


Building mixed reality digital versions of cultural visits/exhibits

Tiago Nunes, Pedro Lourenço, Armanda Rodrigues^{*} , Nuno Correia

NOVA School of Science and Technology, Portugal

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ABSTRACT

The virtualization of cultural activities has the potential to improve visits to museums or galleries, leading to increased visitor participation and collaboration. Cultural institutions need tools to facilitate creation and modification of virtual exhibits, using digital representations of real-world artefacts. The framework presented in this paper tackles these issues, using two extended reality applications and a third exhibit editor application. The first application immerses the user in remote visits, including commenting and annotating activities. The second is a smartphone application to digitally augment the onsite visitor experience, also streaming a camera perspective to the virtual environment. The exhibit editor application, aimed at museum/gallery personnel, allows to create, open, and save virtual exhibits, containing 2D and 3D artworks, which can be imported from local storage. The digital exhibit is organized in a virtual room. These exhibits can then be viewed in the existing virtual platform's Oculus Quest VR application. This framework is intended to benefit both visitors and curators, by providing access to improved virtual exhibits, as well as a workflow that allows for easy creation and modification of Virtual Reality Museum exhibits that does not require previous computer experience.

1. Introduction

The work presented here is designed to promote new engaging and immersive ways to visit cultural institutions by breaking through their physical boundaries. Physical Cultural exhibitions are constrained by the limited interaction and available information support of relevant artefacts. Digitally augmenting the physical visit can increase its interest and potential, by enabling interaction with digital versions of artefacts. The availability of these components also provides support for enabling systematically generated virtual reality exhibits, based on a set of enhanced virtual components. Visits can greatly benefit from remote interaction and can be enhanced by visitors' participation and collaboration in both these environments, in real time. It is also important to provide tools and systems that provide curators and/or other museum professionals, with the ability to dynamically create and edit their own virtual exhibits using images and 3D Models of Artefacts, without requiring any previous knowledge and experience with computer programs.

As a result of project "Património Cultural 360°", a Portuguese national governmental effort involving the digitization of a large set of historically and culturally relevant artefacts and the creation of virtual museum exhibits to show the resulting digital objects, an encompassing framework is currently under development which includes AR and VR

tools to support, on one hand, augmentation of physical visits and, on the other hand, systematic generation of virtual visits of these relevant cultural institutions.

An initial version of this framework, supported by a developed software architecture (see Fig. 2), has been described, in detail, in Lourenço et al. (2023), which includes several key components. The first of these components is an application for *smartphone* devices meant to be used while visiting the premises of the cultural site. It uses AR (Augmented Reality) to superimpose digital textual and graphical information on top of cultural artefacts, concerning the artefact itself (additional relevant information) or user input regarding the artefact (visitor's comments or annotations). The second is an application for *Oculus QuestVR* (Virtual Reality) devices in which a virtual version of the cultural exhibit can be navigated by users, enabling artefact inspection and access to additional information, as shared with the previously described AR application. The third component, which will be the focus of this paper, is an administrative desktop application that allows museum/gallery curators to observe the current state of the exhibit, from a visitor's perspective. It also supports the creation of new virtual exhibits from scratch, as well as their editing, by importing custom exhibition rooms and artworks, and then saving these exhibits to XML files, which can be read by the VR application. The fourth component is a broadcasting server setup, which enables audio and visual

^{*} Corresponding author.

E-mail address: a.rodrigues@fct.unl.pt (A. Rodrigues).

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transmission from smartphones' cameras, carried by visitors currently at the exhibit, to the virtual environment featured in the VR application. The fifth and final component of the project is a file management server responsible for collecting and serving data about the virtual exhibit.

In this paper, we will briefly address the status of described collaboration and presence framework for accessing museums and other cultural institutions, created with the objective of augmenting the local visit with additional interaction possibilities and to give a sense of presence and collaboration to remote visitors. We will also shortly describe the evaluation procedures which were carried out to assess the usability and presence of both digital AR and VR applications. Additionally, the paper will focus on the development of the exhibit editing application as a tool that allows curators to create generic virtual exhibits based on rooms and artefacts, which can be custom made, or obtained through techniques such as 3D Scanning. This editor application has the goal of streamlining the exhibit creation and editing process, to achieve a level of simplicity that does not require curators to have previous experience with computer applications.

2. Related work

Museums and art institutions have come to realize how crucial technological approaches are for the involvement and immersion of the public, namely using virtual and augmented reality. In fact, museums and art galleries all around the world are already considering and putting into practice the digitization of artefacts or digitally assisted tours. Concrete implementations range from mobile applications that allow visitors to collect animals and plants by photographing their virtual representations (at The National Museum of Singapore), or watch paintings come alive (at Ontario's Art Gallery), or even discover how prehistoric animals looked and behaved (in The Smithsonian Institution in Washington) (Coates, 2021). Additionally, examples of Museum virtual tours available online include the Louvre Museum in Paris (Louvre, 2023), the British Museum in London (British Museum, 2023) or the Teatro-Museo Dalí in Figueres (Fundació Gala-Salvador Dalí, 2023). Also, examples of digital experiments and tools developed and made available by diverse cultural institutions, aiming at visitor motivation and satisfaction, include.

- An experiment performed at Universidad Carlos III in Madrid, involving a transparent interactive display located in front of a cultural artefact, allowing gesture-based interactions (Bellucci et al., 2015). These interactions gave support to textual and video input of experiences with the artefact, which provided knowledge sharing between guests. An alternative way to upload content is through the mobile interface on the visitor's personal device and by scanning the QR codes corresponding to each artefact.
- The "Neanderthal" app (Alvermann, 2016), ideally used by visitors before, during and after their tours of the Neanderthal Museum, keeps them updated about current and future exhibitions and other relevant museum details. Active QR code scanning is also available, to allow for content accessing on each location. However, the most prominent feature in this project is the ability to passively access content, by connecting to Bluetooth beacons that send signals to nearby devices.
- The design of a virtual representation of The Phillips Collection (Washington, USA), engaging visitors by capturing a series of omnidirectional images and videos with interesting interaction features (Hayes and Yoo, 2018). Users had three different forms of interaction: gaze-based interactions; hotspot interactions; and zooming and moving in a 360° environment.
- A collaboration between different departments of the University of Konstanz and HTWG Konstanz (Germany) with the goal of educating about the cultural impact of the existence and destruction of the city of Palmyra, in Syria, and discussing if it should be rebuilt (Skowronski et al., 2018). This was accomplished by using

technologies such as an interactive tabletop, interactive projection, tablets, 3D printing, AR and VR in the three initial rooms of the exhibition, each with a different purpose. In the final room, the visitors make their decision about reconstructing Palmyra.

Virtual reality interaction can liberate the user from physical limitations, enabling telepresence and even transforming the space with asymmetric distortions (Carvalho et al., 2016). Augmented reality can be used to transmit ideas, in-context, for example by a remote user, to guide a local user in maintenance and assembly tasks (Zhu et al., 2014) or to enable detailed exploration of artefacts (Ridel et al., 2014). Collaborative AR interfaces are used for both co-located and remote AR collaboration (Gauglitz et al., 2014).

In remote collaboration, they can enhance communication with gaze and non-verbal cues, and for manipulating virtual objects. Asymmetric collaborative interaction, which enables two or more humans, from a combination of the real world, using AR, and a virtual world, using VR, to share a workspace, is a typical example that can be made more efficient by using a uniform representation of XR contents, regardless of the user's context (Huh et al., 2019). XR technologies allow both local and remote users to be immersed in collaborative virtual environments (CVEs) (Orts-Escolano et al., 2016; Piumsomboon et al., 2018). In this context, Dataspace is a collaborative virtual room (Cavallo et al., 2019) where a hybrid of high-resolution screens, AR headsets and projection tables creates an integrated data exploration center. Rizvic et al. (2022) propose a multiplayer VR game to introduce teenagers to the works of Leonardo da Vinci and his role in history.

Interaction methods and interfaces are the forms of communication between humans, resources and AR systems. Some of these interfaces have been experimented with in limited collaborative settings (Zhang et al., 2018; Teo et al., 2019; Bhattacharyya et al., 2019; Correia et al., 2010). The current challenge is to go beyond the state of the art by addressing collaboration in evolving physical and virtual representations, addressing presence and collaboration in complex activities (Páris et al., 2019).

The evolving nature of the structures and the possibility of telepresence (e.g., by remote access in a virtual world to a live video stream or other media from a local user) pose complex system and interaction level challenges, which are addressed in this project. Brockmann et al. (2013) list the collaborative dimensions in the collaborative AR taxonomy: (1) space (co-located, dislocated, variable); (2) time (synchronous, asynchronous, variable); (3) mobility (stationary, mobile, mixed); (4) virtual content (user visualization, object visualization, combined visualization); (5) role concept (one-role-concept, multi-role-concept); and (6) visualization hardware (HMD, handheld display, spatial display, individual spatial display, mixed). The collaborative aspect of the work presented in this paper is aligned with these dimensions.

With respect to the ability to create and edit custom exhibits, VIRTUE, by Giangreco et al. (Giangreco et al. (2019), served as a conceptual basis for the development of the editor component of the administrative application, part of the framework presented in this paper. VIRTUE consists of a modular exhibition creation and visualization system, with a backend Kotlin application aimed at creating museum exhibits, and a frontend Unity application, responsible for displaying said exhibits VIRTUE (2023), so that visitors can examine the exposed works. However, VIRTUE is limited by only relying on a top-down editor and by only using default rectangular rooms, thus not allowing the use of imported 3D scanned rooms. This can contribute to a lack of connection between the real-world exhibit and its virtual counterpart.

