DEPARTMENT OF
COMPUTER SCIENCE

ANA MAISSA ANTUNES
BSc in Computer Science

DIGITAL TOOLS FOR STUDYING LUXURY GLASSMAKING IN ROMAN PORTUGAL

MASTER IN COMPUTER SCIENCE AND ENGINEERING

NOVA University Lisbon
September, 2025

DEPARTMENT OF
COMPUTER SCIENCE

DIGITAL TOOLS FOR STUDYING LUXURY GLASSMAKING IN ROMAN PORTUGAL

ANA MAISSA ANTUNES

BSc in Computer Science

Adviser: Armanda Rodrigues
Associate Professor, NOVA University Lisbon

Co-advisers: Inês Coutinho
Assistant Professor, NOVA University Lisbon

Nuno Correia
Full Professor, NOVA University Lisbon

MASTER IN COMPUTER SCIENCE AND ENGINEERING

NOVA University Lisbon
September, 2025

Digital tools for studying luxury glassmaking in Roman Portugal

This document was created with the (pdf/Xe/Lua)LaTeX processor and the NOVAthesis template (v7.1.29) [25].

Acknowledgements

First and foremost, I would like to express my sincere gratitude to my advisor, Armanda Rodrigues, and co-advisors, Inês Coutinho and Nuno Correia. Their assistance and support were priceless throughout this dissertation.

I am also deeply grateful to the Department of Computer Science for providing all the necessary resources and facilities to carry out this work. My thanks also go to the research center VICARTE for the support, materials, and space that made it possible to conduct the user evaluation.

A special thanks to Inês Vaz Pinto, responsible for the Roman Ruins of Troia, for her openness and availability in welcoming us to visit the space, as well as for the necessary materials she kindly provided, which were fundamental to achieving the desired results.

Finally, a big thanks to my family and friends for their constant encouragement and support for this dissertation and during all my academic journey.

"A dream doesn't become reality through magic; it takes sweat, determination and hard work."

— Colin Powell

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 tomb 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, with the contribution of archaeologists from the Troia Site. The project involves 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 a repository featuring literature on Troia's excavations, and a Virtual Reality (VR) experience focusing on immersing virtually, a visit to existing physical objects, and an interactive base map of this Troia site. At the end of the project, the funerary enclosure, and objects will be integrated into a virtual 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 numa luxuosa tomba descoberta 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 a contribuição de arqueólogos do sítio arqueológico de Tróia. O projeto envolve 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 repositório contendo dados sobre as escavações realizadas em Troia e uma experiência de Realidade Virtual (RV), que permitirá uma imersão virtual a objetos físicos existentes, e um mapa interativo deste sítio arqueológico de Troia. Por fim, estes elementos serão integrados num ambiente virtual 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

Contents

List of Figures

List of Tables

Listings

Acronyms

2D	Two-dimensional *(pp. ix, 8, 14, 20–22, 25, 35, 36, 43)*
3D	Three-dimensional *(pp. iv, vii, ix, x, 3, 5, 7, 8, 12–28, 30, 31, 33–37, 43, 47, 52, 55–59, 74–76)*
6-DOF	Six Degrees of Freedom *(p. 9)*
API	Application Programming Interface *(pp. xii, 31, 37, 38, 42)*
AR	Augmented Reality *(pp. 11, 20, 25, 28)*
AV	Augmented Virtuality *(p. 11)*
BIM	Building Information Modelling *(pp. 21, 22)*
CAD	Computer-Aided Design *(p. 23)*
CAVE	Cave Automatic Virtual Environment *(p. 10)*
CH	Cultural Heritage *(pp. iv, vii, x, 1–3, 5–7, 16–18, 21, 22, 25, 26, 28, 37, 62, 65, 71, 72, 77)*
CIDOC	International Committee for Documentation *(p. 6)*
CIDOC-CRM	CIDOC Conceptual Reference Model *(pp. 6, 17, 18, 77)*
CRUSOE	Conference of Rectors of South-Western European Universities *(p. 18)*
DCH	Digital Cultural Heritage *(pp. vi, 5, 19, 20)*
DCMI	Dublin Core Metadata Initiative *(p. 6)*
DT	Digital Twin *(pp. 7, 19)*
ECCCH	European Collaborative Cloud for Cultural Heritage *(pp. 18, 20)*
ECHOES	European Cloud for Heritage OpEn Science *(pp. ix, 19)*
EDM	Europeana Data Model *(p. 6)*
EU	European Union *(pp. 5, 18)*
FCT	NOVA School of Science and Technology *(p. 31)*

