DEPARTMENT OF
COMPUTER SCIENCE

ANA MAISSA ANTUNES
BSc in Computer Science

DIGITAL TOOLS FOR STUDYING LUXURY GLASSMAKING IN ROMAN PORTUGAL

Dissertation Plan
MASTER IN COMPUTER SCIENCE AND ENGINEERING

NOVA University Lisbon
February, 2025

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Abstract

Nowadays, the significant historical and Cultural Heritage (CH) of Troia remains largely unknown to the public. This project studies luxury glass from ancient Rome, found recently in a luxurious mausoleum discovered in Troia, Setúbal.

The need to raise awareness of this valuable discovery has led to the collaboration between the Computer Science, and Conservation and Restoration departments at NOVA FCT, and archaeologists from the Troia Site. The project will involve the development of several digital tools that will support the dissemination of this study, preserving its cultural value, sharing its findings, and assuring future continuity, with great potential for further progress.

This dissertation covers the analysis and integration of the collected data and artefacts from the site and the preliminary development of a digital interactive platform that will, in the future, realise the dissemination of these findings near the public. This platform should, in its final state, include an interactive map of the Troia Peninsula, a repository featuring literature on Troia's excavations, and a Virtual Reality (VR) experience focusing on immersing virtually, a visit to an existing physical object. At the end of the project, all these elements will be integrated into a digital environment as Three-dimensional (3D) models. These technologies will enrich visitors' experience of the Troia ruins, allowing them to interact with rare luxury artefacts from the Roman Empire. Furthermore, the resulting platform should positively impact people and increase their knowledge about this important archaeological site, while preserving its cultural legacy.

Keywords: Cultural Heritage, Troia, Digital Tools, Virtual Reality, Rare Artifacts, Roman Empire

Resumo

Nos dias de hoje, um tesouro histórico-cultural situado em Troia permanece maioritariamente desconhecido. Este projeto estuda vidros luxuosos e únicos do período romano, encontrados recentemente num luxuoso mausoléu descoberto em Troia, Setúbal.

A necessidade de dar a conhecer esta valiosa descoberta levou à colaboração entre os departamentos de Informática e de Conservação e Restauro da NOVA FCT e os arqueólogos do sítio arqueológico de Tróia. O projeto envolverá o desenvolvimento de diversas ferramentas digitais que permitam a disseminação deste estudo, de modo a preservar o seu valor cultural e partilhar os resultados da sua investigação e garantir a continuidade futura do seu desenvolvimento, com grande potencial para novos progressos.

Esta dissertação abrange a análise e integração dos dados e artefactos recolhidos no local e o desenvolvimento preliminar de uma plataforma digital interativa que, no futuro, permitirá a divulgação destas descobertas ao público. Esta plataforma deverá, no seu estado final, incluir um mapa interativo da Península Troiana, um repositório contendo dados sobre as escavações realizadas em Troia e uma experiência de realidade virtual, que permitirá uma imersão virtual a um objeto físico existente. Por fim, estes elementos serão integrados num ambiente digital sob a forma de modelos 3D. Estas tecnologias irão enriquecer a experiência dos visitantes das ruínas de Troia, proporcionando-lhes a oportunidade de interagir com alguns dos artefactos mais raros do Império Romano. Além disso, a plataforma resultante deverá impactar positivamente as pessoas, expandindo o seu conhecimento acerca deste importante sítio arqueológico e preservando o seu legado cultural.

Palavras-chave: Tesouro Histórico-Cultural, Troia, Ferramentas Digitais, Realidade Virtual, Artefactos Raros, Império Romano

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Acronyms

2D	Two-dimensional *(pp. vi, 7, 13, 19, 20, 23, 27)*
3D	Three-dimensional *(pp. i, iv, vi, 3, 4, 6–8, 11–16, 18–28, 38, 39)*
6-DOF	Six Degrees of Freedom *(p. 8)*
API	Application Programming Interface *(pp. 29, 30)*
AR	Augmented Reality *(pp. 11, 23, 26)*
AV	Augmented Virtuality *(p. 11)*
BIM	Building Information Modelling *(pp. 19, 20)*
CAD	Computer-Aided Design *(p. 21)*
CAVE	Cave Automatic Virtual Environment *(p. 9)*
CH	Cultural Heritage *(pp. i, iv, vii, 1–7, 16–20, 23, 24, 26, 28, 42, 44, 50–52)*
CIDOC	International Committee for Documentation *(p. 5)*
CIDOC-CRM	CIDOC Conceptual Reference Model *(pp. 5, 17, 18)*
CRUSOE	Conference of Rectors of South-Western European Universities *(p. 18)*
DCMI	Dublin Core Metadata Initiative *(p. 5)*
DT	Digital Twin *(pp. 6, 7)*
ECCCH	European Collaborative Cloud for Cultural Heritage *(p. 18)*
ECHOES	European Cloud for Heritage OpEn Science *(pp. vi, 18)*
EDM	Europeana Data Model *(p. 5)*
EU	European Union *(pp. 4, 5, 18)*
FOV	Field of View *(p. 9)*
GIS	Geographic Information System *(pp. iv, vi, 4, 7, 14–17, 19–21, 26, 28)*

HBIM Heritage Building Information Modelling *(pp. 6, 7)*
HIS Heritage Information System *(p. 7)*
HMD Head-Mounted Display *(pp. vi, 9, 10, 28, 29, 40, 41)*

ICOM International Council of Museums *(p. 18)*

LiDAR Light Detection And Ranging *(pp. vi, 12–14, 16)*

OGC Open Geospatial Consortium *(pp. 14, 15, 17)*
OSGeo Open Source Geospatial Foundation *(pp. 14, 15)*

PASEV Patrimonialization of Évora's Soundscape *(pp. 23, 26)*
POIs Points of Interest *(pp. 22, 23)*
PQ Presence Questionnaire *(pp. 42, 50–52)*

SID Spatially Immersive Display *(p. 9)*
SVIFT Simple Virtual Interactor Framework and Toolkit *(p. 8)*

UEQ User Experience Questionnaire *(pp. vii, viii, 42, 47–49, 51)*
UI User Interface *(pp. 28, 30, 34, 45, 52)*
UX User Experience *(pp. 28, 47)*

VE Virtual Environment *(pp. 4, 6, 8, 9, 11, 24–28, 30, 38, 39, 45)*
VICARTE Glass and Ceramic for the Arts *(pp. 1, 2, 29, 39)*
VR Virtual Reality *(pp. i, iv, vi, vii, 3, 6, 8, 10, 11, 21–24, 26–31, 39–42, 44, 50–52)*
VRML Virtual Reality Modeling Language *(p. 21)*

1

Introduction

This chapter includes a concise overview of the topic of this dissertation. Section 1.1 introduces the motivation behind this thesis, while Section 1.2 describes its context. Following, Section 1.3 presents the problems to solve and the main objectives of this study. The expected contributions of this dissertation are discussed in Section 1.4. Finally, in Section 1.5, the organization of the report is outlined.

1.1 Motivation

Archaeology offers methods for interpreting human behavior and societal structures. By studying the past, archaeology provides insights that can be applied to the present [1]. Furthermore, it allows us to analyse the impacts of a changing world and the interactions among diverse countries, regions, and cultures.

This project will study the exploration of luxury glass from ancient Rome. The central motivation of this dissertation is the research of remains and artefacts, not only to preserve the CH but also to transmit ancestral patrimony knowledge to everyone, including future generations. The growing integration of digital tools with arts enhances online facilities for users and democratizes access to art. Additionally, it cultivates a deeper understanding of ancient cultures and traditions, allowing more people to engage with CH in meaningful ways. Moreover, by integrating technology with these archaeological discoveries we want to raise the value of this archeology site and make it accessible on a global scale.

1.2 Context

This thesis will be developed under the umbrella of an interdisciplinary collaboration between NOVA LINCS[2] and Glass and Ceramic for the Arts (VICARTE)[3]. VICARTE is a glass and ceramic research unit created as a partnership between the NOVA School of Science and Technology and the Faculty of Fine Arts, University of Lisbon, with members

[1] https://www.arch.ox.ac.uk/why-archaeology-matters

[2] https://nova-lincs.di.fct.unl.pt/

[3] https://vicarte.org/about-us/

from the Faculty of Fine Arts, University of Oporto, the School of Arts and Design, Polytechnic Institute of Leiria, and Cultural Institutions. The research at VICARTE is based on two interconnecting pillars: Glass and Ceramics in Contemporaneity and in CH.

Historically, the Roman ruins of Troia represent the largest known fish-salting production complex, built in the first half of the first century, and continuously occupied until the 6th century. The site of Troia is located on the southwestern coast of Portugal, on a sand embankment between the estuary of the Sado River and the atlantic ocean [32].

Today, this location is owned by Sonae Capital Group[4] and is associated with the Troia Resort[5]. The ruins extend along two kilometers of the Sado River estuary, comprising twenty-five fish-salting workshops [19]. A site of outstanding universal value, with a unique magnitude, which has influenced the economy of an entire region and its development up to the present day [31]. In 2005, a protocol was established that enabled the hiring of an archaeological team responsible for the preservation, maintenance, and enhancement of the Troia archaeological remains [33]. In 2007, a new project was launched to provide public access to the Roman ruins, leading to the installation of visitor pathways with interpretation panels. The site officially opened to the public in February 2011. Currently, artefacts collections from Troia are exhibited in various institutions, including the National Museum of Archaeology[6], the Museum of Archaeology and Ethnography of the District of Setúbal[7], and the City Council of Grândola[8]. The specific glass artefacts under study are housed at the National Museum of Archaeology.

1.3 Problem Description and Objectives

This study will concentrate on glass relics discovered in the mausoleum of a wealthy woman who lived in the Troia Peninsula. The data collected from the excavations include images of the discovered glasses both before and after conservation, and photographs documenting the entire excavation process. This information was provided by VICARTE.

This project aims to develop three digital tools in parallel, with a subsequent phase dedicated to integrating them into a cohesive web app.

Primarily, a data repository that compiles and organizes and findings from the Troia excavations, focusing specifically on glass objects. A database will be needed to store this data. This database will store essential information such as an object ID, location points, object utility, conservation status, origin, symbolic and decorative meanings, and comparisons with similar glass artefacts, using characteristics such as shape and uniqueness. This repository will serve as a data source for the other tools.

The second tool will be an interactive map of the Troia Peninsula, involving several layers of information, positioning each artefact found inside a grave. These layers will

[4] https://www.sonae.pt/pt/
[5] https://www.troiaresort.pt/en/troia-roman-ruins/
[6] https://www.museunacionalarqueologia.gov.pt/
[7] https://maeds.amrs.pt/
[8] https://www.cm-grandola.pt/

contain not only data from excavations but also, studied evidence enumerated above in the first development phase, the data repository.

Furthermore, an VR experience focusing on immersing a visit of an existing physical artefact to enable visitors to handle precious fragile antiquities, added to the environment as 3D models. Some of these models are already completed and will be supplied by the researchers involved in the project. It should use emerging display methods, such as the ones provided by VR glasses. The database will be the backbone of the two interactive tools described, feeding the interactive map with data and supporting the VR development.

1.4 Expected Contributions

By the end of the development of this dissertation, the following contributions are expected:

- **Virtual Platform:**
  - **Interactive Map** - User-friendly map that allows users to explore geographical and historical locations interactively.
  - **3D Object Manipulation** - Enables users to interact with and manipulate virtual 3D objects, utilizing the implementation of Márcia Campanha's thesis [4].
  - **Data Repository** - A comprehensive database containing all available data, accessible to users through interactions with the map or the 3D models.
- **User's Cultural Enrichment** - Provide users an engaging and interactive experience that enriches their understanding and interest in Roman CH, making learning both enjoyable and meaningful. On top of that, through the integration of VR, users will have the opportunity to virtually interact with glass made historical objects.

1.5 Document Structure

This document is divided into five chapters:

1. **Introduction:** The first chapter introduces the theme of the dissertation and explains its main focus.
2. **Fundamental Concepts:** This chapter provides background on the key areas of this thesis and explains important concepts that will be explored throughout the work.
3. **Related Work:** This segment consists on the research of similar projects and analysis of digital tools from relevant studies that can complement this dissertation.
4. **Proposed Work:** This chapter introduces a specific approach to achieve the project's goals and outlines how this will be implemented in practice.

2

Fundamental Concepts

This chapter introduces key concepts related to this thesis. Section 2.1 provides background of relevant digital aspects in CH. Subsequently, Section 2.2 explores Virtual Environments (VEs), focusing on user interaction and visualization. Section 2.3 presents diverse 3D extracting methodologies. Section 2.4 examines the role of GISs in applications involving map integration, particularly in the context of archaeological sites. The last two sections address important standards, and documentation principles (Section 2.5) to consider when developing heritage applications, as well as a significant European Union initiative (Section 2.6).

2.1 Digital Heritage Foundations

This section covers the fundamental concepts for integrating digital tools to visualize and preserve artefacts during archaeological studies.

2.1.1 Digital Cultural Heritage

CH includes monuments, sites, landscapes, skills, practices, knowledge and expressions of human creativity [11]. Collections conserved and managed by public and private bodies - such as museums, libraries and archives - and film heritage are also part of CH. It enriches the lives of people, constitutes a driving force for the cultural and creative sectors, and plays a role in creating and enhancing Europe's social capital. CH can be tangible (castles, museums, works of art), intangible (songs, traditions, etc.), or digital (born-digital and digitised). In this thesis we will reproduce tangible objects, and represent them in 3D models digitally. While policymaking in this area is primarily the responsibility of member states, regional and local authorities, the European Union (EU) is committed to safeguarding and enhancing Europe's CH. It does so through a number of policy areas and programmes.

Digital technologies provide new opportunities to preserve cultural content and to make CH more accessible to all audiences [12]. Museums and cultural organisations that embrace technology are able to offer innovative visitor experiences, as well as let the public access exhibitions remotely and view material that is not on display. The EU funds an extensive list of projects combining tecnology and art. Europeana[1] is a European digital platform to empower CH in its digital transformation. It supports thousands of European museums, archives and libraries to offer free access to digitalised versions of artworks, books and music.

The visualization of CH collections can involve two classes of data: the data constituting the digital cultural object, and the accompanying metadata, as exemplified below in the Figure 2.1 [49].

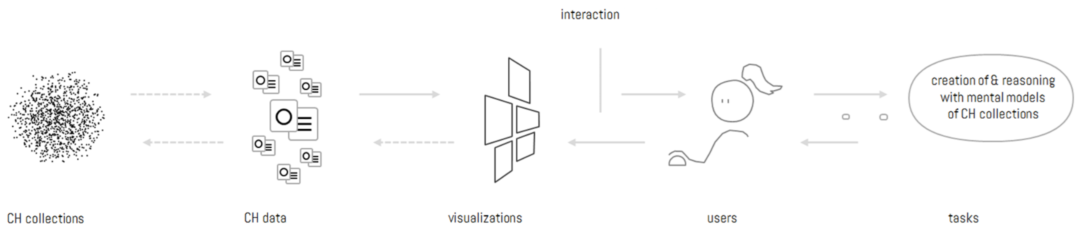


Figure 2.1: Schematic lineup of a visualization system in the CH data domain [49].

The metadata can describe a broad diversity of information associated with CH objects (Figure 2.2), therefore, to systematically classify different types of metadata, it is essential to adopt a unified metadata model. Among several standardization initiatives, the Europeana Data Model (EDM)[2] is one of the most mature efforts. The EDM reuses several existing Semantic Web vocabularies, such as the metadata set of the Dublin Core Metadata Initiative (DCMI)[3], and the CIDOC Conceptual Reference Model (CIDOC-CRM)[4] from the International Committee for Documentation (CIDOC) of the International Council of Museums[5]. Additionally, the target groups of digital CH collections are very diverse, from museum curators to humanities scholars and from highly interested enthusiasts to members of the general public— CH collections can provide useful and interesting information for all of them.