Our framework intends to bridge the gap between pre-made, bespoke virtual exhibits (that do provide users with unique interactive features but require a significant expertise to maintain and evolve), with simple exhibit editors that are relatively easy for museum staff to use, and can thus be used in diverse contexts, but that rely on pre-made rooms and only support limited types of artefacts. Table 1 outlines key distinctions between our system and selected prior work, across 5 key dimensions.

Table 1

Comparative table between our framework and selected systems from the Related Work section.

System	Built-In Editor	3D Scanned Rooms	AR/VR Content or View Streaming	Comment/Drawing Tools (Enhanced Interaction)	Easy to Adapt (Curator-Oriented)
Virtual Museums (Louvre, British Museum, Teatro-Museo Dalí)	X	O	V	O	X
In-Situ AR Experiments (ReBlink, Singapore Museum)	X	X	O	V	X
Dataspace Rebuild Palmyra?	O	X	V	V	O
Neanderthal+	X	X	X	V	X
VIRTUE	V	X	X	X	V
Our Framework	V	V	V	V	V

Legend: X – Unavailable Feature; V – Included Feature; O – Partially Implemented/Implementation Dependent. Some examples include it, and others don't.

The first dimension, **Built-In Editor**, refers to whether the system includes an integrated tool for exhibit creation or content arrangement, allowing curators to author experiences without relying on external platforms.

The **3D Scanned Rooms** dimension relates to support for importing and building custom exhibits based on 3D Scanned Rooms obtained in a real-world environment, allowing for a quick way to create high-fidelity exhibits.

AR/VR Streaming indicates the system's ability to dynamically load content from a backend server during runtime, enabling dynamic data management, as the data on the server can be constantly updated, and saving overall storage space on visitors' devices.

The fourth dimension, **Comment and Drawing Tools (Enhanced Interaction)**, highlights the availability of features that allow users to interact with the exhibited artefacts in immersive and novel ways. In our case, this was implemented through features that allow users to annotate, sketch, and comment on works.

Lastly, **Easy to Adapt** (or Ease of Adaptation) reflects the systems' accessibility factor in relation to being able to easily customize and modify exhibits without requiring any programming and scripting knowledge, as museum staff might not possess these capabilities. Hence the "Curator-Oriented" subtext.

These dimensions were selected based on common constraints observed in XR systems in use by cultural institutions, as well as the state of the art. Our framework fully supports each of these areas, combining a lightweight, curator-oriented authoring tool with backend-powered AR/VR delivery, spatial reconstruction capabilities, and built-in interaction tools. This positions it as a flexible and accessible alternative to more complex or narrowly scoped systems in the domain.

3. Framework design and Overview

The developed platform architecture seeks to globally enable cultural exhibitions, by facilitating integration and collaboration between virtual and onsite visitors, as well as free handling and augmentation of exhibited artefacts. In this context, interaction with the digital representations of the artefacts is valued, not only through the individual visualization and handling of these representations, but also by enabling

the creation of several types of comments and annotations, in line with what is currently popular in social networks but also following graffiti-er's traditions. Drawing over and enhancing well-known artefacts, without the danger of damage, can motivate engagement, while, at the same time, enabling collaboration and broadcasting of these ideas. Finally, the connection between the physical and virtual exhibition spaces is an additional motivator, generating recognition and identification in the visiting audience.

As a result of this reflection, and beyond the needs for curating and managing data needs, the existing designed platform focuses on a mobile phone AR application that grants the visitors the ability to offer, obtain and visualize knowledge about artefacts beyond an exhibit's physical boundaries; A VR application for Head Mounted Displays (HMDs), set up with the intention of performing remote visits to an art exhibit and, consequently, create a sense of presence in it, with additional user collaboration features; A desktop management application that allows curators to supervise and update the current state of the exhibit; And the establishment of data transmission structures and processes between all above-mentioned tools.

As previously mentioned, the design of the framework has evolved from Lourenço et al. (2023), with some improvements on the functionality supported by the VR and AR applications. Increasingly, the focus of the work presented here is on providing the administrative app with a built-in exhibit editor that offers tools to create and edit exhibits, composed of a 3D designed or scanned exhibit room and of 3D representations of valued artefacts to be positioned in the exhibit. Additionally, some more practical functionality was also added, such as OBJ model support (USALOC, 2023), and XML exhibit exporting, to be opened in the VR application, or in the desktop management application itself.

In both visitor applications, either installed on their mobile device, or on an HMD remotely located, visitors may perform several different activities, which include viewing relevant details about the artefact, such as its title and description, by pointing their mobile device's camera at it, interacting with artefacts by choosing, out of a selection of emojis, one which best represents the visitor's emotional outlook on those artefacts, providing personal insights on them, in the form of comments, composed of a title and optional content, and painting over them and appending the result to a comment. Additionally, it's also possible to register and verify one's credentials, such as full name, e-mail and password.

In terms of how data linked to the system is structured, the main concepts and the relationships between them are illustrated in Fig. 1.

An exhibit is composed of several exhibit objects. These correspond to every object that can be placed in an exhibit file. This type of object can be divided into three different categories: **Rooms**, which represent exhibit rooms, spaces where the exhibit takes place, and can be obtained through 3D Scanning/Photogrammetry or created from scratch using 3D modelling software; **3D Artefacts**, which correspond to 3D Artefact Objects, such as sculptures, pottery, or tools, and can be modelled from reference images in 3D modelling software or captured using Photogrammetry/3D Scans; **2D Artefacts** which are a digital representation of bi-dimensional objects, such as paintings, photographs, documents, or posters.

The standard exhibit creation workflow, from a physical artefact in a physical room, to a complete virtual exhibit containing digital twins of said artefacts, can be found below (Fig. 2).

Fig. 3 illustrates the framework's system architecture. Essentially, it is composed of three clients that indirectly interact with each other by communicating with a broadly defined server. These three clients (all based on Unity) are the mobile AR and VR client applications along with the administrative application, which includes the exhibit state editor. The concept of server, present in the figure, currently encompasses a LAMPP web server connected to a Linux file system database, currently, as already mentioned, in XML form, in addition to an Ant Media Server instance that serves as a proxy for broadcasting the current AR

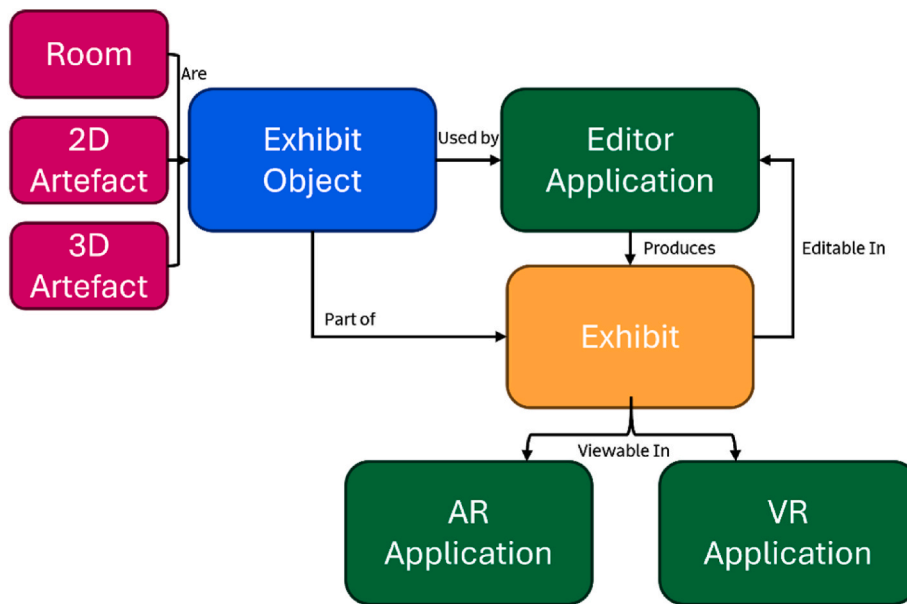


Fig. 1. Object diagram representing how data is structured in the proposed framework.

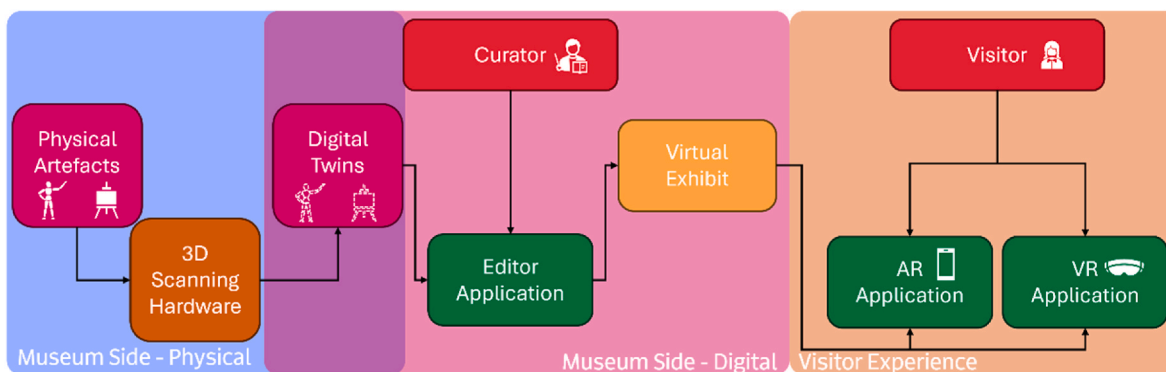


Fig. 2. Object diagram representing a standard exhibit creation workflow from physical exhibits to the VR and AR applications.