FOV Field of View *(p. 10)*

GIS Geographic Information System *(pp. vii, ix, 5, 8, 15–18, 21–23, 28, 37, 76)*

HBIM Heritage Building Information Modelling *(pp. 7, 8)*
HIS Heritage Information System *(p. 8)*
HMD Head-Mounted Display *(pp. ix, x, 10, 11, 31, 36, 58, 60, 61)*

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

LiDAR Light Detection and Ranging *(pp. vi, ix, 13, 14, 16, 20)*

NMA National Museum of Archaeology *(p. 2)*
NOVA NOVA University Lisbon *(p. 2)*

OGC Open Geospatial Consortium *(pp. 15, 18)*
OSGeo Open Source Geospatial Foundation *(p. 15)*

PASEV Patrimonialization of Évora's Soundscape *(pp. 25, 28)*
POIs Points of Interest *(pp. 24, 25, 31)*
PQ Presence Questionnaire *(pp. 61, 71, 72)*

REST Representational State Transfer *(pp. 31, 37)*

SID Spatially Immersive Display *(p. 10)*
SVIFT Simple Virtual Interactor Framework and Toolkit *(p. 8)*

UEQ User Experience Questionnaire *(pp. x, xi, 61, 68, 69, 72)*
UI User Interface *(pp. ix, 19, 36, 38, 40, 42–44, 65, 72, 74–76)*
UX User Experience *(pp. 31, 36, 55, 68)*

VE Virtual Environment *(pp. 2–5, 7, 9–11, 19, 26–28, 31, 33, 34, 36, 38–40, 43, 45, 47, 59, 65)*
VICARTE Glass and Ceramic for the Arts *(pp. 1, 2, 32, 59)*
VR Virtual Reality *(pp. iv, vii, ix, x, 1, 3, 7, 8, 11, 19, 23–26, 28, 30, 31, 33–36, 38, 43, 58–62, 64, 70–72, 74)*
VRML Virtual Reality Modeling Language *(p. 23)*

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 problem and the main objectives accomplished with this study. The contributions of this dissertation are summarized in Section 1.4. Finally, in Section 1.5, the report organization 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 informing the present.

This project studies 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 Cultural Heritage (CH) but also to convey ancestral heritage knowledge to everyone, including future generations. The growing integration of digital tools with arts and material culture enhances online facilities for users and democratizes its access. 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, the goal is to raise the value of this archaeological site and make it accessible in an immersive and engaging VR experience.

1.2 Context

This thesis was developed under the umbrella of an interdisciplinary collaboration among three institutions. The NOVA LINCS[2], Glass and Ceramic for the Arts (VICARTE)[3], and archaeologists from the Troia Site. VICARTE is a glass and ceramic research unit created as

[1] https://www.arch.ox.ac.uk/why-archaeology-matters
[2] https://nova-lincs.di.fct.unl.pt/
[3] https://vicarte.org/about-us/

a partnership between the NOVA University Lisbon (NOVA) and the Faculty of Fine Arts, University of Lisbon, with members 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 [33].

The ruins extend along two kilometers of the Sado River estuary, comprising twenty-five fish-salting workshops [19]. A site of outstanding value, with a unique magnitude, which has influenced the economy of an entire region and its development up to the present day [32]. 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 [34]. 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, artefact collections from Troia are exhibited in various institutions, including the National Museum of Archaeology (NMA)[4], the Museum of Archaeology and Ethnography of the District of Setúbal[5], and the City Council of Grândola[6]. The specific glass artefacts under study are housed at the NMA.

1.3 Problem Description and Objectives

This thesis concentrates on the study of glass relics discovered in the tomb of a wealthy woman who lived in the Troia Peninsula. The data collected from the studies and excavations of this site include data from the artifacts, excavation, and intervention process, such as images of the discovered glasses both before and after conservation. The preservation intervention work was carried out at VICARTE, that provided access to the images mentioned.

This project comprises two digital tools developed in parallel, complemented by a third component responsible for managing communication between them.

Primarily, a data repository was designed to compile and organize findings from a Troia funerary enclosure, focusing specifically on glass objects found inside. A database was structured to store this data. This database stores essential objects' information, such as object ID, dimensions, location details, object utility, shape, conservation status, and provenance. It serves as a data source for the Virtual Environment (VE).

