $SD = 0.17$) compared to the VR scenario ($M = 2.22$, $SD = 0.19$), indicating that participants perceived both experiences as pleasant and visually engaging. Perspicuity, which evaluates the clarity and ease of understanding of the interface, showed a marginally higher mean score in the VR condition ($M = 2.00$, $SD = 0.87$) relative to AR ($M = 1.92$, $SD = 0.80$), suggesting that users found the VR interface slightly more intuitive. Efficiency received comparatively lower ratings ($M = 0.50$, $SD = 0.43$ for VR; $M = 0.42$, $SD = 0.38$ for AR), though still within the positive range. These scores imply that while both modalities were generally usable, some effort was required to complete tasks effectively. Regarding Dependability, the VR experience was rated more favorably ($M = 1.92$, $SD = 0.58$) than AR ($M = 1.67$, $SD = 0.38$), indicating a stronger sense of control and predictability during interaction. Conversely, the AR condition outperformed VR in terms of Stimulation ($M = 2.08$, $SD = 0.29$ vs. $M = 1.83$, $SD =$

0.38), reflecting higher levels of engagement and excitement in the augmented environment. Lastly, Novelty scores also favored the AR scenario ($M = 2.17, SD = 0.76$) over VR ($M = 2.00, SD = 0.75$), suggesting that participants found the AR experience slightly more innovative and original.

In addition, the UEQ metric enables the comparison of user experience outcomes from the evaluated XR applications with a standardized benchmark dataset, which includes responses from 20'190 participants across 452 studies [SHT17]. This dataset supports a relative evaluation of product quality by classifying each UEQ dimension into five qualitative categories: Excellent, Good, Above Average, Below Average, and Poor, according to the distribution of historical scores. The outcomes of this analysis are presented in Table 2 and Table 3, and are also illustrated in Figure 11.

Table 2: UEQ analysis and comparison to the benchmark dataset for the VR application.

Scale	Mean	S.D.	Comparison to benchmark	Interpretation
S1	2.22	0.19	Excellent	In the range of the 10% best results
S2	2.00	0.87	Good	In the range of the 10% best results
S3	0.50	0.43	Bad	In the range of the 10% best results
S4	1.92	0.58	Excellent	In the range of the 10% best results
S5	1.83	0.38	Excellent	In the range of the 10% best results
S6	2.00	0.75	Excellent	In the range of the 10% best results

Note: S1: Attractiveness, S2: Perspicuity, S3: Efficiency, S4: Dependability, S5: Stimulation, S6: Novelty.

Table 3: UEQ analysis and comparison to the benchmark dataset for the AR application.

Scale	Mean	S.D.	Comparison to benchmark	Interpretation
S1	2.33	0.17	Excellent	In the range of the 10% best results
S2	1.92	0.80	Good	10% of results better, 75% of results worse
S3	0.42	0.38	Bad	In the range of the 25% worst results
S4	1.67	0.38	Good	10% of results better, 75% of results worse
S5	2.08	0.29	Excellent	In the range of the 10% best results
S6	2.17	0.76	Excellent	In the range of the 10% best results

Note: S1: Attractiveness, S2: Perspicuity, S3: Efficiency, S4: Dependability, S5: Stimulation, S6: Novelty.

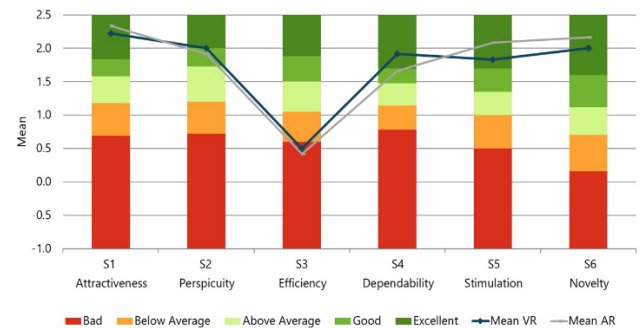


Figure 11: UEQ comparison with benchmark dataset.

The comparison with the UEQ benchmark dataset offers a valuable perspective on the quality of the user experience provided by the two XR applications. Overall, the VR experience was perceived very positively, with most dimensions such as Attractiveness, Stimulation, Novelty, and Dependability classified within the highest benchmark category. This suggests that users found the application engaging, visually appealing, and innovative, while also experiencing a strong sense of control and reliability during interaction.