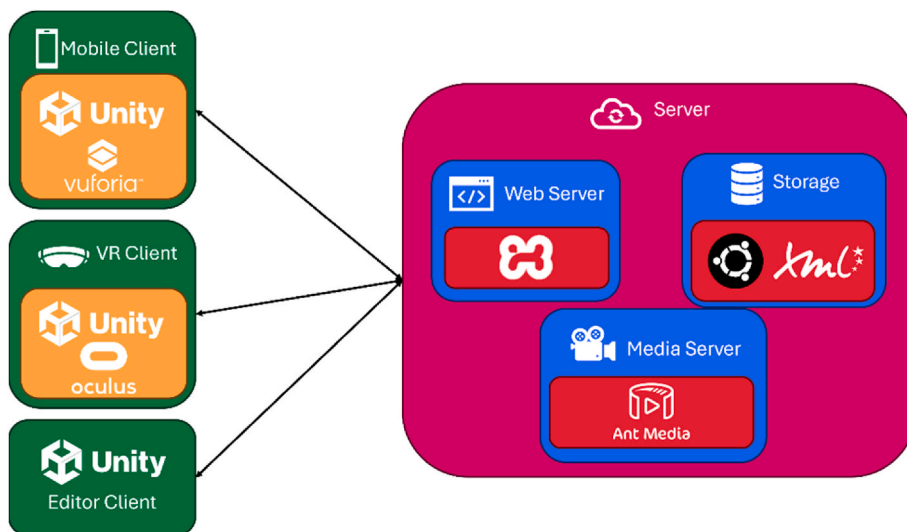


Fig. 3. Framework architecture and technology.

application view to remote users in the VR environment.

3.1. Mobile Augmented Reality Application

The local visitor using the Mobile application, logged into the Main Gallery scene as a registered user (the entrance of the app), will access a view of their smartphone’s camera, enabling a look-through window, accompanied by a couple of Heads-up Display (HUD) constituent elements. This view provides access to a video stream being captured by Vuforia, which is responsible for detecting and tracking real-life targets at the exhibit and for overlaying them with digital information about the art piece, such as its title, description, and comments. Fig. 4 a) shows the augmented view of an artefact, depicting the HUD elements together with the details revealed when the Image Target is detected by the camera.

While on the augmented view, the user may **React** to an artefact by tapping the *emoji* buttons on its side. They may also insert their comments into the artefact (as seen in Fig. 4b)). Additional contributions may take the form of **drawings** overlaid on the **original painting** (as seen in Fig. 4c)). In these drawings, the user may choose the color and width of the strokes to be overlaid on the artefact.

Lastly, the user can broadcast what their phone’s camera is capturing by pressing a button on the application’s UI. This streams the camera’s footage to the XAMPP server. This footage can then be viewed by VR Application users, or by the AR application users themselves, if they open the **Main Menu**. This last viewing option allows for greater visual feedback, as the user can see their own stream and check for possible issues. An example of this can be found in Fig. 4 d). A detailed description of this application can be found on Lourenço et al. (2023).

3.2. Remote virtual reality application - basic behavior

The remote VR application was developed in Unity, with support for *Oculus Quest* and *Oculus Quest 2* virtual reality headsets (MetaQuest, 2023). Despite their different strategies, the mobile client and the virtual

reality application share multiple parallels, which are presented in this section.

The manner in which the Menu screen functions and reacts to user inputs is equivalent in both apps.

The main Gallery scene assembled at the time of development of this application, and shown in Fig. 5, was slightly more elaborate than the one available on the mobile AR application, as it was composed of several models, components, lights and settings that had to be designed, placed and adjusted to fit a three-dimensional and VR space. Nevertheless, some elements of both scenes have compatible implementations.

For the basic gallery room, presented when the visitor successfully signed in, a hallway is revealed, accommodating six different art pieces – three on each side –, a broadcast and a settings menu. This room was the default scene at the time of the initial development of the application and has now become a basic template for creating a virtual visit. This environment can be viewed in Fig. 6 a).

Two Audio Sources are positioned on each of the user’s feet for added realism.

In a VR context, long and precise interactions are not dependent on a smaller “window” to the digital world (represented by a mobile phone) held by the user’s hands. Hence, screens like the comment creation screen and the comment annex screen are here implemented as static panels rendered in front of their respective art piece, as shown in Fig. 7a).

Lastly, upon entering the scene, the visitor can see, from the first menu, one button that reads “Join Live Feed” (Fig. 6a). Accessing this menu allows the user to view several live video feeds of all the different perspectives being streamed simultaneously by visitors roaming the physical exhibit (Fig. 7c)).

3.3. Current state of the remote virtual reality application

As a result of the evaluation process described in Lourenço et al. (2023), several features were developed and implemented to improve overall user experience while using the VR Application.

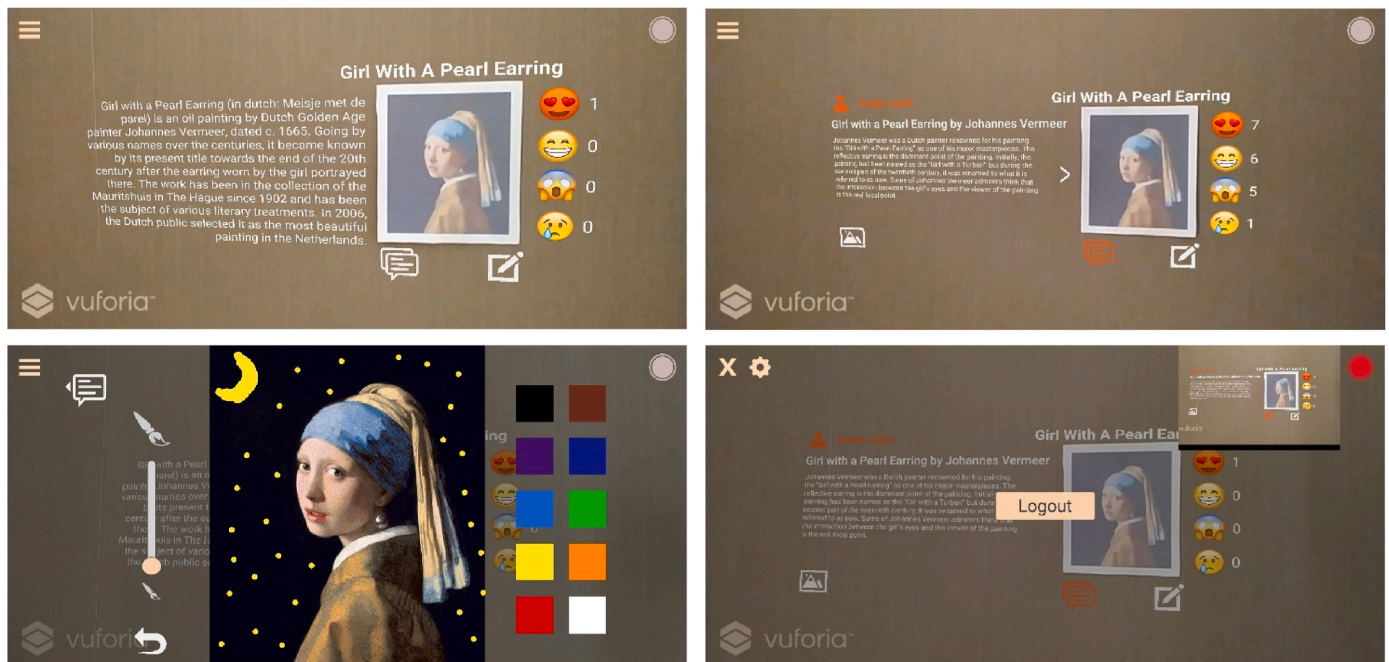


Fig. 4. a) Informative details overlaid next to the artefact upon target detection. The target detected is the actual painting
 b) The comment panel displaying comments pertaining to the currently detected painting.
 c) The drawing module of the comment creation screen.
 d) The main menu of the mobile application’s gallery scene accompanied by the “Broadcast View”, seen on the top right corner when the user is currently streaming their perspective.

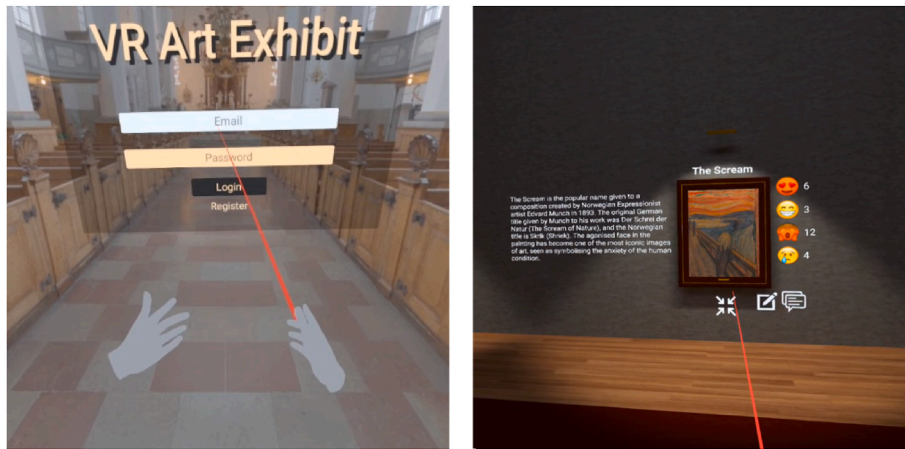


Fig. 5. a) The hand models included in the “LocalAvatar” Prefab together with the UI cursor. b) One of the painting’s UI canvases.