[4] https://www.museunacionalarqueologia.gov.pt/
[5] https://maeds.amrs.pt/
[6] https://www.cm-grandola.pt/

The second tool, and the main focus of this dissertation, is a VR experience focusing on an immersive visit to an existing physical artefact, to enable visitors to handle precious fragile antiquities, added to the environment as 3D models. Two of these object models are already completed and were supplied by the researchers involved in the project. Furthermore, the application provides users with the option to experience a simulation of the original appearance of the glass artefacts. In this environment, an interactive map of the Troia Occidental site is integrated, featuring tooltips, points of interest, and the 3D model of the tomb within the funerary enclosure model positioned above the map, and developed from a photogrammetry capture. The map is the base ground plane on which users can walk and explore, with an additional functionality that enables toggling to another layer of the site. The user interaction with the environment is supported through the use of the VR headset display.

In addition, a backend implementation serves as the backbone of the two interactive tools described, supplying the VE with informative data retrieved from the repository.

1.4 Main Contributions

The main contributions achieved in this dissertation are:

- **Data Repository** - A comprehensive database containing all available data, accessible to users through interactions with the VR environment.

- **VR Immersive Experience** - Enables users to view and explore the funerary enclosure model with the map as ground plane, and interact with and manipulate virtual 3D objects within. An innovative feature is the opportunity for users to virtually interact with glass-made historical relics, offering a sense of traveling back in time. Users can also navigate through a user-friendly map that enhances the feeling of presence within this authentic CH space. Additionally, the system delivers an engaging and interactive experience that enriches their understanding and interest in Roman heritage, making learning both enjoyable and meaningful.

- **Research Paper Publication and Presentation** - During the dissertation, a short paper based on the developed work was written, submitted, and accepted for publication at the *SUMAC Workshop on Analysis, Understanding, and Promotion of Heritage Contents*[7], part of the ACM Multimedia 2025 Conference[8], to be held in Dublin, Irland. The corresponding workshop and poster presentation will take place on 27 October 2025.

1.5 Document Structure

This document is structured into six chapters:

[7] https://sumac-workshops.github.io/2025/
[8] https://acmmm2025.org/

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 significant concepts that were explored throughout the work.

3. **Related Work:** This segment consists of the research of similar projects and analysis of digital tools from relevant studies that can complement this dissertation.

4. **System Design and Implementation:** This chapter describes the architecture, design choices, and the implementation process. Code listings are included to illustrate technical details, while figures demonstrate the system's functionalities.

5. **User Evaluation:** The following chapter describes the evaluation methodology, including the questionnaires and procedures used to assess user experience in the VE developed. The chapter also presents and analyzes the collected results, supported by graphics.

6. **Conclusions:** The final chapter summarizes the achieved goals, encountered challenges, and possible future improvements.

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 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 DCH

CH includes monuments, sites, landscapes, skills, practices, knowledge and expressions of human creativity [11]. Collections preserved 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.

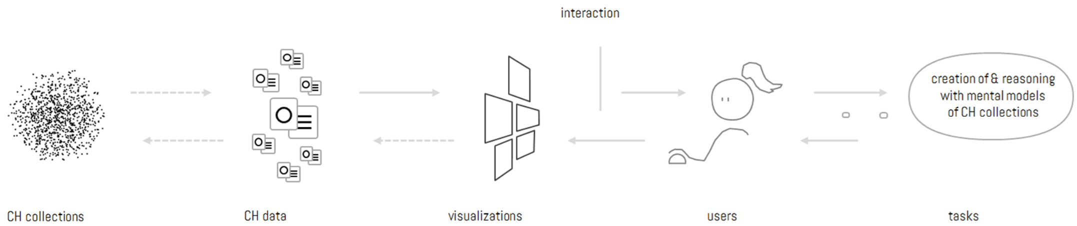


Figure 2.1: Schematic lineup of a visualization system in the CH data domain [50].

The visualization of CH collections (process illustrated in 2.1) can involve two classes of data: the data constituting the digital cultural object, and the accompanying metadata, as exemplified below in the Figure 2.2 [50]. The metadata can describe a broad diversity of information associated with CH objects, 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.