The clarity of the interface (Perspicuity) was also evaluated positively, albeit slightly less prominently. This indicates that, while the system was generally intuitive, some users may have encountered minor difficulties in understanding specific functionalities. The only dimension that did not reach a satisfactory level was Efficiency. In this regard, participants appeared to perceive the interaction as somewhat demanding in terms of effort or responsiveness, highlighting a potential area for improvement in future iterations of the system.

Similarly, the AR experience showed a highly favorable profile, with several scales, particularly those related to emotional and aesthetic appeal, rated as excellent. Users appreciated the novelty and stimulation offered by the augmented content, which enhanced their engagement and motivation. As in the VR case, however, Efficiency emerged as the most critical aspect, falling below the average range when compared to other products in the benchmark dataset. This result points to a shared challenge across both modalities, likely related to the complexity of navigating and performing actions in immersive environments.

Therefore, these findings are also supported by qualitative feedback collected during the testing sessions. Users described the applications as "engaging and enjoyable to explore," and noted that "the visual design and immersive elements were very good." However, comments such as "some actions required more steps than expected" and "it took me a bit to figure out how to complete certain tasks" reflect the lower ratings observed for Efficiency in the UEQ. These insights are also consistent with the SUS results as well, which indicate a generally high level of usability, yet reveal room for improvement in optimizing task execution and system responsiveness.

Nevertheless, this study presents some limitations that should be acknowledged when interpreting the findings. From a methodological standpoint, the participant sample was limited in size and lacked diversity in terms of user profiles, as it was composed exclusively of archaeology professionals. This homogeneity may have influenced the evaluation outcomes, particularly with regard to expectations and familiarity with digital tools in the CH domain. Furthermore, the evaluation protocol followed a structured and guided approach, which, although useful for ensuring consistency across sessions, did not allow participants full freedom to explore the platform or engage in the creation of personalized or alternative experiences. As a result, the system's potential for supporting creative and open-ended authoring processes could not be fully assessed.

From a technical perspective, the current version of the platform still presents some usability challenges, particularly in terms of interaction efficiency, as indicated by the UEQ results. These aspects may have impacted the fluidity of both experiences.

Future work will focus on validating the platform in real-world heritage contexts and involving a broader, more diverse pool of users, including cultural operators with varying backgrounds and levels of digital expertise, as well as end users such as tourists. To better assess the platform's creative and collaborative potential, upcoming evaluation phases will adopt more flexible and exploratory scenarios. In parallel, development will continue with the integration of collaborative features and the exploration of adaptive, AI-driven authoring tools to enhance personalization and scalability. Particular attention will also be devoted to improving interaction efficiency, as well as reinforcing interface consistency and user autonomy to support a wider range of user profiles.

6. Conclusions

This paper introduced HERIX, a modular and scalable platform for the creation of immersive, interactive, and liquid XR experiences in the CH domain. By combining an accessible authoring tool, multi-platform XR applications, and a centralized content management system, HERIX streamlines the development process and ensures flexibility across devices and usage contexts. Two user studies preliminary validated the platform's core objectives. Participants with limited technical skills successfully created interactive and meaningful XR scenarios, confirming the intuitiveness and accessibility of the authoring environment. On the consumption side, users reported a strong sense of immersion and engagement, with positive feedback on usability and overall experience in both AR and VR modes. These results highlight HERIX's capacity to support the rapid prototyping and deployment of high-quality XR experiences, adaptable to diverse settings to its liquid and cross-device nature.

Acknowledgments

This work was funded by the Next Generation EU - Italian NRRP, Mission 4, Component 2, Investment 1.5, call for the creation and strengthening of 'Innovation Ecosystems', building 'Territorial R&D Leaders' (Directorial Decree n. 2021/3277) - project

Tech4You - Technologies for climate change adaptation and quality of life improvement, Pilot Project 4.5.1 "Enabling accessibility and sustainability in minor destinations", CUP H23C22000370006, n. ECS0000009. This work reflects only the authors' views and opinions, neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