[1] https://www.europeana.eu/
[2] https://pro.europeana.eu/page/edm-documentation
[3] https://www.dublincore.org/
[4] https://cidoc-crm.org/
[5] https://icom.museum/

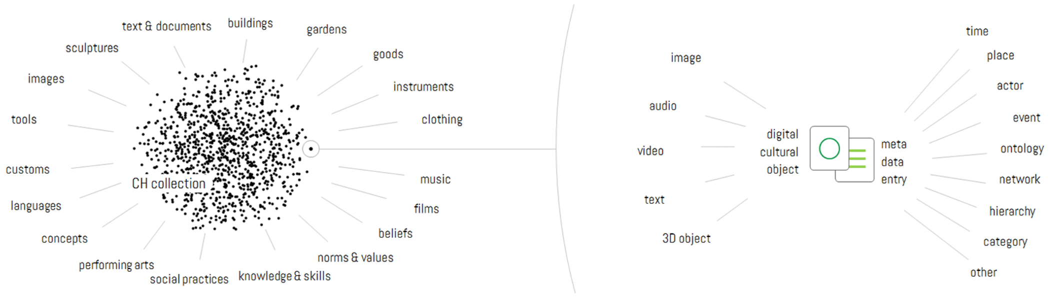


Figure 2.2: Types of cultural objects and related metadata entries [49].

2.1.2 Virtual Heritage Environment

According to Hale and Stanney (2014), "VE is a model of reality with which a human can interact, getting information from the model by ordinary human senses such as sight, sound, and touch" [18]. It also enables control of the model through typical citizen actions, such as the movement and positioning of body parts and voice. Although the terms VE and VR are frequently used interchangeably, some authors reserve the VE for an artificial environment which the user interacts with.

Virtual heritage involves the use of interactive digital technologies to record, preserve, and recreate culturally relevant artefacts and sites [43]. It allows digitally preserved content to be shared globally, providing an educational experience that enables users to explore CH through virtual manipulations of time and space. Given the need for interactivity with virtual objects, we naturally will use a VE to represent heritage artefacts in 3D in this project, enabling users to explore and interact with CH in an immersive and educational way.

Since the 1990s, VR was continuously used to recreate historical sites in a virtual immersive environment [18]. This technology provides a way to protect fragile sites while simultaneously educating visitors on how to explore, comprehend, and appreciate significant heritage sites.

2.1.3 Digital Twin in Cultural Heritage

Generically, the Digital Twin (DT) can be understood as a probabilistic, multiscale, multiphysics integrated simulation of a system that uses the best physical models, sensors, and history to mirror the life cycle of its corresponding twin [8]. The DT consists of three components: physical product in a real monitored space, data and information connections, and the corresponding virtual product in virtual space [16].

The potential application of the DT for heritage is its realistic representation in the form of an intelligent and semantically enriched 3D model Heritage Building Information Modelling (HBIM). First defined in 2009, HBIM is “a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements are accurately mapped onto a point cloud or image-based survey” [28].

This is a powerful tool capable of managing information collected and modeled, improving its availability and accessibility. Additionally, the use of digital scanning technologies to survey the current state of historic buildings, such as photogrammetry and laser scanning, expedites the process of generating a digital model.

Implementing DT for the management and preservation of CH assets requires adopting a collaborative integrated approach and a strong interplay among heritage recorders, conservation experts and information and communications technology specialists. In addition to the modelling of information related to heritage sites, open standards should be adopted for the identification of risks, damage and possible treatments to enable the awareness of DT with respect to their interrelationship and to ensure interoperability among the information systems of multiple organization and institutions. Before developing preventive conservation strategies, a good understanding of the heritage site and its context, including the assessment of its multiple values, is necessary. In this regard, the complex management of information related to the documentation of heritage places involves critical reflection on the adoption of an appropriate Heritage Information System (HIS). The need for 3D visualization in GIS to enable better visualization and analysis of complex issues related to elements of significance has led researchers in the field to progressively consider HBIM as a relevant alternative [21].

2.2 Interaction and Visualization Tecnologies

This section analyses virtual interactions from a technical perspective, and on the technologies used to create them. The first subsection (Section 2.2.1) lists the various user task interactors. Section 2.2.2 explores alternative methods of interacting with displays. Finally, the last sections discuss how to create a virtual simulation environment and enhance immersive interactions (Section 2.2.3 and Section 2.2.4).

2.2.1 Virtual Environment Interactors

A 3D interactor is generally a geometric object with a defined behavior when certain events occur and certain properties of the environment and the objects in it change [18].

As is true of 2D graphical applications, a 3D environment may contain geometric objects that belong to a class that interact with the user and other objects in a well-defined way. In 2D interfaces, these objects are called widgets, components, or interactors and include buttons, menus, scrollbars, and pointers. Each class of object encapsulates an interactive behavior, parameterized to allow for multiple uses.

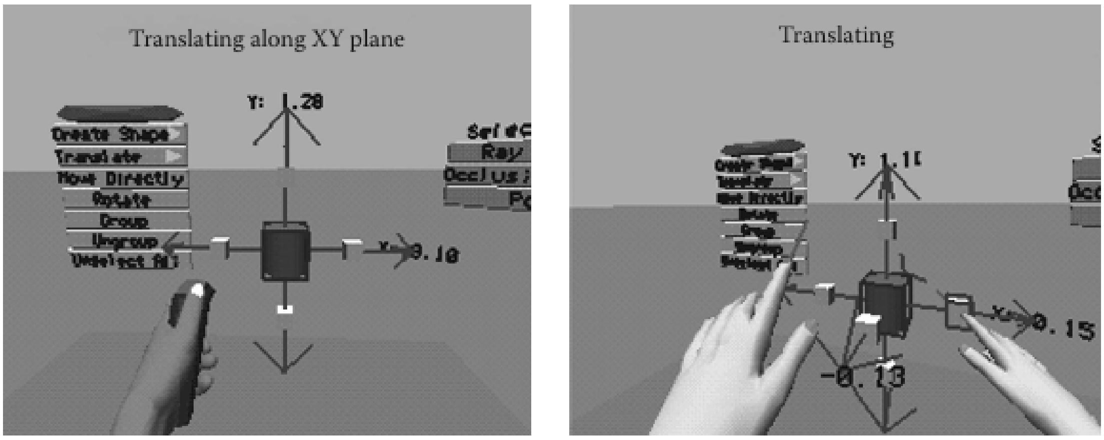


Figure 2.3: VR interface where a user is manipulating a 3D object [18].

Figure 2.3 above contains a set of Simple Virtual Interactor Framework and Toolkit (SVIFT) interactors, including buttons, menus, and tabs that can be grabbed and moved (or bestow the grab and move ability to another object), constraint maintainers (e.g., keeping the manipulated object on a particular plane), and selectors. The image on the left is using a ray selector interactor, while the figure on the right is using a poking selector.

2.2.2 Hardware Interaction

This section presents the possible user interactions with VEs, achieved through user tasks using input controllers and output devices connected to physical displays.

2.2.2.1 Input Devices

Common VE input devices include Six Degrees of Freedom (6-DOF) trackers[6] as exemplified in Figure 2.4, continuous posture-recognition gloves, discrete event gloves, pen-like devices, simple button devices, and special-purpose devices such as the Spaceball or force-feedback joysticks.

In the next paragraphs, I will describe four common available VE task categories.

Selection is the process of specifying an object or set of objects for a particular action. Most selection techniques can be categorized based on how an object is indicated, whether by touching it with a virtual hand, pointing at it, occluding it, encapsulating it within a volume, or selecting it indirectly.

Manipulation refers broadly to the modification of attributes of the selected object. Attributes may include position, orientation, scale, shape, color, or texture. For the most part, research has mainly considered the manipulation of the position and orientation of rigid objects, although some special-purpose applications include object deformation or scaling. Object manipulation tasks have importance in such applications as design, prototyping, simulation, and entertainment, all of which may require environments that

[6] https://www.ar.rocks/glossary/6dof-tracking

can be modified by the user. The design space for manipulation techniques is quite large. To provide a simple overview of the techniques already developed in the design space, three categories are presented in the following— virtual hand, proxy, and indirect.

Travel, also called viewpoint motion control, is the most ubiquitous and common VE interaction task—simply the movement of the user within the environment. Travel and wayfinding make up the task of navigation. Most travel techniques can be categorized as physical locomotion, steering, automated, or manual manipulation. Many of the other interactions found in VE applications fall under the heading of system control.

System Control includes commands, mode changes, and other modifications of system state. Often, system control tasks are composites of the other universal tasks. For example, choosing a menu item is a selection task, whereas dragging an object to a trash can for deletion is a manipulation task. The categories of system control techniques include graphical menus, voice commands, gestures, and tools.

Figure 2.4: HTC Vive controllers(center) and Oculus Touch controllers(at the ends) [41].

2.2.2.2 Output Devices

The three common VE display devices are HMDs, as illustrated in Figure 2.7, Spatially Immersive Displays (SIDs) (fully or semisurrounding displays, such as the Cave Automatic Virtual Environment (CAVE)[7]) (Figure 2.5), and single-screen stereo displays, such as the Responsive Workbench[8]. These display types have very different characteristics, and interaction with these displays is likely to be extremely different as well, as shown in Figure 2.6. HMDs and fully surrounding SIDs provide the ability to view the entire VE by physically turning. Semisurrounding SIDs require the use of virtual rotations, so applications intended for such displays should be designed in a manner to minimize these less-desirable rotations. HMDs that have a narrow Field of View (FOV) require extensive head rotation in order for the user to see the entire environment.

[7] https://steantycip.com/vr-cave/
[8] https://graphics.stanford.edu/projects/RWB/

Figure 2.5: Stereoscopic glasses augmented with a constellation of reflective balls [39].

Figure 2.6: Dual-screen fishtank stereo-capable display [39].

(a) Microsoft HoloLens 2 [51]. (b) HTC Vive [39]. (c) Meta Quest 3 [42].

Figure 2.7: Examples of the most recent and advanced HMDs.

2.2.3 Virtual Reality

VR is a sophisticated technology that enables users to engage with a computer-generated environment in an interactive and immersive way. Instead of relying on traditional screens or input commands, VR provides users a multisensorial experience. Including move freely, view and navigate in digital spaces from multiple perspectives, and manipulate objects as if they were physically present. This is possible through VR devices equipped with motion tracking and controllers, enhancing the sense of presence and realism.

The industry of VR combines expertise from diverse disciplines, including engineering, cybernetics, database management, real-time computing, simulation, computer graphics, ergonomics, stereoscopic imaging, anatomy, and even artificial intelligence. Despite its continuously advancements, VR still faces significant challenges, such as improving software performance, hardware capabilities, user interaction design, and high-speed network integration.

This project will utilize a VR environment which integrates various components to produce an immersive and interactive experience. This includes the use of digital representations such as 3D models of glass artefacts and static images of the Troia ruins. Additionally, the project may incorporate input methods, such as user gestures and touch, allowing for dynamic interactions with the media.

2.2.4 Augmented Reality vs Virtual Reality

While VR technology, or VE as called by Milgram, completely immerses users in a synthetic world without seeing the real world, Augmented Reality (AR) technology augments the sense of reality by superimposing virtual objects and cues upon the real world in real time.

The Virtuality Continuum is defined by Paul Milgram and Fumio Kishino [27] as a continuum that spans between the real environment and the virtual environment comprise AR and Augmented Virtuality (AV) in between, where AR is closer to the real world, and AV is closer to a pure VE, as seen in the Figure 2.8.

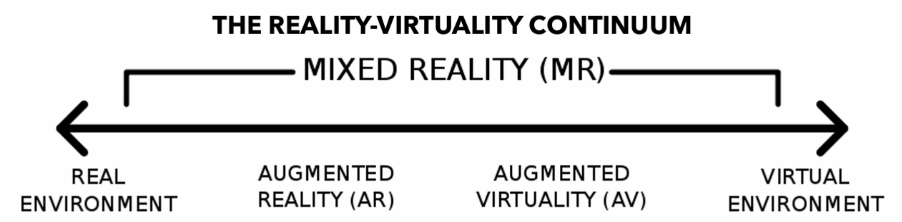


Figure 2.8: Milgram and Kishino's Virtuality Continuum [27].

2.3 3D Data Acquisition and Visualization

This section describes various techniques used for data acquisition, such as digital cameras and scanners and visualization through 3D models created with advanced software and further enhanced. The final subsection explores approaches for artefact reconstruction and the overall process.

2.3.1 Photogrammetry

Photogrammetry is a measurement technique that is used to extract the geometry, displacement, and deformation of a structure using photographs or digital images [3].

Concerning the object(s) of interest and the camera position(s), we distinguish between terrestrial and aerial photogrammetry [24]. In aerial photogrammetry, images are acquired via overhead shots from an aircraft, providing topographic maps and land use details. In terrestrial photogrammetry, images are obtained at locations near or on the surface of the earth and provide detailed dimensional information of an object. When the object size and the camera-to-object distance are both less than 100 meters, terrestrial photogrammetry is further defined as close-range photogrammetry. A fundamental technique in photogrammetry for creating accurate 3D models is Stereoscopic Viewing. By capturing two or more images photos of the same object but taken from different positions, it is possible to calculate the 3D coordinates of any point which is represented in both photos [24].

Multi-image photogrammetry is an advanced technique that combines large groups of images to create detailed 3D models [26]. The process begins with image acquisition, followed by importing the images into specialized software that automatically detects and matches correlated features. This step can be highly time-consuming and demand computer power for large datasets. Once matching points are identified, the software calculates their spatial relationships, producing a sparse 3D point cloud that outlines the subject's shape, as shown in Figure 2.9. Finally, the software refines this sparse model by reanalyzing the images to generate a much denser point cloud, similar to those produced by laser scanners.

Figure 2.9: 131 images of a 3D object in all-around configuration [25].

The most valuable application of multi-image photogrammetry may lie in its ability to facilitate community engagement in archaeological documentation. This approach enables the efficient creation of interactive 3D models, allowing the public to engage with heritage sites in a more immersive way than traditional static representations such as site plans and sectional drawings. In the "Previous Work", a close-range photogrammetry technique was used to generate the 3D excavation model, as detailed in section **??**.

2.3.2 LiDAR

LiDAR sensors enable precise 3D sensing of objects and are widely used in metrology, environment monitoring, archaeology, and robotics [23]. This technology allows for accurate determination of an object's distance and velocity. Similar to photogrammetry, LiDAR scanning is classified into two main types: terrestrial and airborne. The three most significant approaches in LiDAR technology are mechanical, nanophotonics-based, and solid-state. In traditional LiDAR sensors, as shown in Figure 2.10, a mechanical rotator is used for optical beam scanning, which introduces limitations on their reliability, size, and cost.

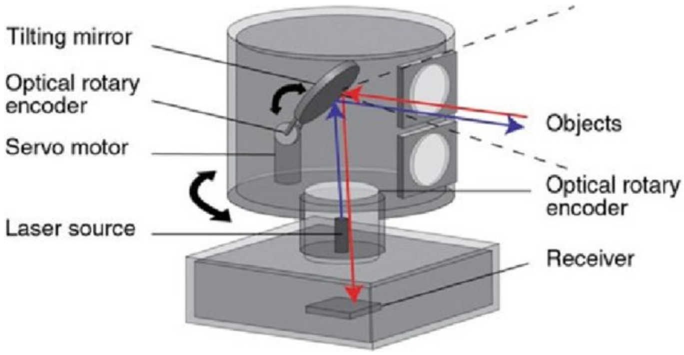


Figure 2.10: Mechanical Spinning LiDAR [20].