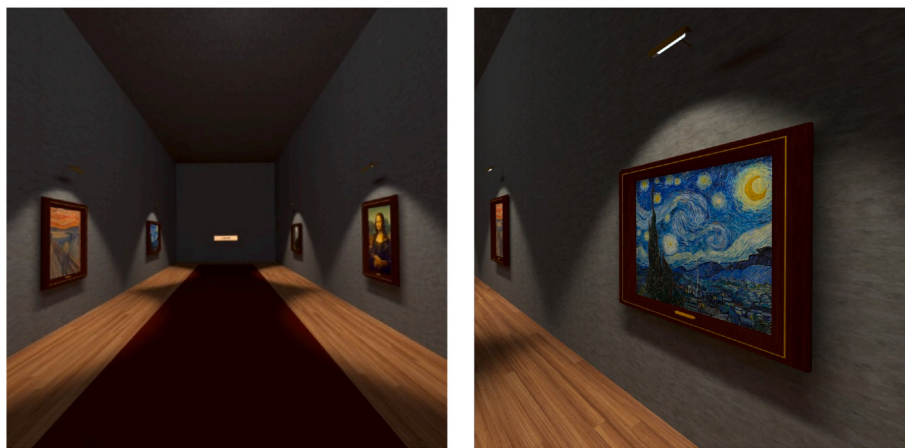


Fig. 6. (a) The front of the gallery scene environment. (b) One of the painting models placed in the virtual exhibit.

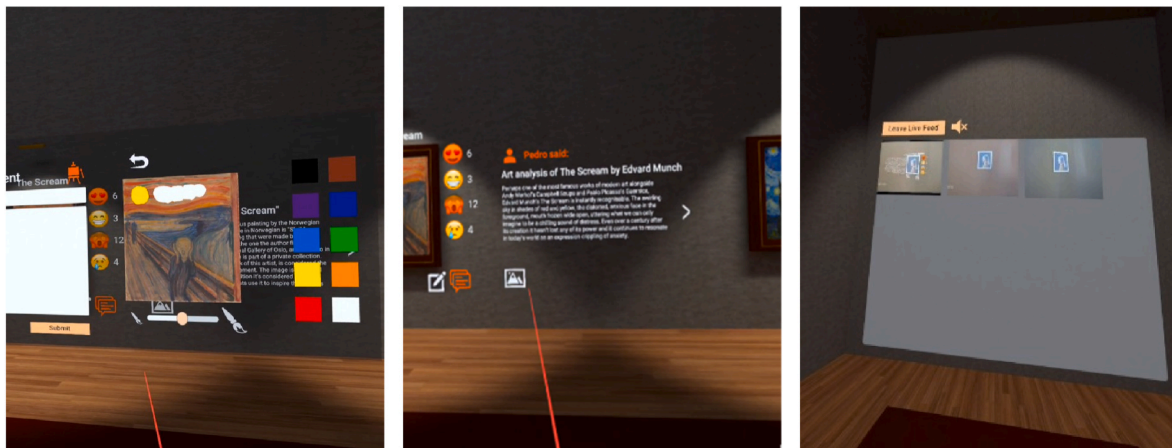


Fig. 7. (a) The drawing module of the comment screen on the VR application. (b) The comment annex screen on the VR application. (c) The “Live Feed” screen with three concurrent live streams.

One innovation was the dynamic instantiation of 2D art pieces, as well as added support for 3D artefacts, and custom exhibit rooms. For every exhibit object present in the exhibit’s XML representation, a digital version of said object is instantiated and placed on the scene, according to the defined coordinates and rotation, be it a 3D Artefact, a 2D

Artefact, or even an exhibit room.

To help users navigate through an exhibit and locate the works they are searching for, an interface, to be made available in both the VR application and the Administrative Application was developed. This is the *Artwork browse menu*. Upon pressing a button on their controller/

keyboard, the user is presented with a list of all existing artworks, as well as a search box. The user can select one of the available works and it will be marked with an animated indicator, producing a 3D sound effect to help visitors locate the artwork (Fig. 8 b)). Each artwork present in the list is represented by a clickable button *prefab*, an image thumbnail of the artwork (using the artwork's own texture) and its title (Fig. 8 a)).

Additionally, as mentioned before, a navigational aid element, commonly called a “*minimap*”, was implemented in the application to provide the user with positional awareness. In this *minimap*, artworks are displayed as circles, with their color depending on the type of artwork, while the user is represented by a red arrow. An overall blueprint or map of the room can also be displayed, as long as the current room has been configured for that. This *minimap* appears on the upper right corner of the screen in the Administrative App, and as a part of the player model in the VR Application (Fig. 8).

3.4. Streaming

Broadcasting video and audio from mobile phones to the *Oculus* VR environment is a crucial part of the system's architecture. The streaming server must be available to the outside world, in particular to users receiving all the different streams on their *Oculus* headset at home or to visitors streaming their perspectives at an art gallery. For this purpose, Ant Media Server (AMS) (Ant Media, 2023a) was the tool of choice for developing the streaming element.

Establishing a connection between each *Unity* application and the broadcast server is supported by components from the *Sora Unity SDK Samples Project* (Ant Media, 2023b).

3.5. Administrative application

The aim of the administrative application is to update and supervise the current state of the system, ranging from user contributions, to live broadcasts, to the virtual environment itself. The initial development process for this tool was achieved in two phases: The first step consisted in reusing the *Oculus Unity* project and adapting it to be used in a new target platform with a different input method – mouse and keyboard. This can be summed up as cloning the VR application and removing non-essential *Oculus* plugins, *prefabs* and components. The second step was to adjust the user's movement, viewing and interactive experience to the new desktop medium. A further description of the Administrative Application's features and architecture can be found in Lourenço et al. (2023).

As mentioned before, the focus of this paper is the description of improvements made to the existing applications by implementing additional functionalities (requested during the initial evaluation process). Among these new features, the most comprehensive component is the built-in Exhibit Editor, a feature rich tool that allows museum or

gallery personnel to easily create and edit custom exhibits, based on real-world locations, and making use of real-world objects. These objects can be obtained either by 3D Scanning the physical artefacts, photographs, or digital replication via 3D modelling software.

It was decided to develop a standalone exhibit editor, instead of creating bespoke exhibits in game engines such as *Unity* or *Unreal*, since this modularity would allow for the creation of an adapted museum exhibit, given a Room Model and Artefacts, using the same application. Furthermore, despite these engines being able to provide custom exhibits with the potential for incredibly complex and immersive features and interactions, they require a steep learning curve which may be out of reach for museum personnel, requiring manually configuring lighting, collisions, and using scripts to set up user interactions. Our editor bypasses these difficulties by providing curators with a simpler set of tools that allow them to directly manipulate exhibit objects in order to create their own custom exhibit, with no scripting or coding knowledge required, including pre-configured interaction types and a simplified scene hierarchy. Enabling further support for additional artefact interactivity may fill some of the feature gaps, such as integration of video and 360-degree images, visitor artefact manipulation, and the possibility of closely examining parts of exhibited objects in various states of preservation. All of the previously described features are made available in the proposed editor.

3.5.1. Exhibit editor interface

The development of the exhibit editor interface involved the creation of a new scene in the administrative app. This new scene consists of an empty object staging area and a UI layer with 2 different panels: A mode selection panel, and an action panel. Possible current modes, which can be changed through keyboard shortcuts are: Select, Translate/Move, Rotate and Scale. Familiar keyboard shortcuts were also implemented to improve user workflow, for clipboard manipulation, Redoing, Saving, Opening, Creating a new Exhibit, and Deleting Items (Fig. 9a)). For an improved first user experience, *tooltips* were added to each button to clarify its function, as the icons used might not be intuitive for every user on their first interaction with the app (Fig. 9b)). Additionally, an object's current position, scale or rotation values are displayed in a small UI component on the top right of the screen in their respective mode (Fig. 9c)).

3.5.2. Interacting with objects - the gizmo

An important part of any editor application is the ability to manipulate and interact with objects. To this end, a custom made “*gizmo*” was created and modelled. This “*gizmo*” is actually a set of three different “*gizmos*”, one for each mode (Select, Rotate, Move), and each one consists of a central hub, and three different and mutually perpendicular axes. When one of the axes is hovered with the mouse, that axis' model is replaced with a larger, lighter colored one, indicating its selection. The

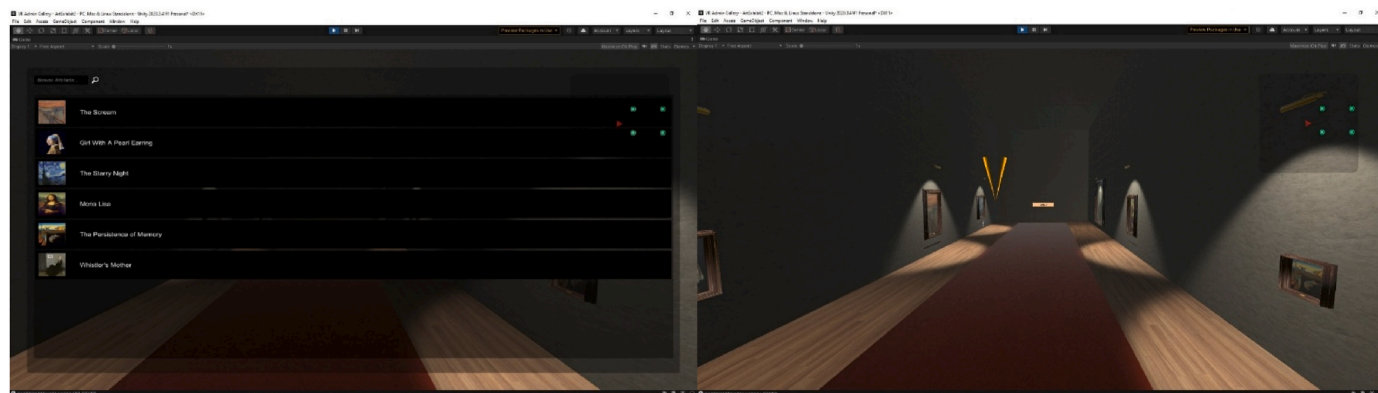


Fig. 8. a) The artwork browse menu as it appears in the administrative application. b) The position indicator displayed when an artwork is selected.