References

- [ATU*21] ABURAMADAN, R., TRILLO, C., UDEAJA, C., MOUSTAKA, A., AWUAH, K. G., MAKORE, B. C. "Heritage conservation and digital technologies in Jordan". *Digital Applications in Archaeology and Cultural Heritage* 22 (2021). DOI: 10.1016/j.daach.2021.e00197.
- [BpAGP22] BARRETO-PAREDES, C., AGUDO, D., GRANDA, M. F., PARRA, O. "Evaluating Extended Reality Application for a Virtual Museum. Case Study: Remigio Crespo Museum". In *Third International Conference on Information Systems and Software Technologies (ICI2ST)* (November 2022), 49-56. DOI: 10.1109/ICI2ST57350.2022.00015.
- [BBG*22] BOBOC, R. G., BĂUTU, E., GÎRBACIA, F., POPOVICI, N., POPOVICI, D. M. "Augmented reality in cultural heritage: an overview of the last decade of applications". *Applied Sciences* 12.19 (2022). DOI: 10.3390/app12199859.
- [BFH*23] BASHEER, S., FAROOQ, S., HASSAN, V., MALIK, Y. M., RESHI, M. A. "Augmented reality and virtual reality in cultural heritage tourism enhancing visitor experiences". In *Exploring Culture and Heritage Through Experience Tourism* (2023), 13-34. DOI: 10.4018/978-1-6684-9957-3.ch002.
- [BPF*18] BEKELE, M. K., PIERDICCA, R., FRONTONI, E., MALINVERNI, E. S., GAIN, J. "A survey of augmented, virtual, and mixed reality for cultural heritage". *Journal on Computing and Cultural Heritage* 11.2 (2018), 1-36. DOI: 10.1145/3145534.
- [BRL*20] BRUNO, F., RICCA, M., LAGUDI, A., KALAMARA, P., MANGLIS, A., FOURKIOTOU, A., VENETI, A. "Digital technologies for the sustainable development of the accessible underwater cultural heritage sites". *Journal of Marine Science and Engineering* 8.11 (2020). DOI: 10.3390/jmse8110955.
- [Bro13] BROOKE, J. "SUS: a retrospective". *Journal of usability studies* 8.2 (2013).
- [CAN*23] CAI, A., ARDAYFIO, C., NGUYEN, A., LIN, T., GLASSMAN, E. "Atomxr: Streamlined XR Prototyping with Natural Language and Immersive Physical Interaction". *Arxiv preprint arxiv:2311.11238* (2023). DOI: 10.48550/arXiv.2311.11238.