Solid-state LiDAR presents an alternative to traditional LiDAR by eliminating the need for a bulky mechanical rotator. Moreover, advancements in optical technology have led to the development of nanophotonics-based devices with high potential and superior advantages for LiDAR sensors. Different scanning techniques produce diverse types of scan outputs. For instance, flash-based LiDAR from solid-state approach captures a full-frame 3D image in a single snapshot, as shown in Figure 2.11, while sequential illumination-based LiDAR scans objects by sequentially illuminating small regions, producing the whole frame, as depicted in Figure 2.12.

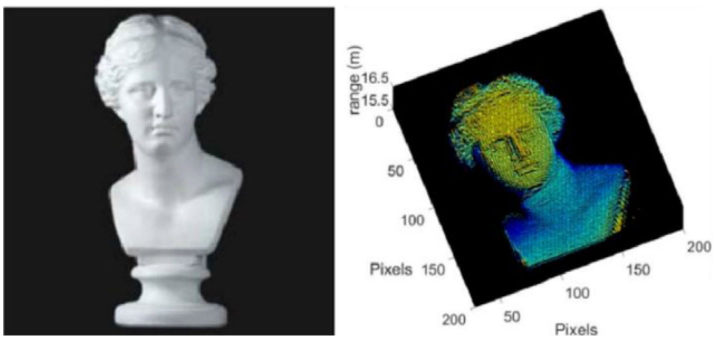


Figure 2.11: Flash-based LiDAR sensor. Left: 2D image of sensing target, Right: Captured 3D image [23].

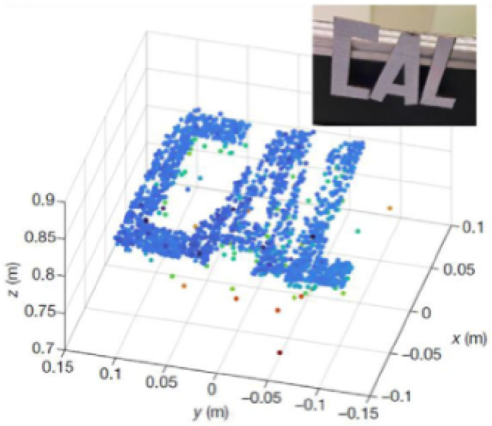


Figure 2.12: A LiDAR sensor based on sequential illumination [23].

2.3.3 Artifacts Reconstruction

Systems capable of automatically reconstructing objects from their fragments can greatly aid in the study of many civilizations [48]. Automated reconstruction systems working from large databases of digitized fragments could uncover numerous partial or complete reconstructions of artefacts that may have been excavated during different years of the same excavation, or possibly from different sites altogether. In this way, reconstruction systems not only save researchers time but, given a sufficient database of fragments, also have the capacity to reconstruct artefacts that would have otherwise remained as an incoherent pile of disjoint fragments .

Precise shape measurement can be achieved using advanced laser scanners or other commercially available shape measuring devices based on stereo vision or structured light [17]. A detailed triangulated 3D model of a corrupted shape is the prerequisite for its subsequent reconstruction. Missing or scarred parts of a shape can be reconstructed from similar parts either from the same object or by using a similar object as reference. If an object has symmetrical features, the missing or damaged part can be restored by copying the undamaged side. To fix scar parts or gaps, a mathematical technique called surface spline patches is used to smoothly fill in and blend the missing areas.

2.4 Geospatial Data and Systems

A Geographic Information System (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth's surface [40]. By relating seemingly unrelated data integrated by geographical location, GISs can help individuals and organizations understand spatial patterns and relationships.

In the context of GIS and geospatial data, two of the most prominent community initiatives are the Open Geospatial Consortium (OGC)[9] and the Open Source Geospatial

[9]https://www.ogc.org/

Foundation (OSGeo)[10]. The OGC is an international voluntary consensus standards organization, constituting more than 450 strong united organizations (such as Esri[11], Nasa[12]). The consortium publishes open standards that ensure interoperability between diverse GIS[13]. The OSGeo is an organization that promotes global adoption of open geospatial technology through an open philosophy and community driven development. For this project, the standards established by the OGC and the open resources provided by OSGeo are particularly relevant. These resources enable the creation of data from public geographic databases, supporting the development of interactive maps and ensuring the interoperability of geospatial data.

The first subsection provides an overview of geospatial data and its usage, while the following section explores its applications in archaeology.

2.4.1 Geospatial Data

GIS applications may include diverse spatial data types, such as cartographic data, photographic data, digital data, or data in spreadsheets. Once all the desired data have been entered into a GIS system, they can be combined to produce a wide variety of maps, that highlight different spatial relationships depending on the selected data layers. One of the most common uses of GIS technology involves comparing natural features with human activity, as illustrated in Figure 2.13.

Maps help visualize relationships between spaces and objects in proximity, aiding spatial analysis to identify patterns and make informed decisions based on data. A classic example of this geographic method is Jon Snow's study during the cholera epidemic in London in 1854 [20]. Jon Snow plotted the locations of cholera cases against the location of water pumps and noticed that the epidemic was concentrated in a certain neighborhood. Through the causal linkages, it was proven that when the contaminated pump was closed, the epidemic quickly came to a halt. A map of just the water pumps or incidences of cholera would have been of little value, but combining both revealed the contaminated source.

2.4.2 GIS Applications in Archaeology

The application of GIS in archaeology has brought about a transformative shift, equipping archaeologists with powerful tools to collect, analyze, and visualize geospatial data from archaeological sites [52]. Since 2000, archaeologists began employing GIS for more complex spatial analyses, including landscape analysis and site distribution patterns. Additionally, the development of 3D GIS technology enabled archaeologists to reconstruct ancient sites in

[10] https://www.osgeo.org/
[11] https://www.esri.com/
[12] https://www.nasa.gov/
[13] https://ogcapi.ogc.org/

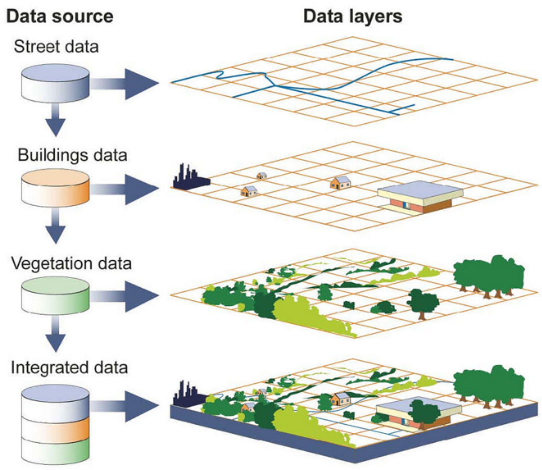


Figure 2.13: Visual Representation of Data Layers Integration in a GIS [30].

virtual environments, offering a better understanding and visualization of archaeological site structures and layouts.

A key technology that complements GIS in archaeology is LiDAR. The employment of LiDAR has been successful as an archaeological surveying tool for locating and identifying sites, sometimes in very remote and difficult to access locations [37]. For example, the recent, and highly publicized, discovery of what is believed to be the Mayan site of Ciudad Blanca in Honduras [44].

GIS also serves as an invaluable platform for the comprehensive management of CH resources. It excels in handling a wide array of unstructured data related to CH, allowing for a more organized and efficient approach to preservation efforts. One significant application of GIS is the inventorying of CH sites, including archaeological, architectural, and historical locations. Traditional recording methods often face limitations in terms of speed and accuracy when it comes to gathering and assessing current situation data.

With advancements in 3D graphics, high-resolution rendering, artificial intelligence, and 3D printing, those methodologies have progressively found widespread application in the preventive protection and restoration of cultural artefacts. In archaeology, GIS is essential for managing spatial data, often integrating spatial databases, such as PostgreSQL[14]/PostGIS[15] or Oracle Spatial[16] for efficient data storage and querying. Moreover, software such as ArcGIS Pro[17] or QGIS[18] is used to visualize, analyze, and interpret this data. These GISs process archaeological data following specific data standards and protocols.

[14] https://www.postgresql.org/
[15] https://postgis.net/
[16] https://www.oracle.com/database/spatial-database
[17] https://www.esri-portugal.pt/pt-pt/arcgis/produtos/arcgis-pro
[18] https://qgis.org/

2.5 Heritage Metadata Standards and Documentation

Standards are critical for systematic and robust development of any emerging technology [18]. Specification standards provide for practical descriptions of product characteristics and limitations, critical to an end user. Interface standards allow for interchangeability of components developed by different manufacturers, thus enabling specialization and robust competition in the marketplace. Safety standards ensure the health and safety of product users. Finally, terminology standards ensure that technical terminology is used in a consistent and rigorous manner, thus preventing confusion and ambiguity in scientific and technical reports and specifications.

International standards and ontologies for data encoding are crucial to speed up interoperability and the process of integration [10]. CIDOC-CRM, which is created to capture the richness typical of CH information, fully fits our needs: its classes and properties work perfectly to capture the concepts underlying database structures, providing a high level of data integration.

In the subsections below, the first presents a commonly used model with aggregated standards, followed by a significant European organization in CH preservation.

2.5.1 CIDOC Conceptual Reference Model

The CIDOC-CRM[19] is a theoretical and practical tool for integrating CH information [10]. It provides formal definitions and a structured framework to describe concepts and relationships that support the organization and connection of information regarding CH objects and their contexts (Figure 2.14). Since 2006, CIDOC-CRM has been recognized as an official ISO standard (`ISO 21127:2023`). The most recent version establishes CIDOC-CRM as a compatible interface for OGC standards, enhancing its application in GIS and facilitating geospatial and spatiotemporal reasoning.

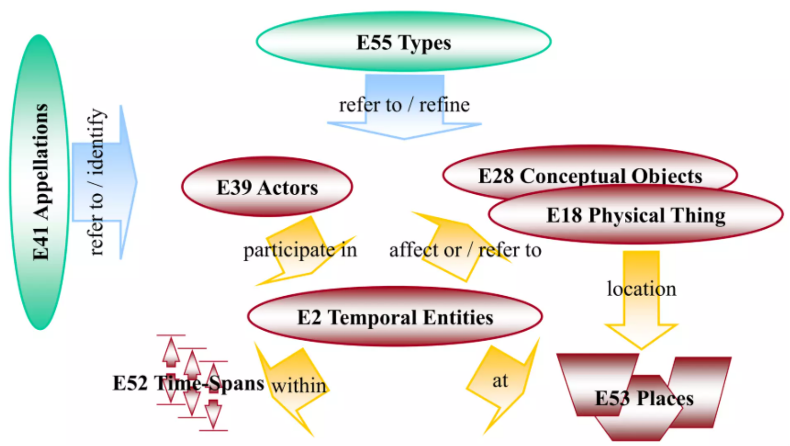


Figure 2.14: Fundamental concepts of `ISO 21127` [9]

.

[19] https://cidoc-crm.org/

From database to CIDOC-CRM

The necessary information is extracted from different archaeological and museum collection data models (with various structured, as well as non-structured data, i.e. text description) to a common standard based on CIDOC-CRM compliant structure. Although the CIDOC-CRM model provides a common, standardized framework for representing data from archaeological and museum collections, it has limitations in representing the characteristics of digital 3D artefacts.

2.6 Cultural Heritage Cloud

The European Collaborative Cloud for Cultural Heritage (ECCCH)[20] is a European Union initiative to create a shared digital infrastructure that connects CH institutions and professionals across the EU. The ECCCH aims to add a digital dimension to CH preservation, conservation, restoration, and enhancement by providing cutting-edge technology for artefact digitisation and artwork research. In Portugal, the International Council of Museums (ICOM)[21] is a beneficiary of the initiative, while Conference of Rectors of South-Western European Universities (CRUSOE)[22] is an ECCCH association partner. CRUSOE is a university association comprising institutions from both Portugal and Spain. While ICOM Portugal and CRUSOE represent the participants in Portugal, the ECCCH also includes other 14 countries' beneficiaries, affiliated entities and/or associated partners across Europe that actively support those CH sectors enumerated above.

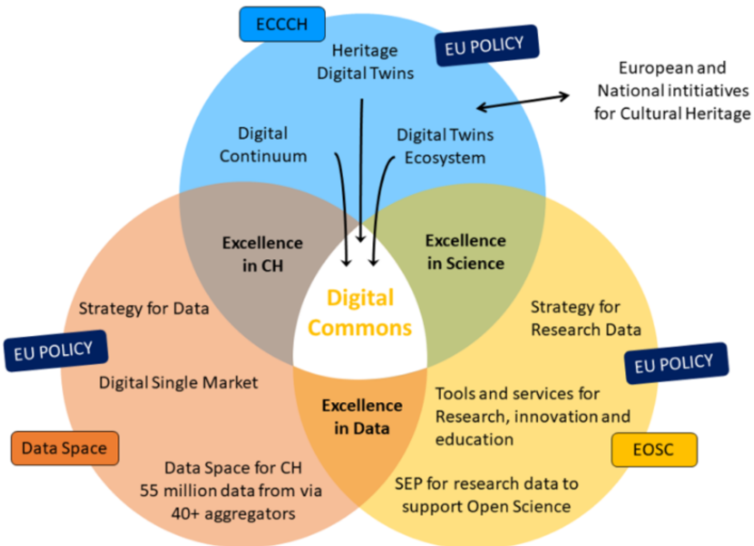


Figure 2.15: ECHOES goals 20.

[20]https://www.echoes-eccch.eu/
[21]https://icom-portugal.org/
[22]https://redcrusoe.com/

3

Related Work

This chapter presents research works related to this thesis theme. These studies were selected based on their relevance to the concepts described in Chapter 2, including GIS integration, 3D modelling, spatial databases, and virtual tours.

3.1 The Turin 1911 Project

General Overview

The "Turin 1911: The World's Fair in Italy" is a research project [42] conducted by the *University of California San Diego* and *Politecnico di Torino* where a multidisciplinary team cooperates to document and investigate the 1911 World's Fair held in Turin. It integrates archival research, 3D reconstruction, and webGIS technology to study and preserve the architectural and CH of the Fair[1].

Process Description

The webGIS and GIS-Building Information Modelling (BIM)[2] web apps are interactive tools to digitally navigate and query the environment. Three types of elements were used to create a 3D webGIS: polygonal feature class, multi-patch feature class, or 3D object.

The historical map of the *Valentino Park Fairground* was georeferenced and digitized, and a 2D/3D map interface was developed using ArcGIS Online[3], allowing users to switch between views seamlessly. To develop the 3D models in the BIM-GIS Web App, not only, photographs of each object, but also, plans, elevations, and sections of some Built Environment Objects, were collected. Using technical drawings, 3D models were generated and compared with historical photographs. The final webGIS application, for both dimensions, was created using ArcGIS Experience Builder[4] configurable widgets (Figure 3.1).

[1] `https://arcg.is/1HfSqG`
[2] `https://www.autodesk.com/solutions/aec/bim`
[3] `https://www.arcgis.com/index.html`
[4] `https://www.esri.com/en-us/arcgis/products/arcgis-experience-builder/`

Interactive Features

Several tools were developed in the webGIS, including a search bar, an option for switching between a 2D map and a 3D scene, a layer list, a legend, navigation controls, filters, and pop-ups, allowing users to explore built environment objects. BIM was used for detailed 3D reconstruction of selected Fair pavilions (e.g., Pavilion of Siam), and to create an interactive 3D scene with those layers. The actual shape of *Valentino Park* was created from an aerial photogrammetric survey and processed in Agisoft Metashape[5]. Applications like Experience Builder enhanced interactivity, offering features like navigation and measurement tools, bookmarks, layer toggles, and camera orientation. The current geolocation feature enables users in the park locate themselves on the webGIS and web app. The digitized archival materials are catalogued and linked to the geometries in a dedicated Geospatial Database.