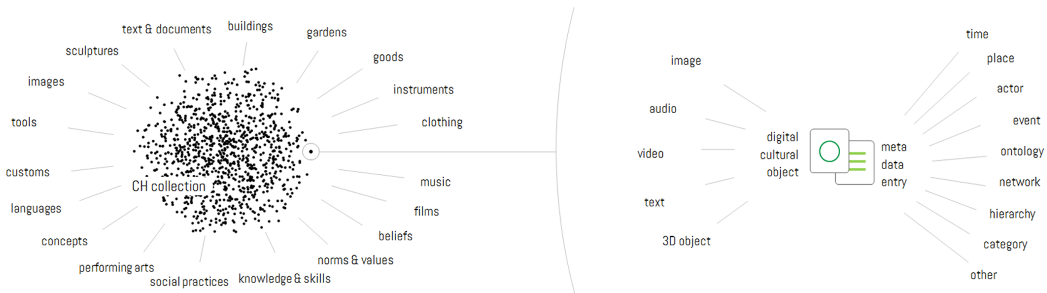


Figure 2.2: Types of cultural objects and related metadata entries [50].

[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/

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 [44]. 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 Twins 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” [29]. 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.

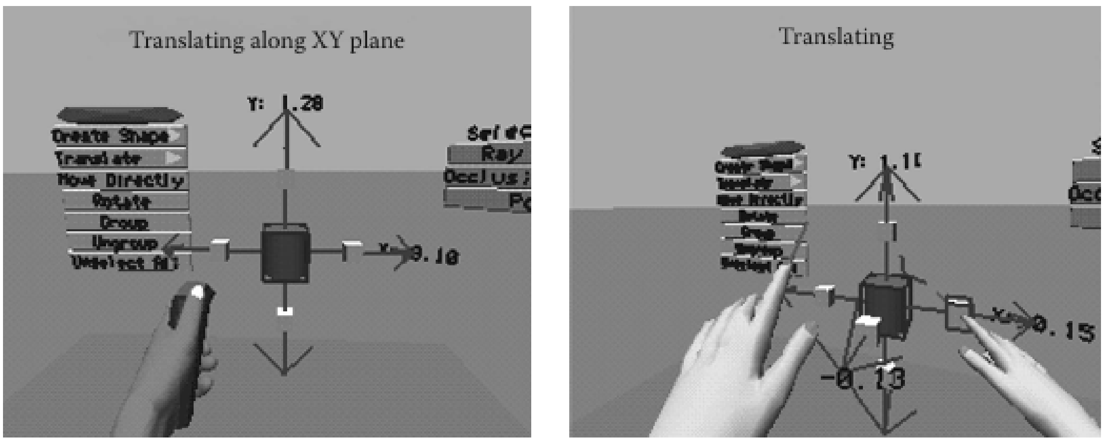


Figure 2.3: VR interface where a user is manipulating a 3D object [18].

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 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.

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

Figure 2.4: HTC Vive controllers(center) and Oculus Touch controllers(at the ends) [42].

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.

Figure 2.5: Stereoscopic glasses augmented with a constellation of reflective balls [40].

Figure 2.6: Dual-screen fishtank stereo-capable display [40].

[7] https://steantycip.com/vr-cave/

[8] https://graphics.stanford.edu/projects/RWB/

(a) Microsoft HoloLens 2 [52]. (b) HTC Vive [40]. (c) Meta Quest 3 [43].

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.

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 [28] 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.

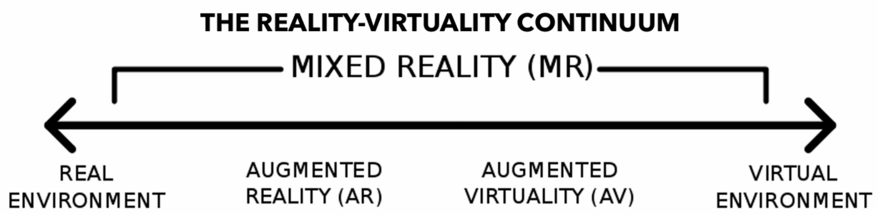


Figure 2.8: Milgram and Kishino's Virtuality Continuum [28].

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 [27]. 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 [26].

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.

2.3.2 Light Detection And Ranging (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.

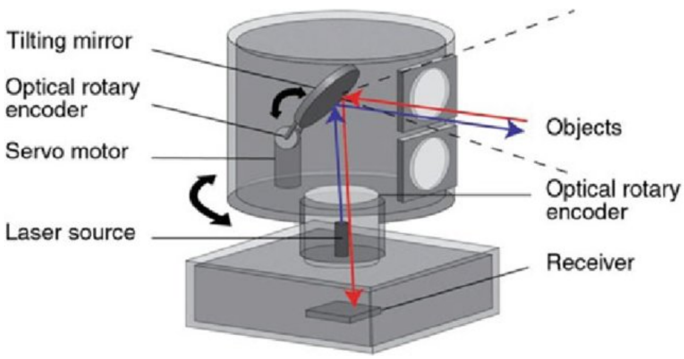


Figure 2.10: Mechanical Spinning LiDAR [20].