- [CB20] CARROZZINO, M., BERGAMASCO, M. “Beyond virtual museums: Experiencing immersive virtual reality in real museums”. *Journal of cultural heritage* 11.4 (2020), 452-458. DOI: 10.1016/j.culher.2010.04.001.
- [CF19] CAVALLO, M., FORBES, A. G. “Cave-AR: a VR authoring system to interactively design, simulate, and debug multi-user AR experiences”. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) IEEE* (March 2019), 872-873. DOI: 10.1109/VR.2019.8798148.
- [CLR*22] CHONG, H. T., LIM, C. K., RAFI, A., TAN, K. L., MOKHTAR, M. “Comprehensive systematic review on virtual reality for cultural heritage practices: coherent taxonomy and motivations”. *Multimedia Systems* 28 (2022), 1-16. DOI: 10.1007/s00530-021-00869-4.
- [CMG*22] COELHO, H., MONTEIRO, P., GONÇALVES, G., MELO, M., BESSA, M. “Authoring tools for virtual reality experiences: a systematic review”. *Multimedia Tools and Applications* 81.19 (2022). DOI: 10.1007/s11042-022-12829-9.
- [CPS24] CHEN, M., PELJHAN, M., SRA, M.: *Connectvr: A Trigger-Action Interface for Creating Agent-based Interactive VR Stories*. In *2024 IEEE Conference Virtual Reality and 3D User Interfaces (VR) IEEE* (March 2024), 286-297). DOI: 10.1109/VR58804.2024.00051.
- [DL24] DOUKIANOU, S., LALIOTI, V. “Ethical Extended Reality: Bridging Technology and Cultural Heritage”. In *2024 IEEE International Conference on Metrology for extended Reality, Artificial Intelligence and Neural Engineering (MetroXRaine)* (October 2024), 301-306. DOI: <https://doi.org/10.1109/MetroXRaine62247.2024.10796742>.
- [DIMBD22] DE LUCA, V., MARCANTONIO, G., BARBA, M. C., DE PAOLIS, L. T. “A Virtual Tour for the Promotion of Tourism of the City of Bari”. *Information* 13.7 (2022). DOI: doi.org/10.3390/info13070339.
- [FFD*21] FANINI, B., FERDANI, D., DEMETRESCU, E., BERTO, S., D’ANNIBALE, E. “ATON: An open-source framework for creating immersive, collaborative and liquid web-apps for cultural heritage”. *Applied Sciences* 11.22 (2021). DOI: 10.3390/app112211062.
- [FHS21] FANANI, A. Z., HASTUTI, K., SYARIF, A. M., and HARSANTO, P. W. “Challenges in developing virtual reality, augmented reality and mixed-reality applications: Case Studies on a 3D-based tangible cultural heritage conservation”. *International Journal of Advanced Computer Science and Applications* 12.11 (2021). DOI: 10.14569/IJACSA.2021.0121126.
- [Fra17] FRANKS, M. A. “The Desert of the Unreal: Inequality in Virtual and Augmented Reality”. *UCDL Rev* 51 (2017).
- [GBL*22] GAUGNE, R., BARREAU, J. B., LÉCUYER, F., NICOLAS, T., NORMAND, J. M., GOURANTON, V. “Extended Reality for Cultural Heritage”. In *Handbook of Cultural Heritage Analysis* (2022), 1405–1437. DOI: 10.1007/978-3-030-60016-7_48.
- [GZK*20] GERONIKOLAKIS, E., ZIKAS, P., KATEROS, S., LYDATAKIS, N., GEORGIOU, S., KENTROS, M., PAPANIKOLAOU, G. “A True AR Authoring Tool for Interactive Virtual Museums”. In *Visual Computing for Cultural Heritage* (2020), 225–242. DOI: 10.1007/978-3-030-37191-3_12.
- [IL24] ISWARA, I. B. A. I., and LAKSANA, M. S. “Evaluating the user experience impact of virtual reality on cultural heritage: a UEQ-based approach.” In *Proceeding International Conference on Information Technology, Multimedia, Architecture, Design, and E-Business 3* (December 2024), 450-456.
- [IUMV23] INNOCENTE, C., ULRICH, L., MOOS, S., AND VEZZETTI, E. “A framework study on the use of immersive XR technologies in the cultural heritage domain.” *Journal of Cultural Heritage* 62 (2023), 268-283. DOI: 10.1016/j.culher.2023.06.001.
- [JL22] JIN, P., LIU, Y. “Fluid space: Digitisation of cultural heritage and its media dissemination”. *Telematics and Informatics Reports* 8 (2022). DOI: 10.1016/j.teler.2022.100022.
- [KGC*20] KOSMAS, P., GALANAKIS, G., CONSTANTINOU, V., DROSSIS, G., CHRISTOFI, M., KLIRONOMOS, I., STEPHANIDIS, C. “Enhancing accessibility in cultural heritage environments: considerations for social computing”. *Universal Access in the Information Society* 19 (2020), 471-482. DOI: 10.1007/s10209-019-00651-4.
- [LBBS23] LUTHER, W., BALOIAN, N., BIELLA, D., SACHER, D. “Digital twins and enabling technologies in museums and cultural heritage: An overview”. *Sensors* (2023), 1583. DOI: 10.3390/s23031583.
- [LS18] LEWIS JR, SAURO J. “Item benchmarks for the system usability scale”. *Journal of Usability Studies* 13.3 (2018). DOI: 10.5555/3294033.3294037.
- [LT18] LYTRIDIS, C., TSINAKOS, A. “Evaluation of the artutor augmented reality educational platform in tertiary education”. *Smart Learning Environments* 5 (2018), 1-15. DOI: 10.1186/s40561-018-0058-x.