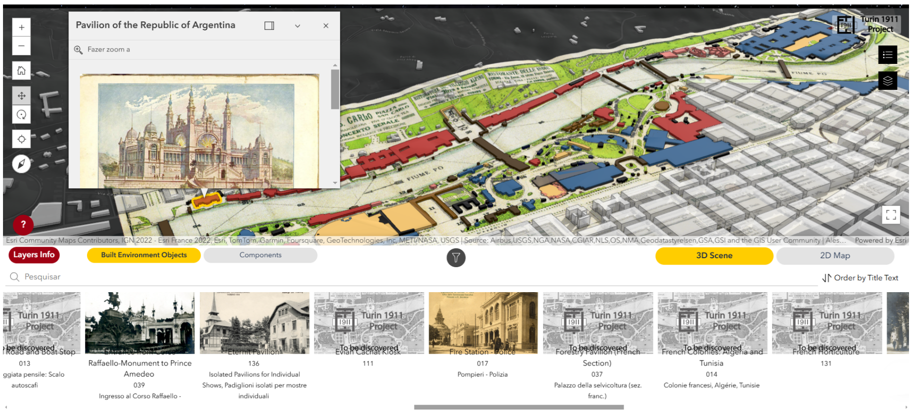


Figure 3.1: The webGIS application. Displayed functionalities: bottom left – search bar and objects list; top left – navigation controls and a pop-up; bottom right – 3D scene/2D map buttons; top right – map legend and layer control buttons.

3.2 Web-Based GIS for CH of Safranbolu, Turkey

General Overview

This study [2] focuses on the documentation and preservation of the CH of Safranbolu, Turkey, a UNESCO World Heritage site[6]. The goal of this project is to establish an internet-based information system and the modelling for GIS of all historical constructions of Safranbolu historical city. This will be accomplished by compiling documentation and preservation of CH, using GIS, 3D models and digital photogrammetry.

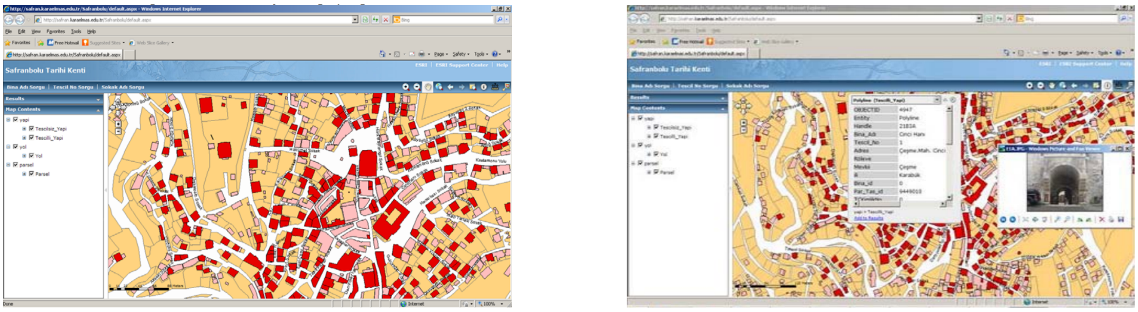
Process Description

The development of this work started with digital photogrammetry, where the objects coordinate system was defined, and control points marked on the ancient artefacts, and

[5] https://www.agisoft.com/
[6] https://whc.unesco.org/en/list/614/

photographs of the antiquities taken.

Pictures then were transferred to computer and evaluated with photogrammetric software (*Photomodeler*[7]). Following this, the 3D modelling of the historical buildings was executed. 3D of the building were obtained using photos from photogrammetry taken from different views, and the object models were covered with different surface and image textures. GIS was used to analyse spatial objects, such as buildings constructed within parcels and roads. Land parcels were represented as polygons, while roads with polylines. The city map of Safranbolu was obtained in Computer-Aided Design (CAD)[8] format, and then transferred to ArcGIS. This data was then evaluated in GIS by building a topological infrastructure. In the next phase of the project, all collected data—such as photos, videos, architectural drawings, and 3D and Virtual Reality Modeling Language (VRML) [5] models—related to the selected historical buildings was prepared.



(a) Registered and non-registered buildings in the old Safranbolu area.

(b) Designed Web-based GIS *Cinci Caravanserai*.

Figure 3.2: Illustrative views of the Web-GIS application.

This project integrates spatial data (e.g., building locations and 3D images) with non-spatial data (e.g., textual descriptions and historical information about the buildings) to document the historic town of Safranbolu. Through the interface (Figure 3.2), users can visualize various types of data, including land parcels, registered and non-registered buildings, roads, ownership details, addresses, and other relevant details about cultural monuments in the old Safranbolu area.

3.3 VR Scenario with Funerary Artifacts from Ancient Egypt

General Overview

This research [15] leverages VR to enhance the accessibility and understanding of Egyptian funerary artefacts in the Sforza Castle, Milan. Aimed at exhibition renewal, the project creates an immersive VR experience to engage visitors of the “Archaeological Museum” in Milan, with the ancient Egyptian "Path of the Dead" ritual, integrating interactive 3D models and hieroglyphic translation tools. Four key funerary artefacts were selected for

[7] https://www.photomodeler.com/

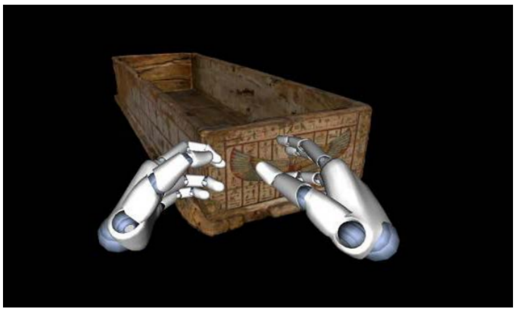
[8] https://www.autodesk.com/pt/solutions/cad-software

their historical and archaeological significance: the Ushabty statuettes (representing a pharaoh or minister), the Heart Scarab amulet, and the Wooden Sarcophagus.

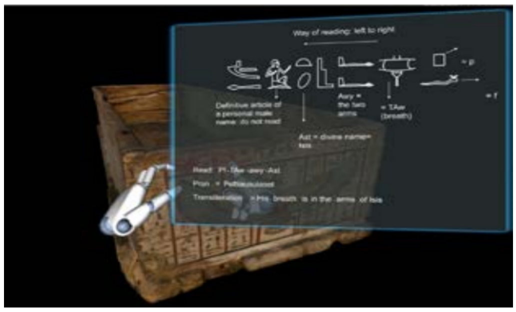
Process Description

Firstly, the photogrammetry survey was built by moving the camera all around these objects to capture all angles. Subsequently, the software *Agisoft Metashape* was used for texture blending. Then, the output file was imported into *Adobe Photoshop*[9] for word delineation, outlining and identification. Finally, *Polyworks*[10] was used to simplify the model, and in resolution/texture optimization. The VR device Oculus Rift DK2 provided stereoscopic visualization, while Leap Motion[11] tracked hand movements for object interaction (grabbing, rotating, and highlighting).

Responsive Points of Interest (POIs) created in the context of the project, were exported in *fbx*[12] format, and the cut parts of the artefacts were then imported to Unity[13], for integration as 3D models. These POIs highlight cultural symbols and texts on artefacts (e.g., religious inscriptions). When selected, they provide detailed descriptions and explanations. The computer graphics program *3D Studio Max*[14] was used to enhance specific elements of the models, to improve hieroglyphs readability. Touch-Triggered Transliteration and Translation allows users to interact with hieroglyphic symbols(Egyptian writing).



(a) Grabbing and rotating the object.



(b) Highlighting and translation the text.

Figure 3.3: Visual representations of the implemented VR scenario

If the user wants to know more about these words, they can touch them, and the word is automatically enhanced and the transliteration and the following translation appear as illustrated in Figure 3.3b. The data involved is the name of the deceased, and descriptions explaining images or drawings on the objects. Users can rotate and grab the 3D models using hand gestures, as shown in Figure 3.3a.

[9] https://www.adobe.com/pt/products/photoshop.html
[10] https://www.innovmetric.com/products/products-overview
[11] https://www.ultraleap.com/
[12] https://www.autodesk.com/products/fbx
[13] https://unity.com/
[14] https://www.autodesk.com/pt/products/3ds-max

3.4 Related Work developed at NOVA LINCS

At NOVA, recent research work has been consistently focused on developing digital tools for museums and cultural institutions, aiming to offer immersive experiences through VR technology or 3D media visualizations of CH objects, often incorporating interactive maps, an approach to be implemented in this dissertation. Over the past year, two Master of Science theses [6, 13] have explored how to present a virtual tour of museums. Vilar's thesis [46] explored interactive games and 3D models, with an emphasis on cultural artefacts from the Portuguese Évora site. The final thesis [4] focuses on 3D object manipulation, which may be integrated into this dissertation.

3.4.1 System for Creating and Exploring Interactive Narratives and Games

Vilar developed his research thesis work [46] as part of the PASEV[15] Project Patrimonialization of Évora's Soundscape (PASEV). The main objective of the project was to analyse new perspectives regarding the cultural manifestations in UNESCO patrimonial city, Évora, which has a significant historical context [47]. The project started by Rosário [36] and was extended by Ferreira [14] which were mainly dedicated to the development of a historical soundscape's web platform[16]. This work focused on the study of sound events that occurred from 1540 to 1910 with the aim of preserving the city's auditory heritage [35]. The user can visualize and display audio and media(including, in some cases, 360º photos and videos) in the web platform.

Vilar expanded the existing PASEV platform by introducing JoNI, an infrastructure designed to support the creation of interactive games, involving motivational techniques, such as interactive narratives, gamification structures and the use of AR. In the end of this project, a mobile application was developed incorporating games with a narrative and characters, including 2D/3D models and auditory data, and object recognition via photos. Two functional prototypes supported by the platform were developed. The first, an interactive card game that teaches children about historical music instruments available at the Evora Museum[17] using audio and visual elements. The second, a gamified app to promote the discovery of diverse locals with their itineraries. Along the route, textual content, videos, audios and a ranking progress are reproduced to generate an interactive and learnable experience. For each game, two main tabs were implemented for managing the map and AR features of the game.

This implementation includes AR and geolocation technologies to immerse users in Évora's CH. The solution was built on top of an existing base map. Afterward, the POIs of Évora were identified and represented with AR markers. Additionally, GPS tracking was integrated to allow users to monitor their location. The solution integrates a native Android environment and Unity game engine for seamless communication. The main

[15] https://pasev.hcommons.org/
[16] https://pasev.uevora.pt/
[17] https://www.visitevora.net/en/evora-museum/

goal of this dissertation is the dissemination of the CH and soundscape of Évora, with the solution integrated into Museu Nacional Frei Manuel do Cenáculo (MNFMC)[18]. The database was extended using PostgreSQL and PostGIS technologies.

3.4.2 Designing and implementing a museum Virtual Tour, Museu dos Coches

Coimbra [6] developed a VE that simulates a museum visit, providing an immersive and interactive user experience. The project integrates a 3D environment with 3D scanned objects, complemented by an intuitive and user-friendly interface. This virtual tour was based on the National Coach Museum[19] and performs as a model for VR museum environments. This approach can revolutionize museum tours, suggesting an alternative, immersive, and innovative platform for cultural enrichment. The technologies used include Unity to create and deploy the VE, and the virtual visit requires a VR headset equipped with hand-tracking capabilities. For this purpose, the Meta Quest 3 Headset [20] was used to improve the processing power over earlier models. Therefore, this software ensures an optimized VR experience. Coimbra's thesis was developed in 2024 and has some points in common with this one. Both use digital tools for an interactive user experience with CH elements.

3.4.3 Web integration of virtual museums tours and 3D media visualization, Academia das Ciências

Last year, Faria [13] developed his dissertation work in collaboration with *Academia das Ciências de Lisboa*[21], one of the oldest scientific institutions in Portugal, active since 1779. The academy is dedicated to promoting and preserving CH, with both physical and digital collections accessible to the public [1]. The project focuses on integrating CH objects in VEs. As part of this work, a website was created to provide a virtual tour of the academy, presenting its spaces and CH objects in an engaging and informative manner. This website is available at the following[22]. Designed with a user-friendly interface, the website offers an intuitive navigation experience, including an audio guide with simulated narration, background music, a 3D viewer, enabling the user to explore the components and history behind each artefact. The project also incorporates an interactive itinerary map, displaying all the available rooms and buttons for instinctive control of the tour. This feature allows users to explore the academy's diverse spaces quickly and effectively. Matterport[23] technology was employed to create the visualization and interaction environments, providing 3D spatial mapping of the academy's rooms. Complementing this, 3D object models

[18] https://www.cm-evora.pt/locais/museu-nacional-frei-manuel-do-cenaculo/
[19] http://museudoscoches.gov.pt/pt/
[20] https://www.meta.com/quest/quest-3/
[21] https://www.acad-ciencias.pt/
[22] https://visita3d.acad-ciencias.pt/
[23] https://matterport.com/

were created and displayed in a Sketchfab[24] viewer. To support these features, several technologies were used, including Matterport Pro3 Camera[25] for the 3D scanning and 360º immersive views, along with frontend and backend frameworks, including Vue.js[26] and Tailwind CSS[27] for the interface, while the backend relied on Node.js[28]. In addition, a database to store and manage the media content was implemented.

3.4.4 Developing support for digital representations of Heritage artefacts in cultural exhibitions

Campanha's thesis [4] aimed to extend the work of Nunes [29], by enhancing user interaction with artefacts in VE. The functionalities implemented in this work focus on object interaction, such as the ability to apply different textures, the possibility to manipulate specific parts of a 3D object independently, and access detailed information regarding these parts. Users can manipulate objects through the three axes (X,Y,Z) by rotating, scaling, or translating them within the virtual space. To obtain detailed information of the antiquities, the user simply selects the desired component. Additionally, users can upload the digital 3D representation of the object to the virtual exhibition and view a gallery menu displaying multiple perspectives of the 3D models associated with the same artefact. The system allows users to apply different textures to individual object components and select specific parts, which are outlined with their associated descriptions. The full interface, including these interactive features, can be observed below in Figure 3.4.

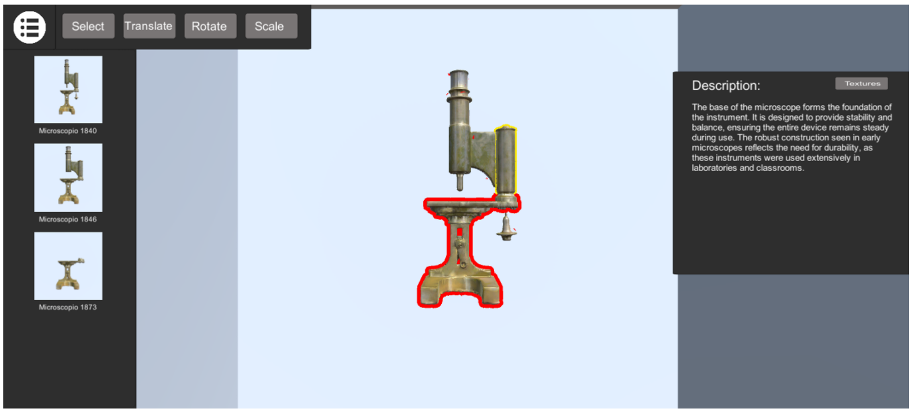


Figure 3.4: Interface for interacting with heritage artefacts.

[24] https://sketchfab.com/
[25] https://matterport.com/pro3
[26] https://vuejs.org/
[27] https://tailwindcss.com/
[28] https://nodejs.org/

3.5 Discussion

This section compares various recent research works and their relevance to this dissertation by analysing their components and contributions. Table 3.1 provides an illustration of these comparisons.