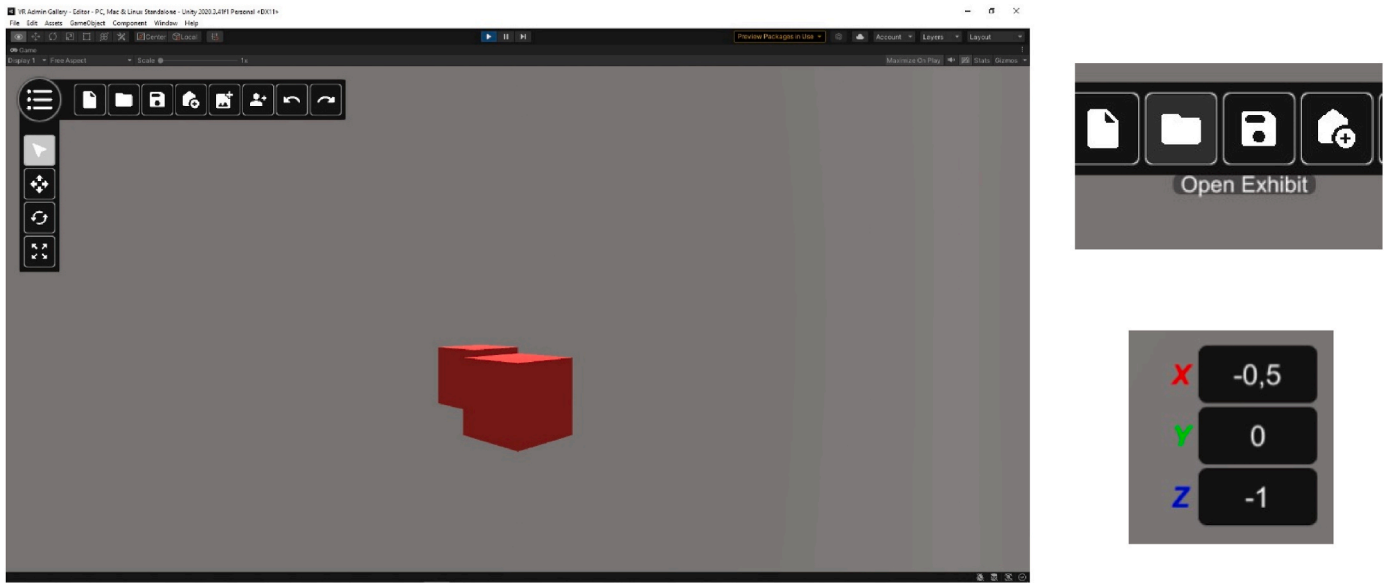


Fig. 9. (Clockwise from Top Left)
 a) The Editor Application's UI
 b) An example of UI Tooltips
 c) Editor's Object Coordinate Display.

program is then informed of which axis is currently selected, so that all future movement is done relative to said axis. *Gizmos* are only visible whenever one or more objects are selected, and its scale changes dynamically in relation to its distance to the camera. This ensures its "apparent size" remains unchanged, when viewed by the user, preventing the use of *gizmos* that are either too small and cannot be interacted with, or too large that take up the entire screen. The *gizmo's* coordinates are the average value of the coordinates of all selected objects. This allows the user to have a common point around which all operations are executed. When clicking and dragging a *gizmo*, the corresponding action is performed.

3.5.3. Moving objects (translation)

If the current mode is "Move", whenever the mouse is held over an axis of the *gizmo*, the distance from the current mouse position to the original click point that originated the dragging movement is calculated, and the corresponding value will be the movement of all of the selected objects (Fig. 10a)).

3.5.4. Rotating objects

Object Rotating, due to its nature, means that objects must rotate a certain number of degrees around a common center. To achieve this, the "distance" value being used by the program is the Signed Angle between the original click point and the current hit point. This angle is then

rounded down to prevent precision errors) (Fig. 10b)).

3.5.5. Scaling objects

Object Scaling works similarly to Object Moving, in that a 3-axis *gizmo* uses the distance between the original click point and the current dragging point (Fig. 10c)).

3.5.6. Selecting objects

Another essential component to being able to manipulate objects is the selection of those objects themselves. To select an object, the user must click it. Per standard editor behavior, if no modifier key is pressed, any other selected objects are deselected. If the same object is pressed again, it is deselected. If the "void" (that is, an empty space) is hit, all selected objects are deselected.

An important aspect of selecting objects is giving the user visual feedback of which objects are currently selected. When an object is selected, a thin, white outline appears around the object, being visible over overlapping objects. This ensures that the user is always aware of the selected object's location in the scene, even if said object is hidden behind other objects (Fig. 11a)).

To select multiple objects, per standard key binds, the Control Key must be held while clicking objects. If more than one object is selected, selecting one of the selected objects without holding the Control Key will deselect all other objects, leaving the clicked object as the only

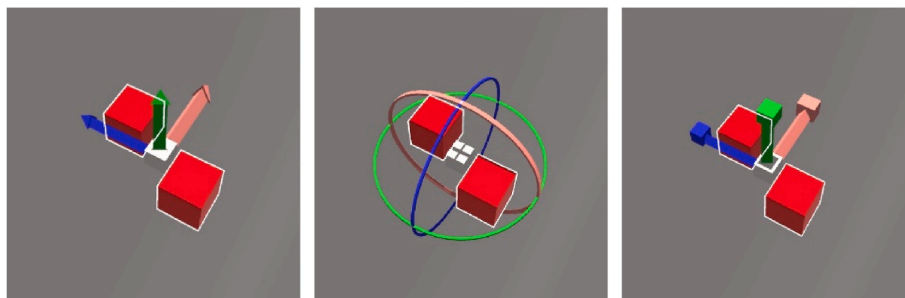


Fig. 10. a) Example of Objects being moved while in Moving mode.
 b) Example of Objects being rotated while in Rotating mode.
 c) Example of Objects being scaled while in Scaling mode.

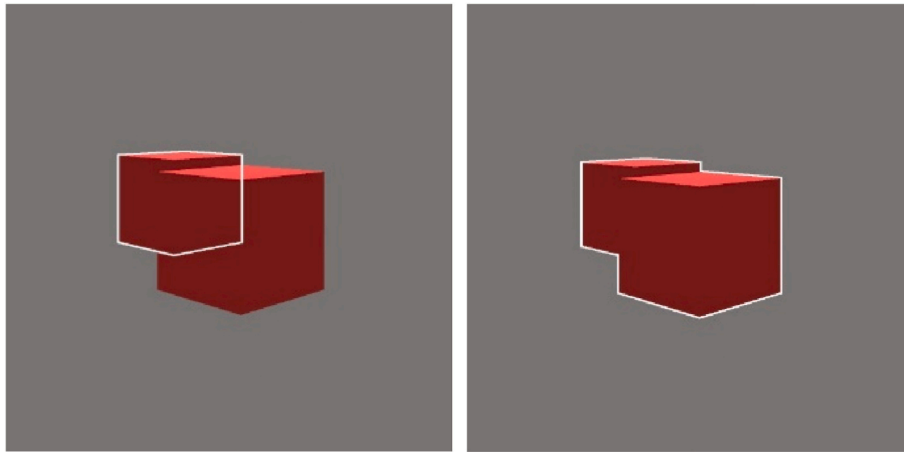


Fig. 11. a) A selected object being visible behind another object due to its outline.
b) Two selected objects. Their outlines fuse into a single shape.

remaining selected object. Reversely, clicking one of the selected objects while holding the Control Key will result in that object being the only object to be deselected (Fig. 11b)).

3.5.7. Making corrections

In addition to basic object manipulation and selection, the ability to correct one's mistakes is of utmost importance in any editor application, as it considerably improves workflow by saving users time and effort, as unintended changes can be reverted easily, and these reversions can be discarded if proven misguided.

This Undo/Redo functionality can be observed upon clicking the Undo and Redo buttons or associated shortcut keys. A user can undo up to 5 stored actions, and redo 5 others. Performing new changes after an Undo will overwrite any available Redos, as per standard editor behavior.

3.5.8. Duplicating, copying and deleting

The functionalities mentioned thus far allow manipulation and interaction within a fixed set of objects. They do not, however, change

the number of objects present in the scene (at least, not visibly). Nonetheless, a user might want to duplicate an object by copying and pasting it, or remove it from the scene by cutting or deleting it, the former allowing for future recovery by means of pasting said object, if it is present in the *clipboard*.

To make this possible, 4 object operations were implemented in the editor: Deleting, Copying, Cutting and Pasting Objects. These operations can, as said before, be performed using standard key binds. They also involved creating a new *clipboard* that stores the Exhibit Objects.

Deleting is the simplest of the 4 operations. It creates an Undo step with all objects in the scene and deletes all *selected objects*.