- [MBBM24] MARINO, E., BARBIERI, L., BRUNO, F., MUZZUPAPPA, M. “Assessing user performance in augmented reality assembly guidance for industry 4.0 operators”. *Computers in Industry* 157 (2024). DOI:10.1016/j.compind.2024.104085.
- [MBSB24] MARINO, E., BARBIERI, L., SOLLAZZO, C., BRUNO, F. “An Augmented Reality tool to support Industry 5.0 operators in product assembly activities”. *The International Journal of Advanced Manufacturing Technology* 135.9 (2024), 4941-4961. DOI: 10.1007/s00170-024-14777-0.
- [MDG23] MENDOZA, M. A. D., DE LA HOZ FRANCO, E., GÓMEZ, J. E. G. “Technologies for the preservation of cultural heritage—a systematic review of the literature”. *Sustainability* 15.2 (2023). DOI: 10.3390/su15021059.
- [MGMB22] MARTO, A., GONÇALVES, A., MELO, M., BESSA, M.: A survey of multisensory VR and AR applications for cultural heritage. *Computers & Graphics* 102 (2022), 426-440. DOI: 10.1016/j.cag.2021.10.001.
- [MYT*19] MAH, O. B. P., YAN, Y., TAN, J. S. Y., TAN, Y. X., TAY, G. Q. Y., CHIAM, D. J., FENG, C. C. “Generating a virtual tour for the preservation of the (in) tangible cultural heritage of Tampines Chinese Temple in Singapore”. *Journal of Cultural Heritage* 39 (2019), 202-211. DOI: 10.1016/j.culher.2019.04.004.
- [SAY22] SUDIPA, I. G. I., ADITAMA, P. W., YANTI, C. P. “Evaluation of lontar prasi bali application based on augmented reality using user experience questionnaire”. *East Asian Journal of Multidisciplinary Research* 1.9 (2022), 1845-1854. DOI: 10.55927/eajmr.v1i9.1531.
- [SBKP21] SAALFELD, P., BÖTTCHER, C., KLINK, F., PREIM, B. “VR system for the restoration of broken cultural artifacts on the example of a funerary monument”. In *IEEE Virtual Reality and 3D User Interfaces (VR)* (March 2021), 739-748. DOI: 10.1109/VR50410.2021.00101.
- [SHT17] SCHREPP, M., HINDERKS, A., THOMASCHEWSKI, J. “Construction of a benchmark for the user experience questionnaire (UEQ)”. *International Journal of Interactive Multimedia and Artificial Intelligence* 4.4 (2017). doi.org/10.9781/ijimai.2017.445.
- [SOO*24] SHIM, H., OH, K. T., O’MALLEY, C., JUN, J. Y., SHI, C. K. “Heritage values, digital storytelling, and heritage communication: the exploration of cultural heritage sites in virtual environments”. *Digital Creativity* 35.22, 171-197 (2024). DOI: 10.1080/14626268.2024.2313585.
- [SbPnPr25] SÁNCHEZ-BERRIEL, I., PÉREZ-NAVA, F., PÉREZ-ROSARIO, L. “Natural Interaction in Virtual Heritage: Enhancing User Experience with Large Language Models”. *Electronics* 14.12 (2025). DOI: 10.3390/electronics14122478.
- [SRH*20] SELMANOVIĆ, E., RIZVIC, S., HARVEY, C., BOSKOVIC, D., HULUSIC, V., CHAHIN, M., SLJIVO, S. “Improving accessibility to intangible cultural heritage preservation using virtual reality”. *Journal on Computing and Cultural Heritage (JOCCH)* 13.2 (2020), 1-19. DOI: doi.org/10.1145/3377143.
- [TLCM22] TRUNFIO, M., LUCIA, M. D., CAMPANA, S., MAGNELLI, A. “Innovating the cultural heritage museum service model through virtual reality and augmented reality: The effects on the overall visitor experience and satisfaction”. *Journal of Heritage Tourism* 17.1 (2022), 1-19. DOI: 10.1080/1743873X.2020.1850742.
- [TLTP23] TSAKOUMAKI, M. C., LALA, D. M., TSAROUCHA, A., PSALTI, A. “Advanced digitization methods for the protection and dissemination of cultural heritage towards digital transformation: the archaeological museum of delphi.” *Procedia CIRP* 118 (2023), 1056-1060. DOI: 10.1016/j.procir.2023.06.181.
- [VMN*22] VERVERIDIS, D., MIGKOTZIDIS, P., NIKOLAIDIS, E., ANASTASOVITIS, E., PAPAZOGLU CHALIKIAS, A., NIKOLOPOULOS, S., KOMPATSIARIS, I. “An authoring tool for democratizing the creation of high-quality VR experiences”. *Virtual Reality* 26.1 (2022). 105-124. DOI: 10.1007/s10055-021-00541-2.
- [WDL*25] WANG, H., DU, J., LI, Y., ZHANG, L., LI, X. “Grand Challenges in Immersive Technologies for Cultural Heritage”. *International Journal of Human-Computer Interaction*, 1-22 (2025). DOI: doi.org/10.1080/10447318.2025.2475996.
- [WZB*19] WANG, P., ZHANG, S., BAI, X., BILLINGHURST, M., HE, W., SUN, M., JI, H. “2.5 DHANDS: a gesture-based MR remote collaborative platform”. *The International Journal of Advanced Manufacturing Technology* 102 (2019)..
- [YWC*25] YU, J., WANG, Z., CAO, Y., CUI, H., ZENG, W. “Centennial Drama Reimagined: An Immersive Experience of Intangible Cultural Heritage through Contextual Storytelling in Virtual Reality”. *ACM Journal on Computing and Cultural Heritage* 18.1 (2025), 1-22. DOI: 10.1145/3705613.