The "The Turin 1911 Project" integrates an interactive map with multiple functionalities, while incorporating 3D models and a spatial database.

Another significant research project focused on the preservation of an archaeological site is Safranbolou GIS. This study used 3D modeling to map historical buildings and integrate CH monuments as metadata relevant to the site.

The following research, integrated VR to provide an immersive environment, enabling users to interact with valuable artifacts from ancient Egypt. Features such as zooming, scaling, Egyptian writing translation, highlighting, and object manipulation were implemented to enhance the user experience.

To include contemporary Portuguese projects relevant to this research, Section 3.4 was added, exploring digital representations of cultural artefacts, and the dissemination of archeological sites and institutions. The following three projects integrate a virtual tour. Primarily, PASEV project extends an existing historical soundscape web platform by integrating AR. This work also incorporates 3D interactive models, a digital map and was selected due to its completeness and the use of technologies, such as PostgreSQL with the PostGIS extension and Unity, that will also be employed in this dissertation. Another relevant project is the National Coach Museum Tour, chosen for its VR development within a 3D environment. Similarly, the *Academia das Ciências* virtual tour provides an interactive experience by presenting 3D object models and integrating a spatial database. Additionally, an itinerary map of the Evora site and academy rooms allows transitions between the map and the VE, enabling users to virtually transport themselves to a specific academy room.

Finally, the last thesis provided an intuitive way to interact with 3D artefacts. This research developed a user interaction approach, allowing the manipulation with object's individual components. The outcomes of this study may be integrated in this dissertation, to support the 3D artefacts environment.

Project Name	**Interactive Map**	**3D Models Interaction**	**AR/VR Experience**	**Data Repository**	**Virtual Tour**
Turin 1911 Project	✓	✓	✗	✗	✗
Safranbolu GIS	✓	✗	✗	✗	✗
VR Funerary Artifacts	✗	✓	✓	✗	✗
JoNI (PASEV)	✓	✓	✓	✓	✓
Museu dos Coches Virtual Tour	✗	✓	✗	✗	✓
Academia das Ciências 3D View	✗	✓	✗	✗	✓
Digital Representations of Heritage Artifacts	✗	✓	✓	✗	✗

Table 3.1: Comparison of Projects Functionalities

4

System Design and Implementation

4.1 Adopted Tools and Tecnhologies

The following section focuses on the technologies and tools used in implementing this project. These include environments used, backend, database, and 3D development tools.

4.1.1 Working Environment

The VR environment was developed using the Unity editor, with code scripts written in C# within the **Visual Studio Integrated Development Environment (IDE)**. Its features, such as debugging tools, error detection, code navigation, Unity-specific types recognized automatically, and IntelliSense suggestions, greatly enhanced productivity. To further support this integration, the Visual Studio Editor package was utilized.

For the backend implementation, comprising the Node.js server and the database, **Visual Studio Code (VSCode)** was utilized. The same IDE was also adopted for the report writing in LaTeX, due to Overleaf limitations.

The version control system used initially for project management was **GitHub**, providing effective tracking of updates and overall code organization. However, as a consequence of storage limitations in handling large files, such as the 2D ground view or the funerary enclosure 3D model, the **Diversion** tool was employed as an alternative solution for managing these system.

4.1.2 Unity

Unity is a cross-platform engine that provides a robust environment for developing 2D and 3D applications. Its component-based architecture simplifies 3D development by allowing developers to define object behaviors through scripts in VEs. Unity also offers a community forum and repositories available in **Unity Asset Store**[1] where developers can access resources and adapt them for their projects.

[1] https://assetstore.unity.com/

For this study, Unity was selected for developing the VR environment. The C# programming language within Unity facilitates the management of game objects and user interactions in the VE. Its integration enables users an immersive experience while interacting with User Interface (UI), using the HMD. The headset device used for testing during the implementation and for user evaluation was **Meta Quest 3**.

The following packages of Unity Asset Store were used to enhance the UI and streamline the development process:

- **Free UI Click Sound Pack**[2] - This package provides a collection of diverse clickable sounds, designed to provide an immersive and complete User Experience (UX).
- **Simple Pie Menu**[3] - A radial menu system implemented as the main menu of the project. Further details on its functionality are provided in Section X.
- **White & Black GUI**[4] - This package includes a range of trivial and useful icons used to guide users in navigating menu items and to support image gallery switching between pre- and post-intervention object states.

4.1.3 Tools

Blender is an open-source computer graphics software useful to a wide range of tasks, such as model, animate, create textures, materials. This tool was used to create an aproximation of the original texture of the glass object. Originally transparent, translucent.

GIMP, an open-source cross-platform image editor, was used to edit the map draw for integration as ground in Unity (rotated and cropped). Additionally, GIMP was useful in editing the post-intervention object images. The object's images were cut out from their backgrounds, which were then replaced with a neutral grey. This enhanced clarity for users and allowed easy comparison between the object's before and after the cleaning and conservation treatment.

4.1.3.1 Photogrammetry

The software used to process digital images and generate the 3D model of the funerary enclosure was *Agisoft Metashape*[5]. This software performs photogrammetric processing of digital images to generate 3D spatial data, which can be applied in various fields such as GIS applications, CH documentation, visual effects production, and indirect measurements of objects of diverse scales.

A total of 143 images were collected after the excavation campaign by an archaelogist of this site. (INCLUO NOME DA INES VAZ PINTO?) Based on these images, a 3D model was generated from the photogrammetric survey and subsequently imported into the *Sketchfab*

[2] https://assetstore.unity.com/packages/audio/sound-fx/free-ui-click-sound-pack-244644

[3] https://assetstore.unity.com/packages/tools/gui/simple-pie-menu-radial-menu-asset-270056

[4] https://assetstore.unity.com/packages/2d/gui/icons/white-black-gui-by-gamertose-168805

[5] https://www.agisoft.com/

viewer for intuitive interaction. Within the grave where the deceased was buried, three open triangular areas were identified, containing the precious artefacts of the defunct, as shown in Figure **??** below. By stitching together photographs, *Agisoft Metashape* captured the geometry, texture, and visual appearance details of the physical funerary enclosure.

Two already built models of artefacts provided were provided by VICARTE.

4.1.4 Backend & Data Management

4.1.4.1 Backend

The backend technology selected for this thesis was **Node.js**, an open-source, cross-platform JavaScript runtime environment. Node.js enables developers to create servers, web applications, command-line tools, and automation programs.

In this thesis, Node.js was used to support the web server and to improve performance and scalability when handling repository data. Additionally, it will streamline the communication between Unity and the database repository.

Express.js is the most popular Node.js web application framework, widely used for building web applications and Application Programming Interface (API)s, with a minimal and flexible design. In this study, the web server Express.js[6] was used to expose the REST endpoints.

4.1.4.2 Database Repository

There are several alternatives for storage management systems, but the option shelt for this project was **PostgreSQL** for its geographical extension, PostGIS, and its relational database is more appropriate due to its flexibility and consistency. Additionally, because of its high performance and flexibility in managing spatial data.

PostGIS is widely used for spatial data storage, geometry processing, and efficient geospatial querying.

4.1.4.3 Testing Tools

One of the most relevant features during the development phase on controller support was the **XR Device Simulator** included in XR Interaction Toolkit. This utility allowed for testing VR interactions without the need for a physical HMD. It simulated input from VR controllers using a standard mouse and keyboard. Despite its usefulness along this dissertation, it's important to note that certain interactions did not behave identically compared to testing with the actual headset.

[6] https://expressjs.com/

4.1.5 XR Components and Plugins

4.1.5.1 XR Plugin Management

The **XR Plugin Management** package was used to simplify the integration and management of various XR plug-ins. This package is primarily responsible for loading, initializing, configuring settings, and providing build support for XR features. It was used in conjunction with the OpenXR.

OpenXR is an open-standard API enabling cross-platform development, with a high-performance access to AR and VR paltforms and devices. In this sudy this plugin, handles communication with the VR headset.

4.1.5.2 XR Interaction Toolkit

The **XR Interaction Toolkit** was a central component in the development process, providing essential interaction capabilities and abstracting much of the low-level complexity of VR development. It enabled features such as Hand tracking, Object interaction (e.g., grab and release), Teleportation-based locomotion, UI interaction, and Controller support.

4.1.5.3 User Movement Components

The **XR Origin** served as the root GameObject that encapsulates the main camera and controller setup. It handles camera tracking based on the user's head movement and manages controller positioning and orientation. Within this structure, the XR Rig was used as the container for the camera and associated controllers.

To implement user movement within the VE, the Locomotion System package was utilized. The following components were integrated:

- **Continuous Move Provider:** Allowed smooth movement via the right joystick.
- **Snap Turn Provider:** Enabled rotational movement in fixed increments, chosen over continuous turning to reduce motion sickness.
- **Teleportation Provider:** Enabled teleportation across the plane surface using the left joystick.
- **Teleportation Anchors:** Defined specific teleportation points, represented as buttons.

4.1.5.4 User Interaction Components

For interaction within the virtual scene, the toolkit offered components such as the XR Near-far interactor, that provided a way to interact with the scene through the ray emitted from the controllers, and the XR Grab Interactable enabled direct manipulation of virtual objects through grabbing, holding, and releasing actions.

For input handling, Unity provides two systems: the old Input Manager and the newer **Input System Package**. While the Input Manager is built into the Unity engine and used by default, the project adopted the Input System Package due to its flexibility, and scalability. This newer system supports a wide range of input devices and enables precise configuration through a centralized interface. Input actions are defined and managed using the Input Action Manager, which allows the developer to specify actions and map them to devices or controls. Each input action is activated as needed during runtime, offering an adaptable input handling framework.

Character Controller ?

4.2 System Architecture

The system is divided into three application layers. The **Presentation Layer** manages the VR environment and its interaction with users. The **Application Layer** includes the management of Unity Requests, with the support of the framework "UnityWebRequest" REF, acting as an intermediate between the Unity client and the database. The communication flow between these layers is managed through a Node.js REST API, chosen for its flexibility and lightweight design. Finally, the **Data Access Layer** contains the database, which stores all information related to object data, excavation, and object interventions. The architecture of the system can be observed in Figure 4.1.

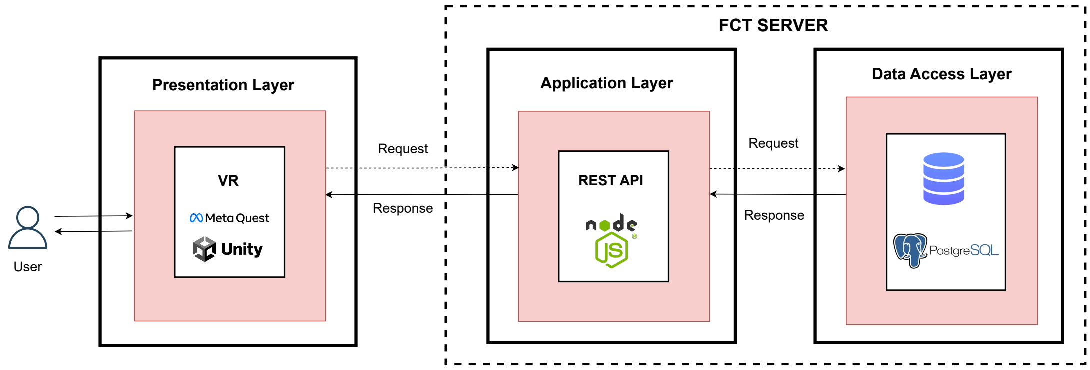


Figure 4.1: System Architecture Overview of the Developed System.

During the development stage, the database was hosted locally on a PostgreSQL server managed via pgAdmin[7], an Open Source management tool for PostgreSQL. To access and present data in Unity, it was necessary to manually execute the "index.js" file, which contained the Node.js API endpoints. Subsequently, before the user testing phase, the backend code, comprising both the API endpoints and the PostgreSQL database, was deployed to the FCT Server with a dedicated service. This deployment ensured that the server hosting the API endpoints remained continuously active, allowing Unity clients to retrieve data seamlessly without manual intervention.

[7]https://www.pgadmin.org/

4.3 System Implementation

4.3.1 Communication between Unity and Database

4.3.1.1 Dropdown Options Retrieval

Listing 4.1: Method used to load artifact IDs and define as options in the Dropdown.

```
 IEnumerator GetOptionsIds(string url)
{
   UnityWebRequest www = UnityWebRequest.Get(url);
   yield return www.SendWebRequest();

   if (www.result == UnityWebRequest.Result.Success)
   {
      string wrappedJson = "{\"items\":" + www.downloadHandler.text + "}";
      ArtifactList artifactList = JsonUtility.FromJson<ArtifactList>(wrappedJson);

      List<TMP_Dropdown.OptionData> options = new List<TMP_Dropdown.OptionData>();

      options.Add(new TMP_Dropdown.OptionData("--␣Select␣ID␣--"));

      foreach (Artifact artifact in artifactList.items)
      {
         string id = artifact.id.ToString();

         options.Add(new TMP_Dropdown.OptionData("␣␣␣␣␣" + id));
      }
      dropdown.AddOptions(options);
   }
   else
   {
      Debug.LogError("Error:␣" + www.error);
   }
}
```

4.3.1.2 Object Images Retrieval

```
 private void GetImages(int id, string[] images_path)
{

   if (images_path.Length != 0)
   {
      changeView.SetActive(true);

      for (int x = 0; x < images_path.Length; x++)
      {
         var imagePath = images_path[x];

         if (x > images_path.Length / 2)
```

```
            {
                height = 0;
            }
            else if (x == images_path.Length / 2) { x_pos = 1.5f; height = 0; }
            else { height = 1; }

            Sprite sprite = Resources.Load<Sprite>("Images/" + imagePath);

            if (sprite != null)
            {
                GameObject newImgObj = new GameObject("Image_" + imagePath, typeof(RectTransform), typeof(CanvasRenderer), typeof(Image));
                newImgObj.transform.SetParent(imageParent, false);

                RectTransform rectTransform = newImgObj.GetComponent<RectTransform>();
                rectTransform.sizeDelta = new Vector2(1, 1);
                rectTransform.localPosition = new Vector3(x_pos++, height, 0);

                Image imgComponent = newImgObj.GetComponent<Image>();
                imgComponent.sprite = sprite;
            }
            else
            {
                Debug.LogWarning("Couldn't load sprite at path: " + imagePath);
            }
        }
        x_pos = 1.5f;
    }
    else
    {
        Debug.LogWarning("Couldn't load Images for Object ID" + id);
    }
}
```

4.3.1.3 Object Textual Data Retrieval

```
 IEnumerator GetData(string url)
{

    UnityWebRequest www = UnityWebRequest.Get(url);
    yield return www.SendWebRequest();

    Debug.Log($"Getting objects data.. {www.result}");

    if (www.result == UnityWebRequest.Result.Success)
    {
        artifact = JsonUtility.FromJson<Artifact>(www.downloadHandler.text);

        string displayText = "<b>Object Details:</b>\n\n";
```

```

            string new_string = artifact.material.Split("{")[1];
            string new_string1 = new_string.Split("}")[0];

             displayText += $"ID:␣{artifact.id}␣|␣Name:␣{artifact.name}␣\nMaterial:␣{new_string1}␣|␣Epoch:␣{artifact.epoch}␣\nProvenance:␣{artifact.provenance}" +
                         $"\nDimensions:␣{artifact.dimensions.height}␣x␣{artifact.dimensions.width}␣cm,␣Weight:␣{Mathf.Round(artifact.dimensions.weight␣*␣10.0f)␣*␣0.1f}␣g";

            resultText.text = displayText;

            GetImages(artifact.id, artifact.images_path_b_interv);
        }
        else
        {
            resultText.text = "Error␣loading␣data.";
            Debug.LogError("Error:␣" + www.error);
        }
    }
```

4.3.1.4 API Endpoints

To retrieve information for each object, requests are made to the repository layer. Two main API endpoints were implemented for this purpose:

1. **/GET (get-objects_data)**

   Retrieves a list of object IDs by querying the **"object"** table. These IDs are used to populate the dropdown menu options in the UI.