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.

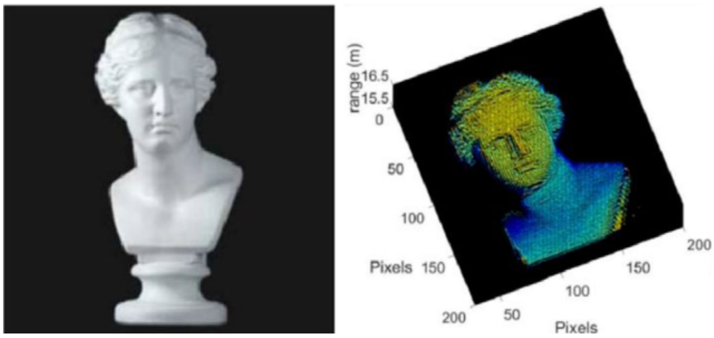


Figure 2.11: Flash-based LiDAR sensor. Left: 2D image of sensing target, Right: Captured 3D image [23].

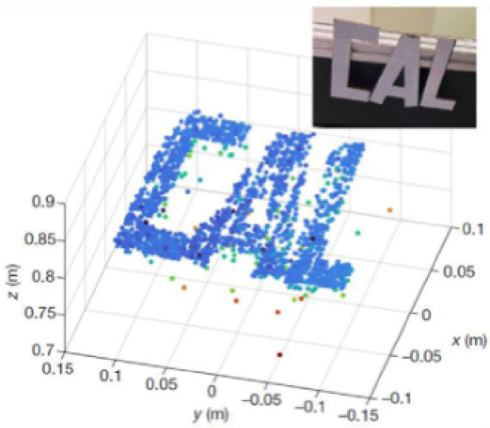


Figure 2.12: A LiDAR sensor based on sequential illumination [23].

2.3.3 Artifacts Reconstruction

Systems capable of automatically reconstructing objects from their fragments can greatly aid in the study of many civilizations [49]. 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 [41]. 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 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

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

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.

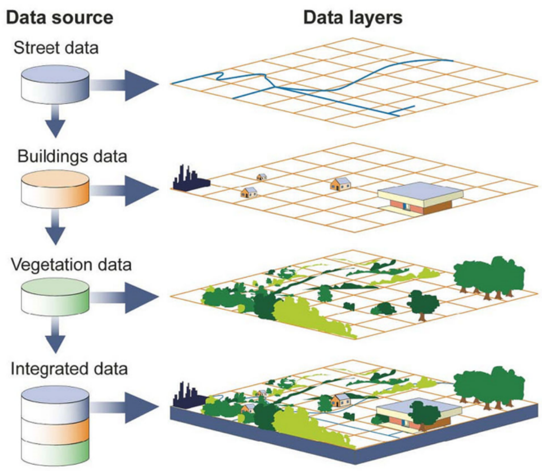


Figure 2.13: Visual Representation of Data Layers Integration in a GIS [31].

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 [53]. 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 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 [38]. For example, the recent, and highly publicized, discovery of what is believed to be the Mayan site of Ciudad Blanca in Honduras [45].

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.

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

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

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.

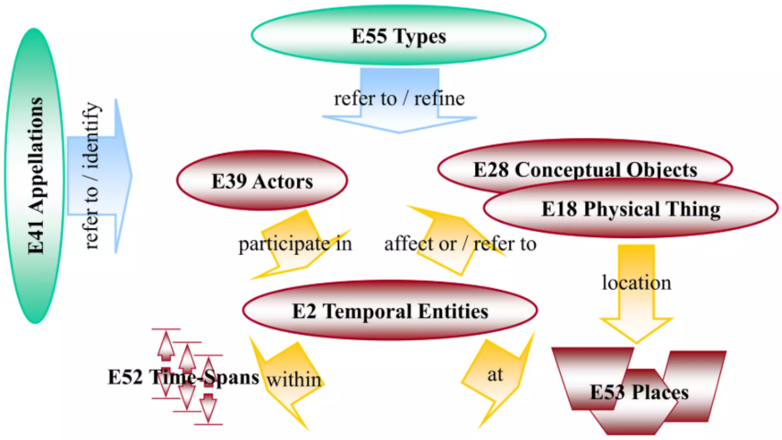


Figure 2.14: Fundamental concepts of `ISO 21127` [9]

.