Cut and Copy are essentially the same operation, with the distinction that Cut also deletes all *selected objects* in the end, and thus creates an Undo step. These methods clear the existing *clipboard* and create new *clipboard* copies of all *selected objects*.

The Paste operation, compatible with Undos and Redos, starts by saving the current *exhibit state* to an Undo. Then, for each object in the *clipboard*, it will paste them on the scene and move the pasted objects by (1,1,1) in relation to the original object's position, so that the user has

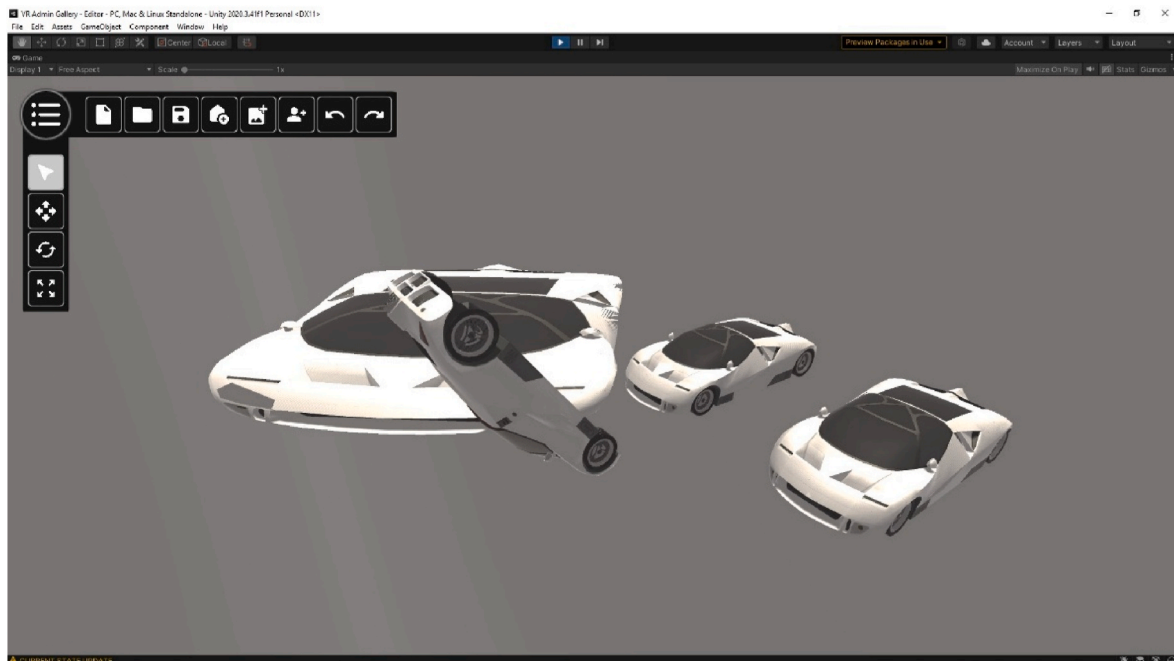


Fig. 12. Several copies of the original object, manipulated in distinct ways such as translation, rotation, and scaling.

some visual feedback of existence of the new object.

An example of multiple copies of the same object being manipulated in different ways can be found in Fig. 12.

3.5.9. Creating an exhibit and updating its state

To ensure exhibit changes are preserved, methods that track the global state of the Exhibit and allow the user to interact with the XML data file used by the VR and AR applications are needed. To this end, the following operations were implemented: New Exhibit, Open Exhibit and Save Exhibit.

Creating a New Exhibit can be done by pressing Control + N, or by clicking the “New Exhibit” button. If the scene has been previously saved, the entire scene is cleared, the Undos and Redos are cleared. The editor mode is reverted to select, and the camera position is reverted to its default state. Per standard behavior, the *clipboard* is preserved, so that its contents can be used on a new exhibit.

Opening an Existing Exhibit, similarly, can be accomplished by clicking the respective button, or by pressing Control + O. A system explorer dialog will appear, prompting the user to select an XML file to open. Upon selection, a similar process to creating a new exhibit takes place, where the scene is cleared, the Undos and Redos are reset. Next, the XML file is read. For each object entry in the XML file, the object is then added to the scene, according to their saved properties.

Saving an Exhibit, in accordance with standard key binds, is achieved by pressing Control + S, or by clicking the “Save Exhibit” button. The user is then prompted with a system explorer dialog similar to the one shown when opening an existing exhibit. Upon saving the exhibit, the current *ExhibitState* is saved, preventing the user from losing any progress by displaying a warning dialog box whenever the user tries to close, open or create a new exhibit. For every object present in the scene, a serialized entry is created in an XML file, containing its type, ID, properties like name and description, and its coordinates in the scene.

3.5.10. Importing artefacts

The final core component of the editor application is the possibility of importing custom 3D or 2D models. Since the editor itself does not yet provide the user with premade sample objects, it is essential for the user to be able to import models of exhibit rooms or artefacts, to be able to set up a virtual exhibit.

Taking *3D Artefact Object* importing as a baseline example, the user can import this type of object by clicking the appropriate button on the UI. An explorer dialog window appears, and the user is prompted to select standard 3D model format file (.obj). If successful, an undo step is created, the object is imported into the scene (Fig. 13 b)). Afterwards, an in-editor dialog appears freezing all functionality until the confirm or cancel buttons are pressed. In this dialog the user can, depending on the type of Object, input information about the object. In the case of a *3D artefact object*, the user can input the name and description of the imported object. Upon confirming the dialog, the imported object is renamed to what was input in the dialog. Cancelling the dialog undoes the object importing and clears the redos (Fig. 13 a)).

As stated before, importing *2D Artefact Objects* and *3D Room Objects* is not too dissimilar from importing 3D artefact objects. However, some modifications had to be made to the importing process, but also on the import dialog specifically, since the types of data the user needs to input are different.

When importing *2D Artefact Objects*, the Artefact Import dialog that is displayed upon importing is different from the one used when importing *3D artefact objects*. In addition to title and description, the user must input the object’s real-world height and width in centimeters. If no values are introduced, a value of 1 m is used (Fig. 13 d)). The artwork is then re-scaled according to these values (although the user can manually re-scale it again later).

The process of importing *3D Room Objects* is the same as importing *3D Artefact objects*, the only differentiating factor being the Import dialog that is displayed. In this Dialog, a small window is shown, with a button that says, “Add Room Plan” (Fig. 14 a)). This is where the user

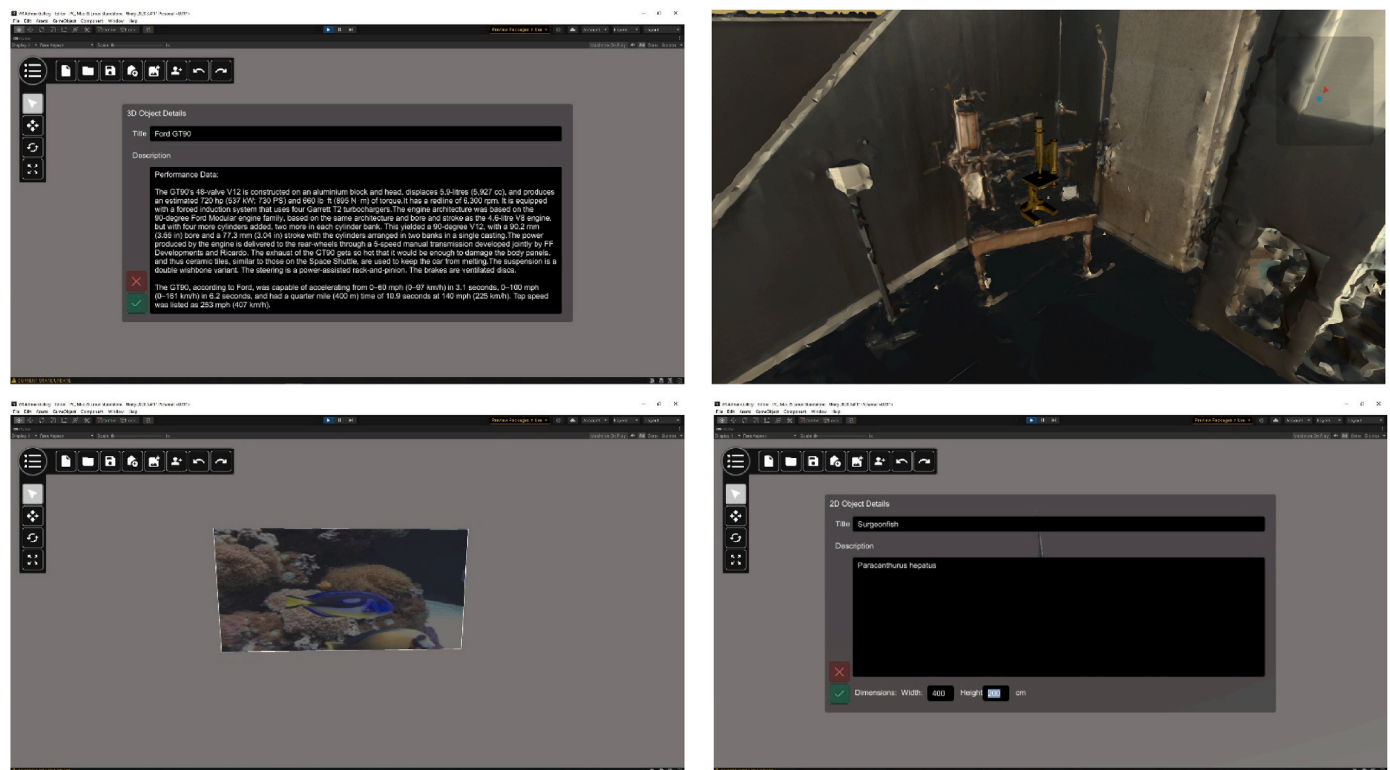


Fig. 13. a) The editor dialog that is displayed when importing a 3D Artefact Object. b) An example of an imported 3D Artefact Object imported into a museum 3D exhibit room. c) An example of an imported 2D Artefact Object. d) The editor dialog that is displayed when importing a 2D Artefact Object.