2. **/GET (get-objects_data/:id)**

   Fetches detailed information for a specific object based on its ID. This request is triggered when a user selects an object ID from the dropdown menu in the UI Whenever the ID in the dropdown is changed, the system issues a new request for the corresponding ID, and the visualization panel and image gallery are updated accordingly.

   The representation of this endpoint is shown in Listing 4.2. As illustrated int line 5, the query joins two tables, **"object"** and **"object_intervention"**, to fetch simultaneously object data and images before and after interventions for display in the Image Gallery (REF FUNCIONALIDADE). This SQL query enables the system to retrieve all necessary information with a single request after the user selects an object ID, thereby improving efficiency and reducing the need for multiple requests.

Listing 4.2: Example of defining an API endpoint in Node.js.

```
app.get('/get-objects_data/:id', async (req, res) => {
  const id = req.params.id;

  try {
    const result = await pool.query('SELECT * FROM object inner join object_intervention on object.id = object_intervention.object_id WHERE object.id = $1', [id]);
    res.json(result.rows[0]);
  } catch (error) {
    console.error(error);
    res.status(500).send('Server Error');
  }
});
```

4.3.2 Virtual Environment

Objects UI

The UI includes a canvas where users can interact with and explore object data. A dropdown menu allows the user to select an object by its identification number. Once selected, the corresponding data is retrieved from the database, as described in the "Database Section".

Image Gallery

The VE also contains an image gallery that is activated upon object selection. This gallery displays images of the object before and after the intervention. Users can switch between these states by hovering the controller ray over the gallery arrow. In this manner, the users can view the images of a concrete object, compare the visual differences, and acquire a clearer understanding of the intervention's impact on each object.

Object Slider

The Object Slider was designed as an interactive feature within the VE, allowing users to visualize an object's transformation over time—from its original condition to its current, restored state. The goal was to provide an immersive experience, creating the sensation of traveling back in time to observe the physical changes the object has undergone throughout the years.

Several experimental approaches were conducted to achieve this effect, focusing on shader development. Two main approaches were explored, as described below:

The first attempt involved creating a shader that utilized a single texture input—specifically, the texture of the object after restoration. A white color was used to control the alpha (transparency) values, and the transition effect was managed using a linear interpolation (lerp) function. This shader was developed using Unity's Shader Graph, which provided a visual, node-based interface for building the transition logic.

The final solution involved a more advanced shader developed using Unity's Surface Shader. This version accepted two texture inputs: the original appearance of the object, and the current state.

A **Lerp function** was used to blend between the two textures based on the user's interaction with the virtual slider. To enhance realism, additional lighting and reflection techniques were integrated into the shader, including: **Reflection Probes** to simulate environmental reflections, **Fresnel effects** to model light behaviour at glancing angles, and adjustments to **specular** and **diffuse** lighting properties. This shader enabled a more faithful representation of the object's original appearance.

User Navigation

The user can navigate in the environment with the controllers. Using them you can simplify moving by walking as in real world or teletransporting with the controllers.

Map Functionalities

Activate 3D model of the funerary enclosure.

4.3.3 Key Techniques

4.3.3.1 Light Technique

There is a main directional light that illuminates the entire environment along, simulating reality. However, it was understood that depending on the angle, the user might see the tomb and objects black due to shadows. To address this, a secondary point light was added that follows the user, so the user can view the tomb with clarity and have a good visibility while navigating in the environment.

4.3.3.2 Funerary Enclosure model reduction

The resolution of the burial site model was significantly reduced in Agisoft Metashape software through "Decimate Model" property. This adjustment was necessary due to warnings of potential collision issues arising in the model's size of over 2 million triangles. Therefore, the number of faces was reduced from 1.9 million to approximately 100 thousand, preserving the essential level of detail while improving efficiency.

4.4 Database Management

4.4.1 Data Structure

The database consists of 11 tables that ensure the significant data of excavation and objects are stored. These tables cover data on the necropolis, funerary enclosure, tombs, objects, excavations, and interventions. The detailed structure, including relationships and attributes, is illustrated in Figure 4.2.

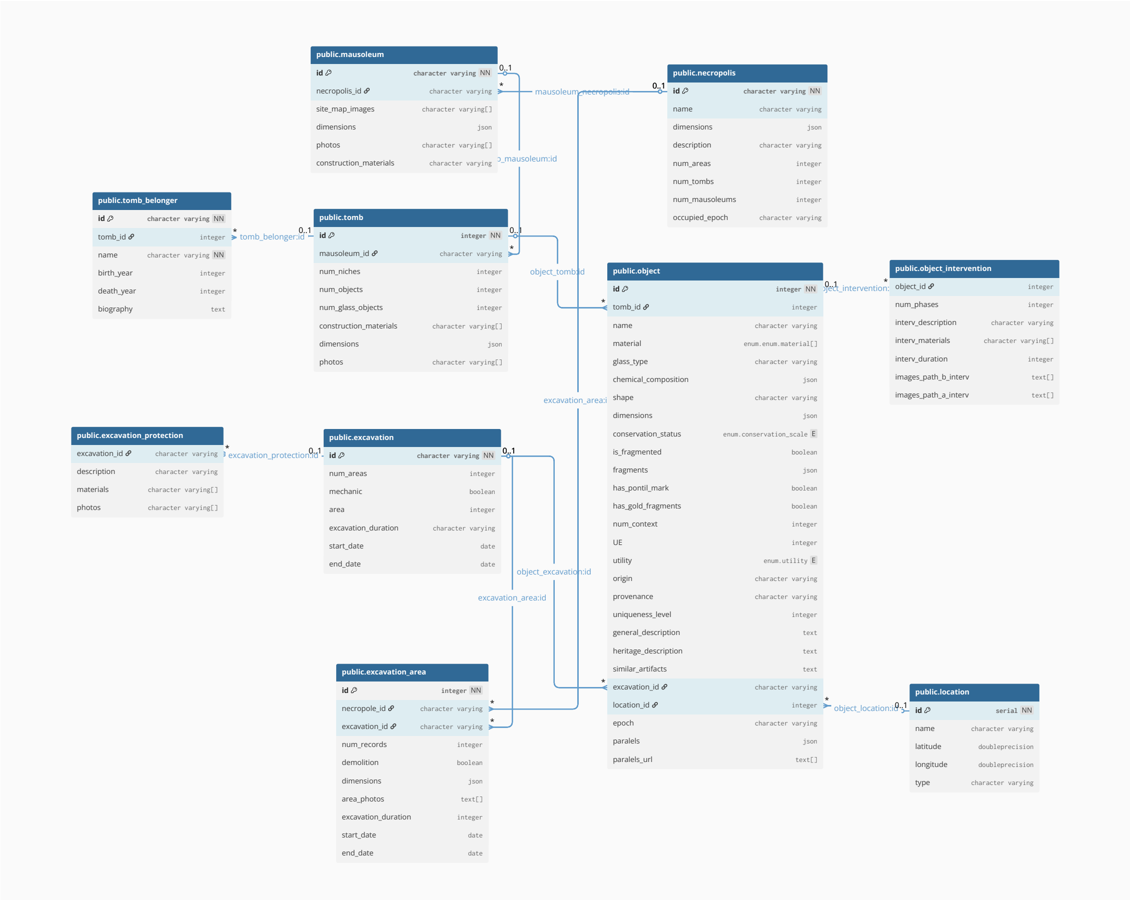


Figure 4.2: Relational Database Model.

The database model was designed considering future extensibility. Initially, it was structured to store significant data from the necropolis, including the funerary enclosure and tomb under study. The structure was generalized to improve scalability, flexibility to possibly include data, such as other tombs, associated objects, and aggregate the maximum information. Throughout the thesis period, the database structure was continuously refined and restructured with new tables, relations, and data fields.

It was decided to not store the entire image, as binary data in the database. Instead, only file paths to the images were saved. This allowed for efficient access and manipulation of images, while other object-related data, such as text and links, was fully stored in the database.

For generating the data model, SQL was used to create a database dump. Using "dbdiagram.io", this dump was translated into a visual diagram showing tables and their relations. This tool streamlined the creation of the Entity-Relationship diagram through code.

4.5 Potential Usage and Future Expansion

4.5.1 Mixed Reality Integration

The integration of a mixed reality experience, where, upon clicking a button, users would be redirected and teleported into the developed VR environment.

4.5.2 Design Choices

Initially, the idea involved creating a map using JavaScript and its Leaflet.js[8] library. However, the dissertation's direction shifted towards integrating the map with the funerary enclosure and its elements directly in Unity, forming a unified VE. This way, the users can walk across the map as if in reality, while simultaneously viewing the 3D model accurately positioned in space. The map itself still holds potential for further enhancement, which could contribute to a more complete and immersive experience within the VE.

[8] https://leafletjs.com/

5 User Evaluation

This chapter introduces the user evaluation conducted in the scope of this dissertation. Section 5.1 describes the methodology and procedures adopted for the evaluation, while Section 5.2 presents the results obtained from the questionnaires, including a description of each type of questionnaire used and its intended purpose.

User testing was conducted in person with several groups of participants. VICARTE experts, archaeologists (including the director of the Roman Ruins of Troia), and regular users provided more experienced and comprehensive feedback. To differentiate and collect statistics from these groups independently, a question was added to the form to filter participants by professional specialty. In this context, testing with experts was particularly relevant, considering these archaeologists had visited the site and examined the real objects. They contributed with their expertise in evaluating aspects such as the original glass texture generated REF and the tomb's 3D model REF.

In total, 28 tests were carried out in presence: 16 with standard users, 3 with archaeologists, and 9 with VICARTE members, including conservation and restoration specialists. The last group provided essential technical feedback in this field, as they were directly involved in interventions with the real objects. The remaining users contributed a broader perspective on the usability of the VE. Colleagues with prior VR experience offered more informed insights, while standard users provided suggestions from a regular user's perspective.

5.1 Protocol

This section describes the protocol adopted for the user evaluation questionnaire, which was organized into three subsections of the user form, each with a brief description and the corresponding test results.

The tests were fundamental in evaluating the usability of the developed environment, as well as the sense of presence and the overall experience. The users had to answer a set of questions provided through Google Forms, divided into four sections.

First, it was given a brief context of the project and the structure of the test. Before using the headset, participants completed a personal questionnaire for statistical user analysis. Subsequently, it was time to make use of the HMD and its right and left controllers. The usage of the controllers and main buttons was explained. Then, the users were asked to complete a set of predefined tasks for the experience, which were:

1. Try walking in continuous motion and/or teleporting in the environment.
2. Activate the 3D model of the funerary enclosure.
3. Walk to the tomb or select its blue icon to teleport.
4. Inside the tomb, point at an object until you see its blue outline and grab it.
5. Exit the tomb with the object in your hand.
6. With the object in your hand, use the other controller to move the slider and view its original appearance.
7. Release the object by releasing the side button on the controller.
8. Teleport to a Point of Interest by selecting one of the blue icons.
9. Activate the main menu and select the visible icon.
10. Close the main menu.
11. In the panel in front of you, select the Object ID 21684 and view the displayed information.
12. Walk to the blue panel and hover over the arrows to view object images after the intervention.
13. In the black panel in front of you, change the ground plane by selecting the "Toggle Layer" option and explore.

While the users were wearing the HMD and controllers in their hands, as displayed in Figure 5.1, the tasks were repeated to them, since the goal was not to evaluate memory, but usability.

During the tasks phase, time was measured for each user while interacting with the VR environment, and using the headset. As shown in Table 5.1, the average time spent was around 10 minutes, with the exception of faster users and 3 cases where the application had to be restarted after users fell out of the environment, which increased the experience time. Furthermore, the "Meta Horizon" app was employed to manage the headset. Through the app, with the "Cast" option activated, it was possible to view on the phone exactly what the user was viewing in real-time. With this feature, users were guided to perform the intended tasks and receive immediate assistance if any issues arose.

Figure 5.1: User Testing the VR Environment with the HMD and controllers.

Identifier	Time
1	00:12:25
2	00:10:28
3	00:10:16
4	00:13:03
5	00:10:24
6	00:13:49
7	00:15:37
8	00:10:20
9	00:13:46
10	00:10:30
11	00:10:23
12	00:10:03
13	00:09:12
14	00:05:28
15	00:16:19
16	00:16:04
17	00:08:44
18	00:17:29
19	00:09:27
20	00:10:55
21	00:10:03
22	00:14:19
23	00:06:54
24	00:20:42
25	00:12:28
26	00:16:12
27	00:10:07
28	00:11:05

Table 5.1: Registered Times spent by each Participant to Execute the provided Tasks.

Finally, the users evaluated the experience through three separate sections. The first measured task success and the perception of key functionalities. The following section evaluated the sense of presence in the environment. The third and final section assessed the overall experience within the environment.

5.2 Tests Results

Starting with the subsection "User Analysis", which presents statistical information about the participants, followed by "Tasks Difficulty and Feedback", which reports their perceptions after completing the tasks. In addition, the Presence Questionnaire (PQ) and UEQ are employed to evaluate the overall experience and sensation. Finally, the subsection "Graphics Comparison" provides graphical representations that highlight relevant relationships between the users and their responses after performing the tasks.

5.2.1 User Analysis

This set of questions was designed to collect information on users' characteristics, enabling the identification of statistical differences and supporting the interpretation of the evaluation results. It includes demographic data such as age, gender, and education, along with information on professional or academic background. In addition, it assesses prior experience with VR, and digital technologies applied to CH.

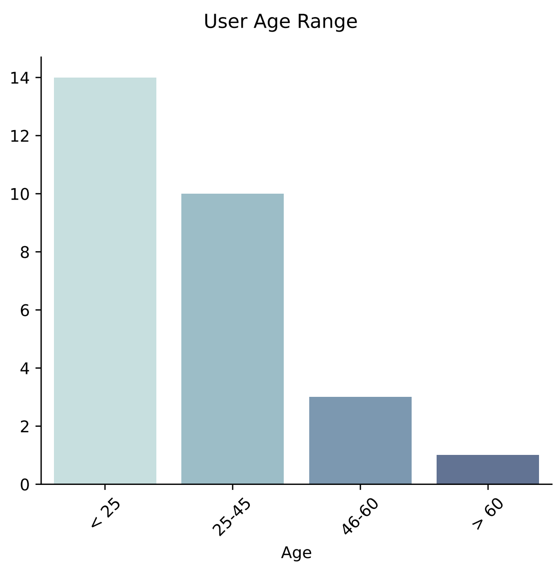


Figure 5.2: Age Distribution of the Test Participants.

The bar plot in Figure 5.2 illustrates the distribution of participants across age groups. A decreasing trend of users can be observed with increasing age. Notably, the majority of participants, 86%, are younger than 45 years old. We can conclude that we have a good age range despite a smaller sample of older people.

There is a diversified gender distribution as we can see in Figure 5.3.

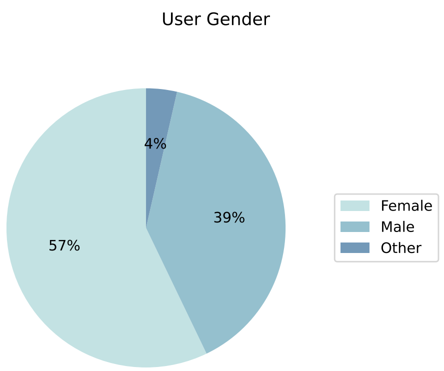


Figure 5.3: Gender Distribution of the Test Participants.