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.

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

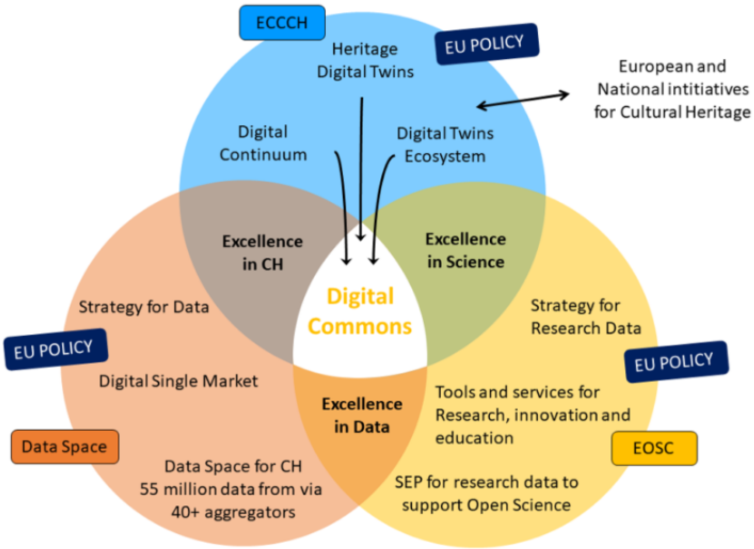


Figure 2.15: ECHOES goals 20.

2.7 Discussion

The theoretical concepts introduced in this chapter provided the theoretical basis for the practical implementation described in Chapter 5. In particular, the principles of DCH, interaction and visualization techniques, input/output devices, and 3D reconstruction methods affect the implementation of the developed VE. This work utilized a VR environment that integrated 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.

This dissertation is strongly grounded in the concept of DCH, understood as the digital representation of cultural assets in forms such as images, texts, and 3D models (Figure 2.2). Within this context, the DT emerges as a highly relevant paradigm, offering a dynamic way to mirror physical artefacts and environments.

Interaction and visualization techniques, such as ray-based selection and menu-driven interface (Figure 2.3), were essential to user engagement. These techniques allowed users to manipulate objects, navigate menus, and interact with the VE intuitively. While manipulation was limited to rotation and positioning, excluding transformations such as scaling or zooming, the implemented interactions ensured that users could meaningfully engage with the artifacts. These interaction techniques depended directly on the input/output devices employed. Controllers served as the primary input device, supporting the four VE task categories outlined in Section 2.2.2.1: selection, manipulation, travel, and system control. For example, selection was used both to grasp artefacts and to interact with UI elements; travel was enabled through teleportation and continuous locomotion; and system control allowed users to position objects in the environment when released. The *Meta Quest 3* headset, regarding the ones studied in this chapter, was the modern output device used, with a high-quality immersive display crucial for user testing.

Photogrammetry was applied to generate 3D models of glass artifacts and the funerary enclosure. Although LiDAR scanning was not explored due to time constraints, it remains a possibility for future developments. Artefact reconstruction also played a significant role, with specialists producing 2D documentation of interventions such as cleaning and restoration. These reconstructed elements can be explored in digital analysis.

The project integrated a database to organize object data, including identifiers, locations, functions, and conservation states. While geospatial data storage was prepared with Postgres' "location" table, it was not yet applied in practice due to time constraints. Nevertheless, the system was deliberately designed for scalability, ensuring compatibility with future enhancements. Standards and documentation, although only briefly considered, remain essential for ensuring the long-term sustainability of cultural heritage digitization.

This way, the dissertation not only contributes to the field of DCH but also aligns with European initiatives such as the ECCCH described in this chapter, which emphasizes the preservation, conservation, and dissemination of material cultural heritage. Moreover, while AR was not explored within this work, it is suggested as a direction for expanding into mixed reality in future developments, as discussed in Chapter 7.

3

Related Work

This chapter presents research works that were considered 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 [43] 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.