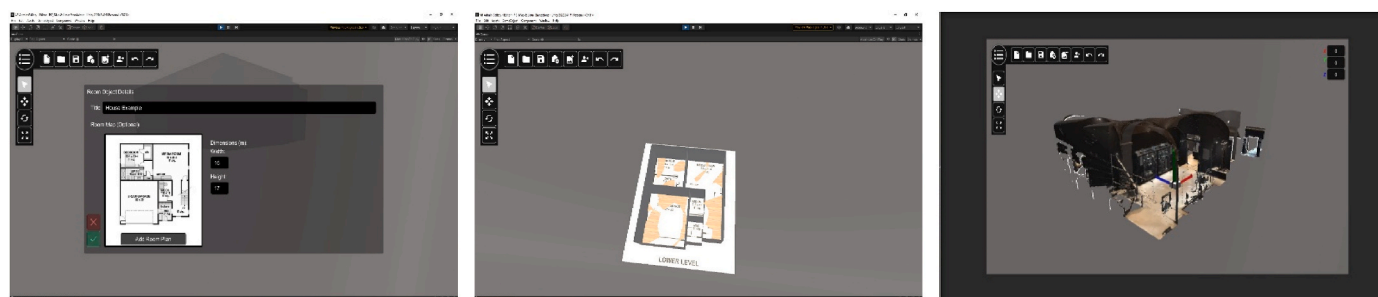


Fig. 14. a) The editor dialog that is displayed when importing a 3D Room Object. b) An example of an imported 3D Room Object. c) An example of an imported 3D Room based on data from a 3D Scan.

can supply a complimentary map image, to serve as a basis for the *minimap* shown in the Exhibit Scene. The user can also adjust the dimensions of the room in two input fields, to scale the image according to the real-life dimensions of the room. If nothing is inserted, default values are assumed.

4. User evaluation

4.1. Previous evaluation

The applications described in sections 3.1 and 3.2 had already been subjected to a complete usability and presence evaluation process, with good results, described in Lourenço et al. (2023). The aims of the evaluation were to assess presence in both client applications and user experience for the whole interconnected system. The test was composed of five primary modules.

The first module consisted of a Subject background information assessment. This allowed for an initial grouping of candidates into categories based on age, gender, education, and previous experience with XR and 3D Modelling. Next, participants participated in a Hands-on experiment, where they could freely explore and interact with the system without any specified objectives. Following this was a Feature-oriented user evaluation, where participants were asked to perform increasingly complex tasks within the system. Once this was complete, participants filled out a Presence Questionnaire (Witmer and Singer, 1998), to assess the degree to which participants experienced presence on a virtual setting, and a User Experience Questionnaire (Laugwitz et al., 2008), with the objective of evaluating the users' overall experience with the developed interconnected system.

Overall, the results of the testing phase were significantly positive, demonstrating that the system could be tried in a realistic scenario. Most participants found the system easy to use, even those less familiar with technology. There were some differences regarding the time to complete the tasks, most likely due to some participants' unfamiliarity with digital concepts, like the creation of application accounts or live streaming and what those terms entail, as well as a necessary adjustment to the equipment and controls.

During the evaluation process, the main issues identified by test participants were the excessive precision of the Oculus controllers, Low AR target detection performance under dark lighting conditions, and some unclear UI elements. Nonetheless, none of these issues severely impacted the testing process or user experience.

4.2. Current framework evaluation

An expanded evaluation of the exhibit editor and newly added features was carried out to provide feedback into some future user requirements and identify usability issues. This evaluation process was carried out by 14 participants, and consisted of a Hands-On Test, where users could freely explore the system for a limited period of time, a Feature Specific Test, where users were asked to perform increasingly

complex tasks and, finally, a User Experience Questionnaire, where users gave their subjective opinion regarding the system. After both the Hands-On Test and the Feature Specific Test, users were asked to fill out an online questionnaire to gather usability feedback. The results were gathered and statistically analyzed. From this analysis, the mean, median, mode, variance, standard deviation, and quartiles were calculated, when applicable. These metrics provide valuable insight into the central tendency and variability of the data. In addition, to test any possible associations and correlations, a modified version of Pearson's Correlation Coefficient (PCC) was applied to subsets of the test sample to identify possible correlations. This expanded evaluation revealed some additional nuances related to the system's evaluation, which can be taken into consideration when further developing the system. Some correlation was shown between user's answers and their previous experience with XR Applications and 3D Editing Applications, as well as their scores in the UEQ.

No Presence Questionnaires were performed on this application since it is a specific type of questionnaire, tailored towards immersive experiences.

Regarding sample demographics, a table containing all personal data provided by all participants is shown in Table 2.

With regards to ages, the average/mean age was 37.4 years, with a mode value of 23, a median of 24, a variance of 428.1 and a standard deviation of 20.7 years. Concerning user gender, test results show that 11, or 78.6 % of test subjects, were male, while 3, or 21.4 %, were female. With respect to User Education Levels, 8, or 57.1 % of participants answered that they had completed a bachelor's degree or above, whilst 6, or 42.9 % of participants, answered they had only finished high school. Next, users were asked to rate their experience with XR Applications and 3D Editing Applications in a scale of "Never Used" to "Regularly Uses". The results showed that 1 user (7.1 %) "Never Used" any XR application, 7 (50 %) "Used at least Once", 4 users (28.6 %) "Rarely Use", and 2 (14.3 %) "Frequently Use" XR Applications. Regarding the 3D Editing Application Experience, users rated their experience in a similar way to their experience with XR Applications, that is, in a scale of "Never Used" to "Regularly Uses". In this question, 6 users (42.9 %) "Never Used" any 3D Editing Applications, while 1 user (7.1 %) "Used at least Once", 4 (28.6 %) "Rarely Use", 2 (14.3 %) "Frequently Use" and 1 user (7.1 %) "Regularly Uses".

The Hands-On Test Questionnaire included 4 questions:

The first question asked whether the user had managed to discover most functionalities in both applications. All 14 test participants answered "Yes" to this question. While a promising result from a development standpoint, it is, nonetheless, statistically irrelevant. Question 2 asked if the user interfaces were found to be intrusive to normal task completion. 1 user (7.1 %) said "Yes", whereas the remaining 13 (92.9 %) said "No". The third question related to user interface descriptiveness. All 14 users answered "Yes". That is, users found the user interfaces to be useful and descriptive. Once again, these results are not statistically relevant, or interesting to analyze. In contrast, question 4 asked if the system functioned in a logical and

Table 2
Table showing Test Participant Demographics.

Identifier	Age	Gender	Level of Education	VR/AR Experience	3D Editing Experience
1	52	Male	High School Graduate	Used at least once	Rarely Uses
2	52	Female	Bachelor's Degree or Above	Used at least once	Never Used
3	23	Male	Bachelor's Degree or Above	Frequently Uses	Frequently Uses
4	72	Female	High School Graduate	Used at least once	Never Used
5	78	Male	High School Graduate	Used at least once	Never Used
6	24	Male	High School Graduate	Used at least once	Rarely Uses
7	24	Male	Bachelor's Degree or Above	Rarely Uses	Uses Regularly
8	23	Male	Bachelor's Degree or Above	Used at least once	Never Used
9	60	Male	High School Graduate	Never Used	Never Used
10	23	Male	Bachelor's Degree or Above	Rarely Uses	Rarely Uses
11	24	Male	High School Graduate	Used at least once	Never Used
12	23	Male	Bachelor's Degree or Above	Rarely Uses	Rarely Uses
13	23	Male	Bachelor's Degree or Above	Frequently Uses	Frequently Uses
14	23	Female	Bachelor's Degree or Above	Rarely Uses	Used at least once

expected way, based on the users' previous experience. In this question, 10 participants (71.4 %) answered "Yes", while 4 (28.6 %) answered "No".

During the Feature Specific Evaluation phase, the participants were asked to perform the following 5 tasks of increasing complexity.

1. In the VR gallery application, while facing a wall, the user must browse through the works currently on display (Home button to open the artwork browse menu) and search for "The Starry Night." Then the user must turn to the works and approach the searched work. This task would test the artwork browse menu and navigational aids.
2. In the exhibit editor, starting with 3 yellow objects and 3 green objects, the user must select 2 green objects and 1 yellow object simultaneously. This task would test object selection and basic Editor UI interaction.
3. In the exhibit editor, starting with 3 yellow objects and 3 green objects, the user must eliminate 2 from yellow objects and replace them with 2 copies of the green objects. This task would test cut/copy/paste/delete operations.
4. In the Exhibit Editor, starting with 6 equally sized, randomly rotated cubes, the user must build a 6-step pyramid, with increasingly smaller cubes. This task would test object manipulation through Translation, Rotation, and Scaling.
5. In the Exhibit Editor, the user must import one instance of the Room "Room A.obj", two instances of the 3D Object "Model A.obj", three instances of the 3D Object "Model B.obj", and one instance of the 2D Object "Object A.png". When importing the 2D Object "Object A.png", the object dimensions must be 120 by 120 cm. Finally, the user

must save the exhibit. This task would test Object Importing, as well as exhibit saving.