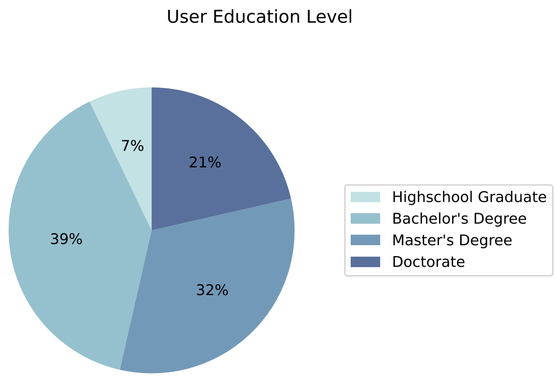


Figure 5.4: Education Level Distribution of the Test Participants.

In the pie chart of Figure 5.4, the educational degrees of the participants is depicted. The distribution indicates a predominance of higher education (bachelor, master, and doctorate degees), whereas only a small proportion of participants reported lower levels of education.

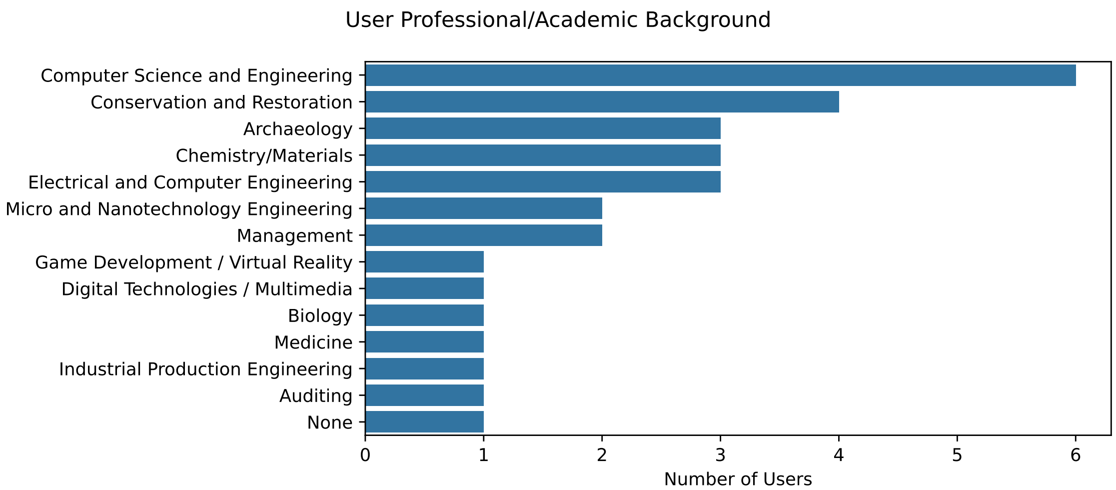


Figure 5.5: Distribution of Training Levels among Participants.

In Figure 5.5, a horizontal bar plot illustrates the distribution of participants' technical backgrounds. The areas are ordered in descending frequency, with priority given to those most relevant for this thesis. This results in a meaningful sample, comprising mainly technology developers, specialists in conservation and restoration, and archaeologists working in contexts comparable to the site under study.

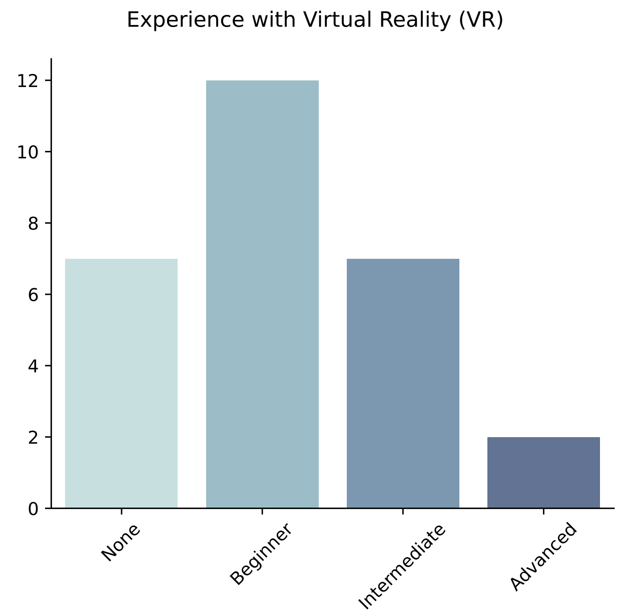


Figure 5.6: VR Experience Levels among Participants.

As illustrated in Figure 5.6, it is evident that the majority of the participants have prior experience with VR, while only a small portion are experts.

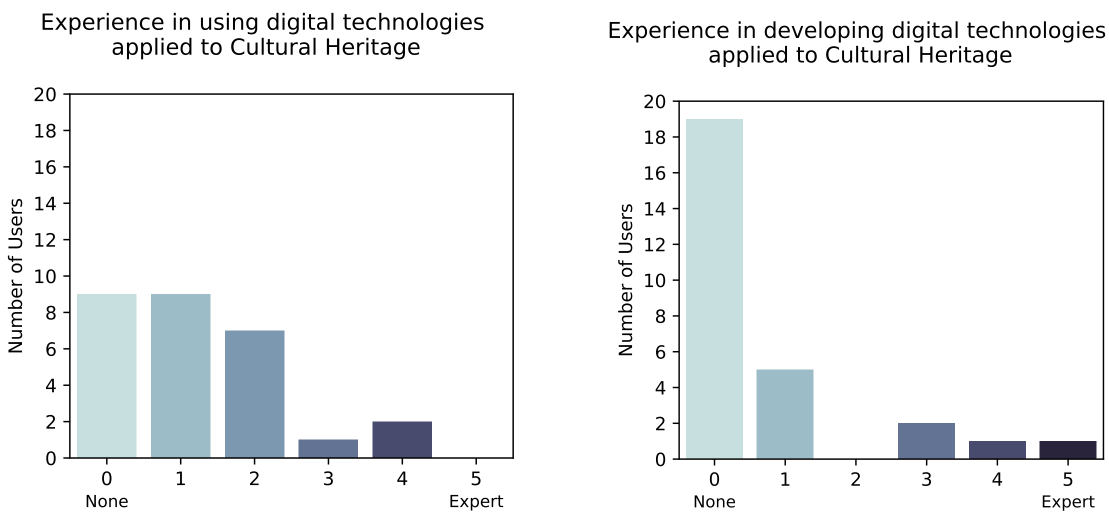


Figure 5.7: Participants' Experience with Digital Technologies Applied to CH.

The two distributions in Figure 5.7 show a clear disparity between participants' experiences in using and developing digital heritage technologies. Most participants (19) report having some experience as users, generally clustering around moderate levels (ratings 1–2). In contrast, almost all participants (18) report no development experience. For evaluation purposes, the key factor is the intended use of the system, as this determines who will actually engage with it. Developers remain valuable mainly for offering technical feedback and suggestions for improvements, such as efficiency.

5.2.2 Tasks Difficulty and Feedback

This segment of questions was answered immediately after the users completed their tasks in the VE. The first question in this section used a 5-point Likert scale to measure the perceived difficulty of each task, providing insights that may support future improvements or adjustments to the UI. The second and final question in this section presented a list of ten statements, tailored to the evaluation of this environment, which users rated on a 5-point Likert scale according to their level of agreement. This helps to capture more specific perceptions regarding each relevant functionality and the overall experience within the environment.

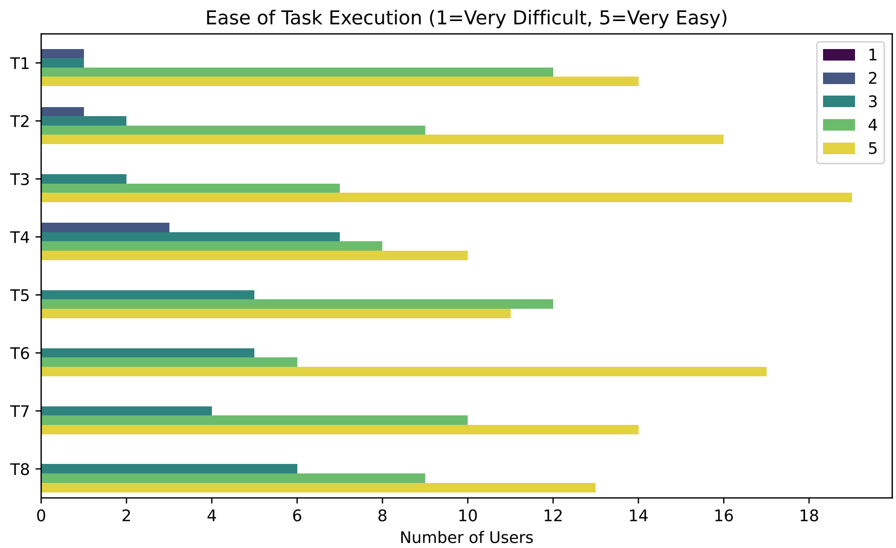


Figure 5.8: Perceived Task Ease among Participants.

Analyzing the graph in Figure 5.8, we can observe the overall ease of completing the tasks. The results indicate that the most difficult task was T4 – "Access to the main menu", likely because participants did not remember that it required pressing the back button on the right controller. Task T5 – "View original appearance of the object with the slider", also presented difficulty, possibly due to the diffculty of interacting with the slider bar. It is important to note that this issue was later improved by making the entire slider bar visible and removing the need sometimes to cross the arms to move it. This improvement is further explained in Section 5.3.1.

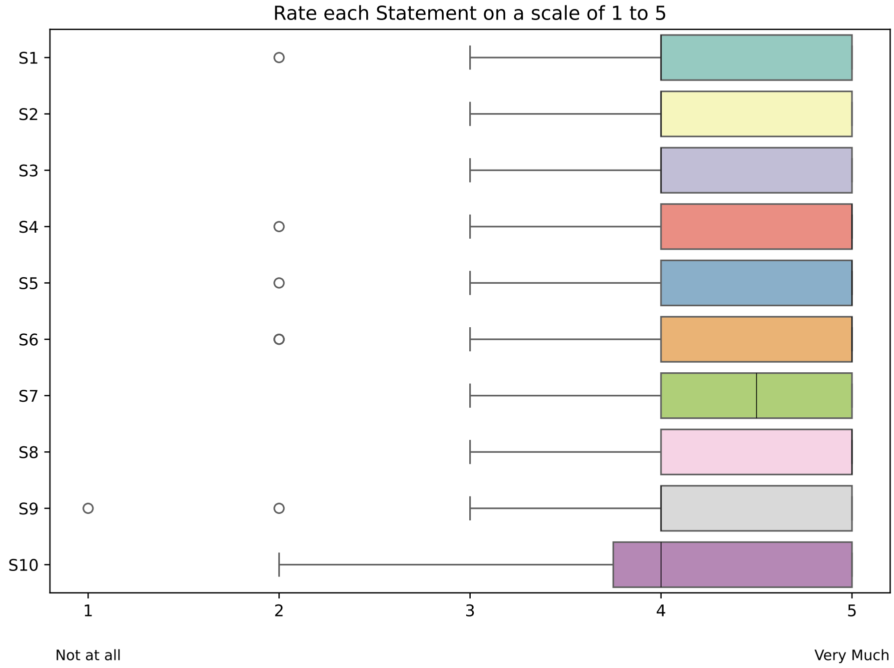


Figure 5.9: Participants' Agreement with Task-Related Statements.

The results shown in Figure 5.9 indicate a general agreement among users with the statements concerning their interaction, exploration, and navigation within the environment. In particular, statements 4, 5, and 6 received the highest levels of agreement, regarding the effectiveness of the slider in displaying transformations and the engagement of the information provided about the objects. The median values of all statements range between 4 and 5, highlighting a very positive outcome.

5.2.3 Presence Questionnaire (PQ)

The evaluation of presence was conducted using the Portuguese validated version of the Presence Questionnaire, adapted by Vasconcelos-Raposo et al. [45] was used, from which eleven items were removed "in order to improve the validity of the constructs and their internal consistency." The original Presence Questionnaire by Witmer et al. [50] consists of thirty-two questions, covering four major factor categories: Control, Sensory, Distraction, and Realism. In the translated version, ten of the twenty-one validated and translated questions were selected, as they were considered the most relevant for this research. Questions addressing less important topics, such as sounds during the experience, were excluded. This questionnaire section was applied using a 5-point Likert scale.

It is represented in Figure 5.10 the participants' sense of presence during this evaluation.

It is interesting to note that Q6 – "How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?" – shows that quartiles 1, 2, and 3 coincide at the value 4. This indicates a very strong consensus among participants, with at least 50% reporting good navigation and understanding of the environment after

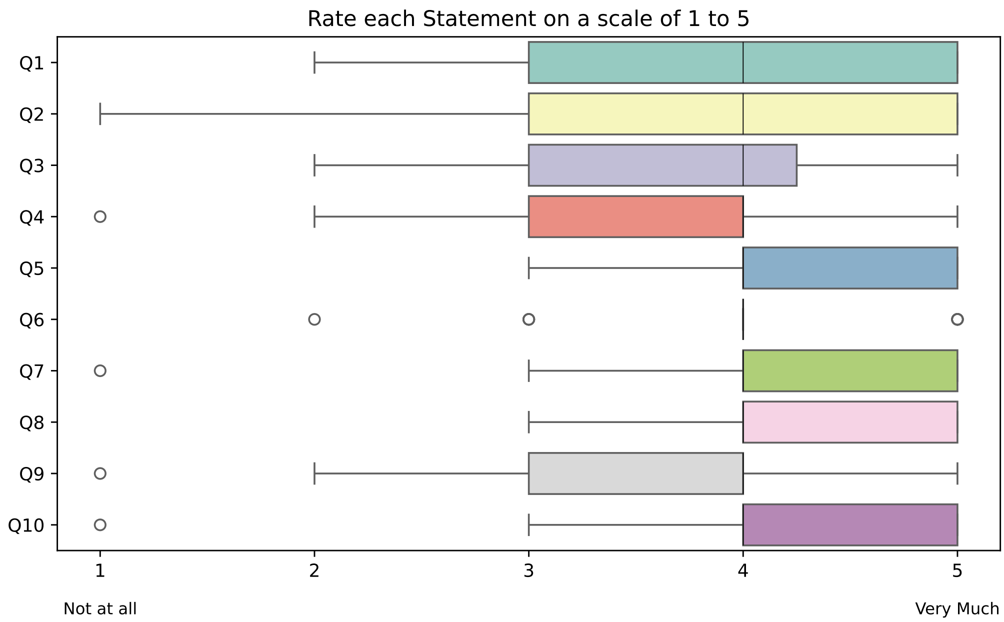


Figure 5.10: Perceived Sense of Presence among Participants.

the experience, reflected in a median score of 4 out of 5. Overall, most participants rated their proficiency as 4, showing strong agreement, with only a few outliers providing lower or higher ratings.

5.2.4 User Experience Questionnaire (UEQ-S)

The overall user experience was measured using the Portuguese version of the User Experience Questionnaire[1], constructed by Laugwitz et al. [22], and translated by Cota et al. [7].

The UEQ-S is the short version of the User Experience Questionnaire (UEQ), comprising a list of eight items selected from the original twenty-six. [38]. These items are grouped into two meta-dimensions, illustrated in Figure 5.11: pragmatic quality and hedonic quality, each containing four items. In addition, the mean value across all items is reported as an overall UX score. The questionnaire is structured around pairs of contrasting attributes that may describe the system. Participants provide their evaluation on a seven-point scale, where each circle represents a gradation between the two opposites.