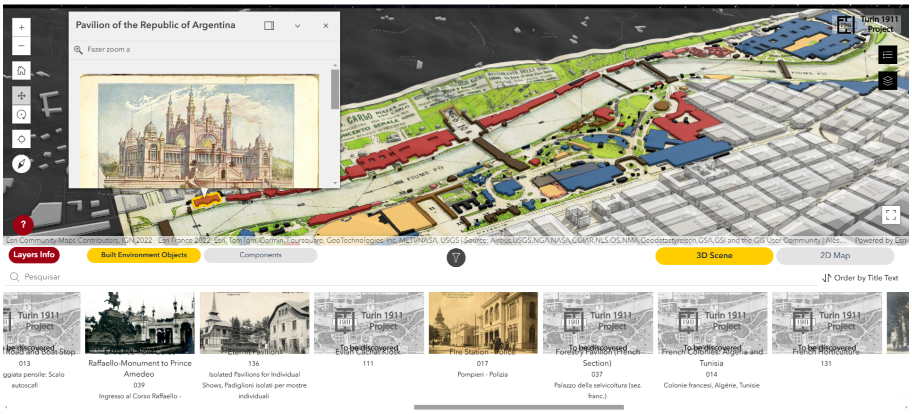


Figure 3.1: The webGIS application. Displayed functionalities: bottom left – search bar and objects list; top left – navigation controls and a pop-up; bottom right – 3D scene/2D map buttons; top right – map legend and layer control buttons.

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.

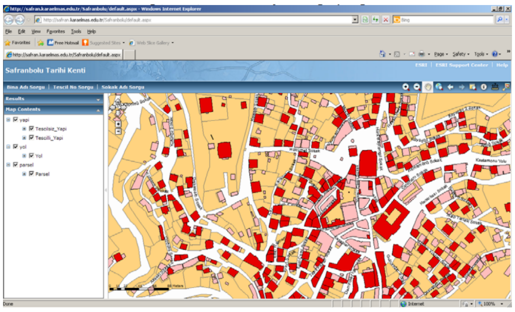
Process Description

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

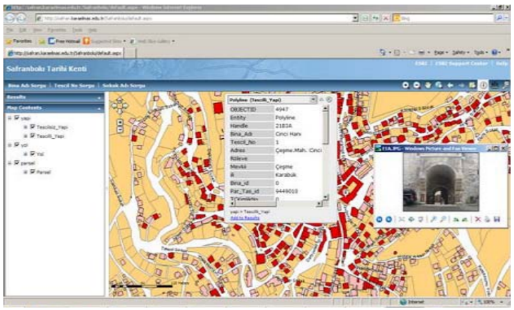
[5] https://www.agisoft.com/
[6] https://whc.unesco.org/en/list/614/

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 [47] 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 [47] 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 [48]. The project started by Rosário [37] 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 [36]. 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 [30], 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.

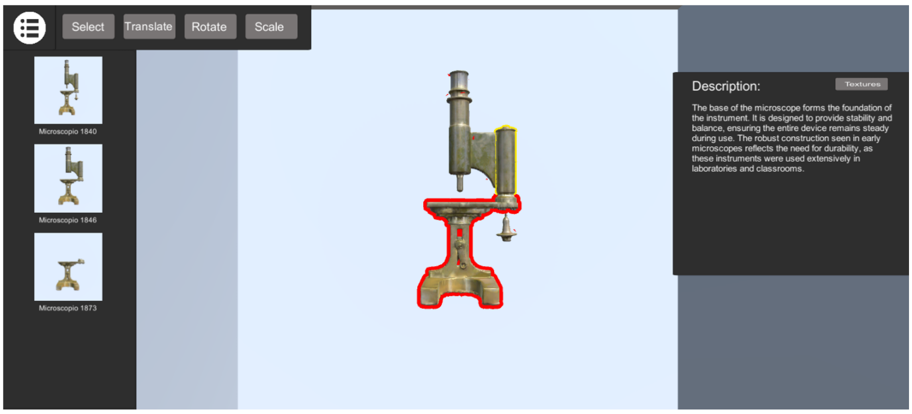


Figure 3.4: Interface for interacting with heritage artefacts.

[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 "Turin 1911 Project" integrates an interactive map with multiple functionalities, while incorporating 3D models and a spatial database. Similarly, the Safranbolu GIS project focused on the preservation of an archaeological site, using 3D modeling to map historical buildings and integrating CH monuments as metadata relevant to the site. Both projects illustrate the use of 3D models and digital tools for documentation and preservation. However, while these studies remain primarily centered on mapping and geospatial analysis, other research has expanded the focus towards immersive VR visualization, as the following VR scenario study.