The Feature Specific Evaluation part of the Questionnaire consisted of 4 questions:

The first question asked whether users managed to complete all required tasks. All (100%) users answered "Yes" to this question, thus making any further statistical analysis irrelevant.

Next, users were questioned if they needed external developer help to perform any of the required tasks. Here, 6 subjects (42.9 %) answered "Yes", whereas 8 (57.1 %) answered "No". Users who replied with "Yes" were prompted to list which tasks they needed help with. Out of the 6 participants that answered "Yes", 4 mentioned task 1, 2 mentioned task 2, 4 mentioned task 3, and 3 mentioned task 4 and task 5.

The third question in the Feature Specific Evaluation asked if the users found the tasks to be simple and straightforward. That is, if they managed to understand what was being asked of them. 12 users (85.7 %) said "Yes", while 2 (14.3 %) said "No". Users who found some tasks to not be straightforward were then asked about which tasks proved to be confusing or complicated, as well as users who had answered that tasks were straightforward, but nonetheless felt there were tasks that required more attention. In these cases, 4 answers were obtained. Of these 4 answers, 1 included Task 2, 1 included Task 3, 3 included Task 4, and 2 included Task 5.

Finally, users were asked if their opinion regarding the system had changed since the hands-on test. 12 users (85.7 %) had not change their opinion, while 2 (14.3 %) answered affirmatively.

Lastly, in the UEQ, 6 metrics were evaluated, in a 7-Point Likert Scale. These were Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. Concerning **Attractiveness**, 1 user gave a value of 3, 2 users gave a value of 4, 3 users gave a value of 5, 5 users gave a value of 6, and 3 users gave a value of 7. Regarding **Perspicuity**, 3 users gave the system a value of 4, 5 users gave a value of 5, 4 users gave a value of 6, and 2 users gave a value of 7. With respect to **Efficiency**, 3 users gave a value of 4, 7 users gave a value of 5, 2 users gave a value of 6, and 2 users gave a value of 7. With regards to **Dependability**, 1 user gave the system a Dependability value of 2, 3 users gave a value of 4, 4 users gave a value of 5, 5 users gave a value of 5, and one user gave a Dependability value of 7. In relation to **Stimulation**, 4 users gave the system a score of 4, 5 users gave a score of 5, 4 users gave a score of 6, and 1 user gave a score of 7. Lastly, regarding the **Novelty** factor, 1 user gave the system a Novelty value of 1, 1 user gave a value of 3, 1 user gave a value of 4, 4 users gave a value of 5, 2 users gave a value of 6, and 5 users gave a value of 7.

Table 3 shows these values side by side.

As one can see from the table, the attribute with the highest mode value is Novelty, with a value of 7, followed by Attractiveness and Predictability, both with values of 6. Clarity, Efficiency, and Stimulation received the lowest mode value, 5, which is still above average in the 1–7 point range. However, in terms of mean/average, the highest value is Attractiveness, at 5.5, followed by Novelty and Clarity, at 5.35.

In addition to the descriptive metrics shown in the above table, inferential statistical analysis tests were conducted to determine if previous experience with Extended Reality technologies and 3D Editing Software had any palpable influence on the test results.

First, we conducted a two-sample Student's t-test between users who identified themselves as "experienced", versus "inexperienced" to compare their answers regarding each of the six UEQ attributes. Five of the arguments did not reveal any statistical significance (conventionally defined as $\alpha = 0.05$), however the p-value for Efficiency was 0.0511, representing some significance. This value suggests a possible correlation between user experience with Extended Reality and 3D Editing Applications, and the perceived efficiency of our framework, where more experienced users are able to perform their tasks more efficiently.

Table 3

Table containing participants' answers to all questions in the User Experience Questionnaire section of the system evaluation.

Participant	Attractiveness	Clarity	Efficiency	Predictability	Stimulation	Novelty
1	6	5	5	2	6	7
2	6	5	5	4	5	4
3	6	7	5	5	4	5
4	6	4	6	4	5	7
5	5	5	5	5	6	6
6	6	5	5	4	5	7
7	5	5	4	6	4	1
8	4	6	5	6	4	5
9	7	7	7	6	7	7
10	3	4	4	5	5	3
11	7	4	5	5	6	6
12	4	6	4	6	4	5
13	5	6	6	6	5	5
14	7	6	7	7	6	7
Mode	6	5	5	6	5	7

Next, to explore any further relations between user background and experience, and their overall performance during the test, the participants' answers to the questionnaire were analyzed and Pearson's correlation coefficients to relevant questions were calculated.

In particular, it was relevant to investigate whether a participant's previous experience with XR or 3D Editing would affect their ability to complete the required tasks without assistance. This corresponds to question 2 of the Feature Specific Questionnaire. The correlation values for XR and 3D Editing experience were $r = 0.4583$ and $r = 0.5774$, respectively, indicating a moderate correlation. These values indicate a need for onboarding materials and tutorials for users less familiar with these applications, particularly, 3D editing environments.

This evaluation process had encouraging results, which have informed future iterations of the administrative applications, towards a more robust product currently under development. However, due to the limited sample size and the exploratory nature of the current evaluation, this type of inferential testing was not further applied. As such, additional evaluation iterations will be led as a result.

4.3. Results discussion

Our developed system benefits from a high degree of modularity paired with a relatively low technical barrier. These characteristics make it particularly valuable for small to medium-sized museums and cultural institutions with limited digital infrastructure and budgets that do not allow for the development of bespoke systems.

The built-in editor empowers curators to build their own custom exhibits from the ground up with relative ease, without having to rely on programming and scripting languages, simplifying the creation workflow through the use of drag-and-drop editing and room and object importing.

It is worth noting that, throughout the framework development process, several challenges emerged that required or still require technical or architectural reconsideration.

The major constant and current issue is integrative design, enabling the framework to grow, while maintaining an interesting and motivational user experience. Additionally, technically linking the newly developed parts of the system with the existing ones required additional caution in order not to break the existing system.

Secondly, it was significantly challenging to develop a proper 3D

object rotation for 3D objects that took into consideration the angle the user is looking from. The final solution was a complex system that still needs improvement.

A third concern is that, due to the way vertex calculations occur in both the AR and the VR application, cross-sharing user drawings between applications is still under consideration.

Lastly the technical challenges associated with the tools used to develop the application led to intermediate solutions that still need to evolve, specifically in the connection between the insertion of spaces by the user and the system's interaction capabilities.

In addition to these technical challenges, early system deployments presented several usability-related challenges to novice users. The evaluation process demonstrated a need for more descriptive interfaces to provide a clearer and simpler onboarding process to new users, as object manipulation was not initially clear for most participants, leading them to require external assistance. On the exhibit's side, leaving a comment was not entirely obvious for most participants as well. While the system as a whole demonstrated a general ease of use, as confirmed by the usability testing regimen, these issues need to be addressed if the system is to ever be deployed in a real environment.

Some recommendations to address these issues would be the inclusion of present, blank rooms, where curators could place objects without needing to model a room in an external editor or using expensive 3D scanning equipment, the addition of a right click context menu to allow users to copy and paste, scale, rotate and delete objects using only the mouse, without relying on obscure key binds, and a "Help-me" tutorial page with concise information regarding some of the framework's functionalities. As the framework is designed with modularity in mind, it can, by definition, be used in several contexts without any significant changes. However, if specific changes for a particular context are to be made, then these would be straightforward implementations. Additional types of objects can be easily implemented through code and are already supported in the XML files. Being a Unity-based system, implementing new functionalities does not pose a significant challenge for a programmer. However, this type of "under the hood" extension cannot be carried out by museum staff without any previous programming experience.

5. Conclusions and future work

The work developed in the scope of this paper may prove essential for cultural institutions looking to improve visitor experience and exhibit creation workflow, since it unifies, in the same platform, a Virtual Reality Application, an Augmented Reality Application, and an Editor Tool that can provide content for these applications. A complete data flow among all applications is paramount to achieving this level of cohesion.

However, it is worth noting that the currently developed system can benefit from several improvements, such as Built-In room presets, so that curators do not have to waste time modelling an entire exhibit room or resources acquiring expensive 3D scanning equipment. Support for other types of media, such as sound and video, will also improve user experience. Additionally, adding dynamic attributes to artefacts, or including interactable individual parts of a larger artefact might also provide users with a greater understanding of said artefacts, especially if the user could learn further information about an artefact from a small detail in one of its parts. Having an ancient machine move to showcase its original purpose, or a timeline of the artefact's status evolution, are sometimes difficult to implement in a physical setting and are being considered in this context. These features could be implemented in a standalone sub-application that would be launched whenever the user wishes to learn more about a certain work. This would launch a "detailed view" window, where these extended features would be available. Currently, both visitor applications are being extended towards supporting digital artefact interaction and augmentation in virtual visits and in artefact analysis, this latter possibility to support curators' and conservators' analyses and studies. To determine which of these features would be best received by museum curators and visitors alike, it is important to conduct a thorough User and Task Analysis Study together with Domain Experts in the Field of Cultural Heritage Preservation. A workshop involving domain experts is planned, with this goal in mind. This study will be conducted using Design Thinking Methodology, where the domain experts are involved in the design process and their ideas are used as feedback, and starting points for new features.

CRedit authorship contribution statement

Tiago Nunes: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Pedro Lourenço:** Writing – original draft, Validation, Software, Methodology, Conceptualization. **Armanda Rodrigues:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Conceptualization. **Nuno Correia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.daach.2025.e00447>.

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