The UEQ results, as demonstrated in Figure 5.12, show a highly positive overall experience. The evaluation factor hedonic quality, reflecting user satisfaction and enjoyment, was particularly high, while pragmatic quality denoted the system's usefulness and effectiveness.

On a scale from -3 to 3, Figure 5.13 illustrates the mean responses of the participants per item. We can conclude that there is a good average, especially in the Hedonic Quality. The y-axis shows the list of UEQ items, with participants grouped by scale dimension:

[1] https://www.ueq-online.org/

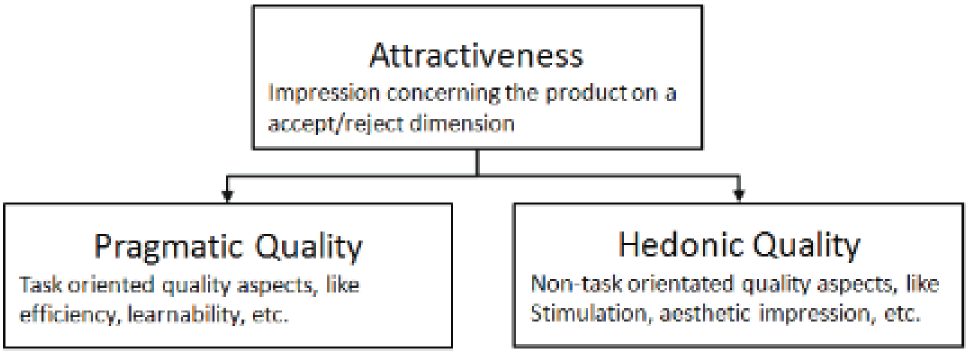


Figure 5.11: Grouping of the two quality attributes [34].

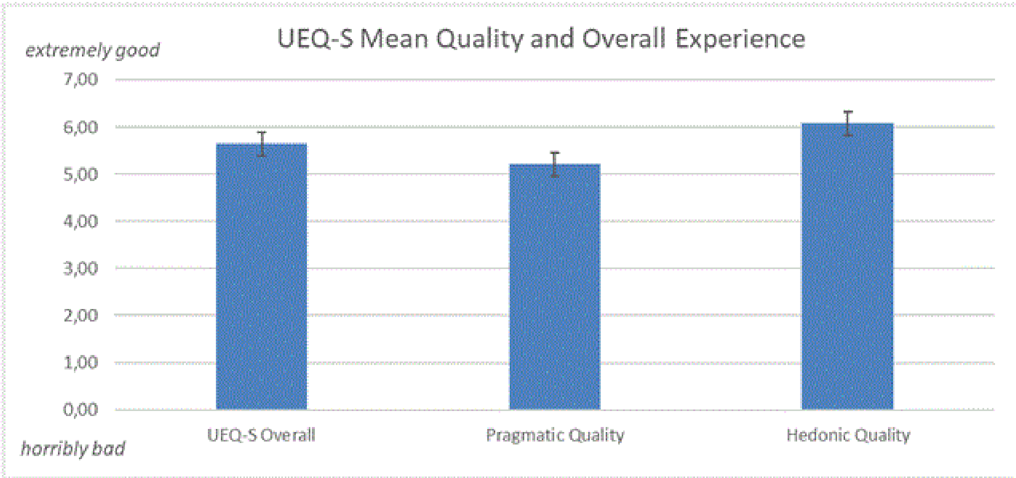


Figure 5.12: Overview of the UEQ Evaluation Distribution among Test Participants.

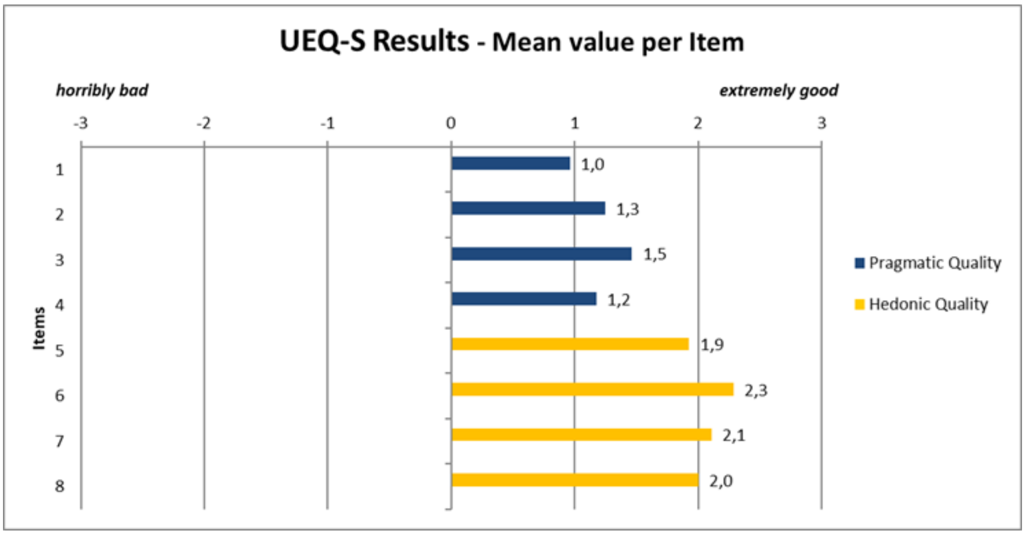


Figure 5.13: Mean value of UEQ Items of the Participants' Experience.

Pragmatic or Hedonic Quality. Table 5.2 supports this graphic with this and more relevant information of the UEQ used.

Item	Mean	Std. Dev.	Negative	Positive	Scale	
1	1,0	0,8	obstructive	supportive	Pragmatic Quality	
2	1,3	1,0	complicated	easy	Pragmatic Quality	
3	1,5	0,7	inefficient	efficient	Pragmatic Quality	
4	1,2	1,3	confusing	clear	Pragmatic Quality	
5	1,9	1,0	boring	exciting	Hedonic Quality	
6	2,3	0,8	not interesting	interesting	Hedonic Quality	
7	2,1	0,9	conventional	inventive	Hedonic Quality	
8	2,0	0,9	usual	leading edge	Hedonic Quality	

Table 5.2: UEQ Items, their Mean responses, Standard Deviations, and the corresponding Opposite Pairs by Scale.

5.2.5 Graphics Comparison

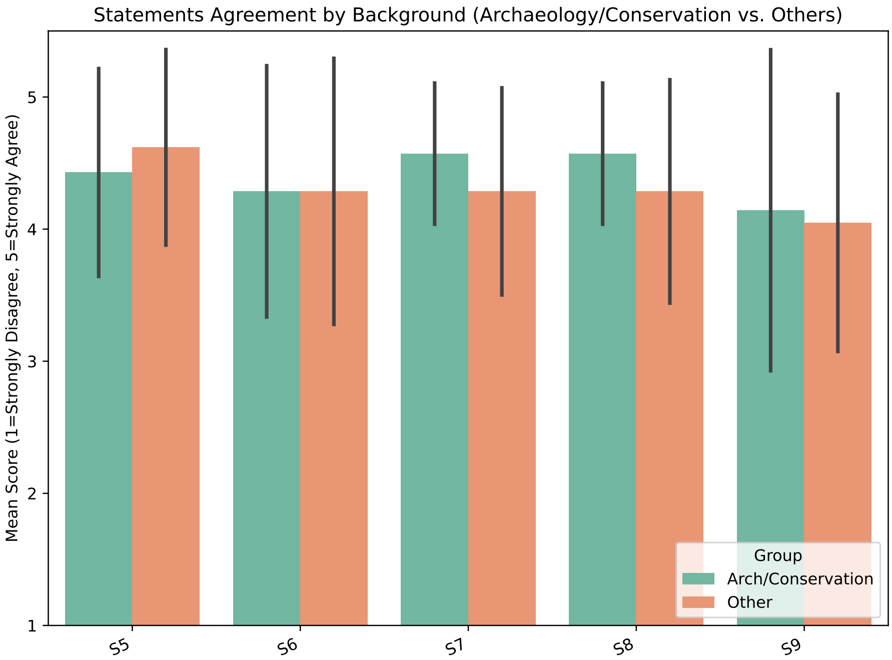


Figure 5.14: Comparison between Participant Groups, regarding Agreement with Statements about their Experience.

The graph illustrated in Figure 5.14 compares agreement with statements, distinguishing participants with a background in Archaeology/Conservation from those in other fields. The error bars represent the standard deviation, indicating the variability in the responses. The statements correspond to the ones used on the y-axis of Figure 5.9, with a focus on those considered most meaningful for an Archaeology or Conservation/Restoration specialization. Those are:

- S5 - I clearly distinguish between the artifact's original and restored state.
- S6 - The information provided helped me better understand the artifact.
- S7 - The experience contributed to a better understanding of the site.

- S8 - The experience helped me better understand the presented artifacts.
- S9 - The experience provoked a sense of presence in the historical site.

In general, as represented above, specialists provided a better average score to the statements, except statement 5, presumably due to the greater critical demand of professionals who have direct experience with artifacts in the field of conservation and restoration.

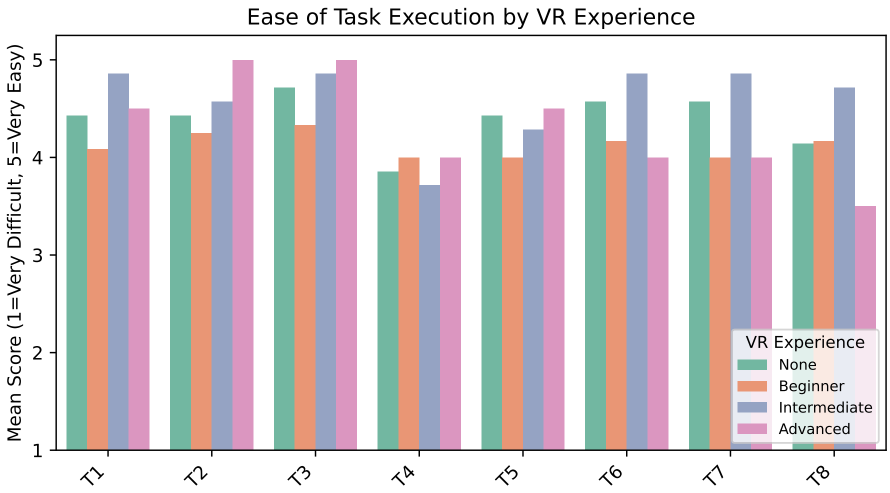


Figure 5.15: Ease of Task Execution according to Participants' VR Experience.

The results presented in Figure 5.15 indicate a general ease in completing the tasks among participants with higher levels of experience in VR. However, in some cases, the scores for the Intermediate group exceeded those of the Advanced group (specifically in T1, T6, T7, and T8). This outcome may be explained by the fact that, as illustrated in Figure 5.6, only two participants were classified as "Advanced", representing a very small sample that may not provide fully reliable results.

The bar chart in Figure 5.16 demonstrates that users with greater experience in technologies applied to CH generally found the tasks easier to execute, except for T7 – "Access a point of interest", and T8 – "Change the base (ground) plan".

In Figure 5.17, a bar graph illustrates the Sense of Presence results from the PQ, organized by participants' VR experience. Remarkably, users with no previous VR experience reported, in various questions (Q2, Q3, Q5, and Q8), a stronger sense of presence than those proficient.

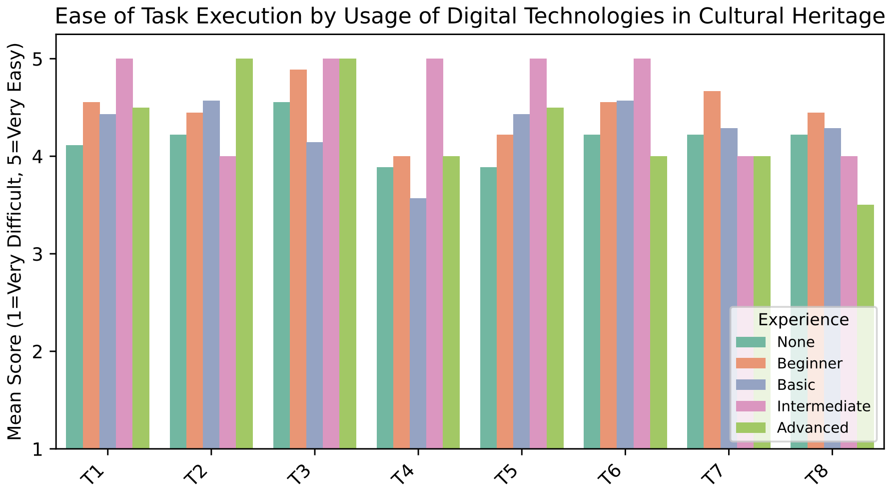


Figure 5.16: Ease of Task Execution according to Participants' Experience with Technologies applied to CH.

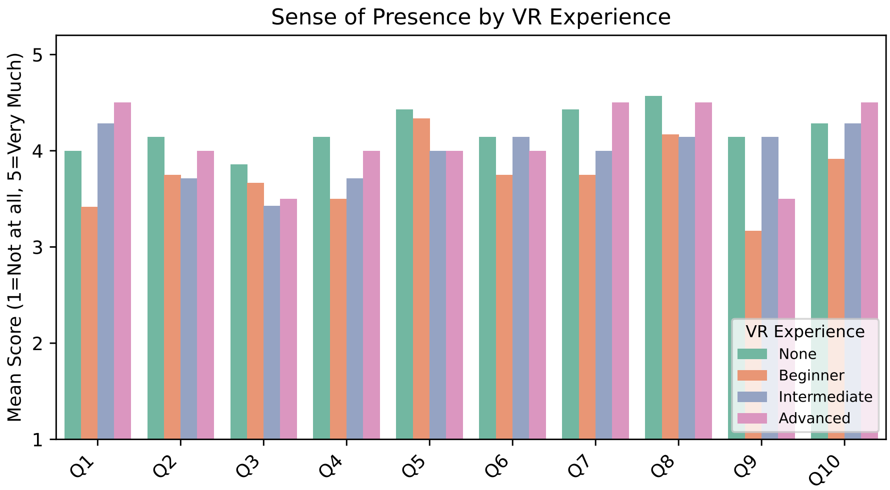


Figure 5.17: Participants' reported Sense of Presence according to their VR Experience.

5.3 Discussion

Overall, the results obtained of the User Analysis were balanced, showing a generally younger age group with higher education levels. Professional backgrounds were well distributed, with a larger proportion in Computer Science and Engineering, and Conservation and Restoration. Most participants had at least some prior experience with VR and in using digital technologies applied to CH. The tasks were generally completed with ease, as showed in Figure 5.8. In addition, the PQ results indicated a good median sense of presence among participants, and the UEQ reflected a very positive overall user experience as demonstrated by the mean. In Section 5.2.5, participants with specialist knowledge in Conservation and Restoration, and Archaeology showed slightly higher average scores on statements related to their field, compared to others. As expected, prior experience with VR and in technologies associated with CH helped participants solve the tasks. Finally, the sense of presence was generally stronger when participants were previously engaged with VR, although there were some exceptions for certain PQ items.

5.3.1 Improvements After User Testing

Some minor improvements were made following user testing. These mainly concerned the UI and small implementation bugs:

- Enabled the possibility to activate or deactivate the model throughout the entire experience, rather than only the first time. Previously, the collider component that allowed this functionality was deactivated after the user entered the tomb.
- Allowed teleportation to the tomb icon even when the menu panel was open. Those were interfering, so previously, the teleportation was only possible when the panel was closed.
- Added a legend when selecting the correct option in the main menu to guide users.
- Simplified slider interaction: it is no longer necessary to cross the arms to move the slider. When grabbing the object with the right controller, the bar now correctly repositions on the corresponding side.

6 Conclusions

6.1 Final Overview

6.2 System Limitations and Future Work

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