The following described project, 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 and Unity, that were 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 work provided an intuitive way to interact with 3D artefacts. This research developed a user interaction approach, allowing the manipulation with 3D object's individual components.

We can conclude that there is a wide variety of approaches to the use of digital tools in CH. Among the projects analysed, the PASEV project appears to be the most comprehensive, integrating all the features considered, as illustrated in the Table 3.1. While an interactive map is included in this work, it remains at a preliminary stage compared to other features. Instead, priority was given to developing an immersive VR experience, which constitutes the main component of the system. The virtual tour is also present, but limited to a specific 3D model component. In general, most of the studied research works integrate only two of these features, highlighting the novelty of combining multiple approaches in this dissertation.

Table 3.1: Comparison of Projects Functionalities

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	✗	✓	✓	✗	✗

4

System Design

This chapter presents the overall design and conceptualization of the system developed. It begins in Section 4.1 with a description of the system requirements, followed by an overview of the system architecture in Section 4.2 and database structure in Section 4.3. Finally, it ends with a discussion of the implementation choices made during development, in Section 4.4.

4.1 Requirements

This section describes the requirements of this dissertation, categorized into the following areas: Interactive Map, 3D Model Interaction, and VR environment.

Interactive Map

A map of the Troia archaeological site under study was incorporated into the project to offer interactive functionalities.

- **Map Navigation:** Users can navigate in the environment, and explore different locations.
- **Perspective Switching:** Toggle between top-down and profile views for better spatial understanding.
- **Layer Toggle:** Toggle visibility of layers, overlay a *.tif* map illustration, such as excavation campaigns.

3D Models & Interaction

A focus on the interaction with 3D models, which are integrated into a VR environment.

- **Artifact Interaction:** Allows users to virtually manipulate the glass artefact models.
- **Contextual Overlay:** Display descriptive data about the artefact, such as its origin, period, and historical usage.

- **Reconstructed Models:** Showcase how artefacts would look originally (having in consideration characteristics such as: colourless glass, archaeological drawings and symmetry).
- **3D Models Integration:** The user can zoom the map to visualize the perspective of a specific 3D model.

VR Environment

VR functionalities to provide an intuitive User Experience (UX), enabling interaction with the VE through the use of HMDs.

- **Immersive Experience:** VR allows users to immerse in a virtual tomb visit, enabling interaction with glass relics.
- **Device Accessibility:** Primarily user-friendly and enabling haptic interaction, while supporting VR glasses as an emerging display option.
- **Localization & Wayfinding:**
  - **POIs:** Use colors, text, visual markers, or direction arrows to emphasize and guide users to historically significant locations.

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"[1], acting as an intermediate between the Unity client and the database. The communication flow between these layers is managed through a Node.js Representational State Transfer (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.

During the development stage, the database was hosted locally on a PostgreSQL server managed via pgAdmin[2], 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 NOVA School of Science and Technology (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.

[1] https://docs.unity3d.com/6000.2/Documentation/ScriptReference/Networking.UnityWebRequest.html

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

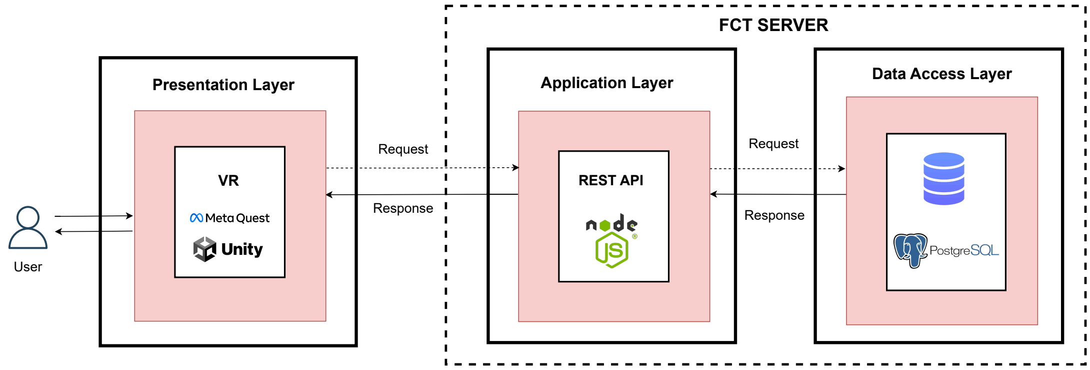


Figure 4.1: System Architecture Overview of the Developed System. © Ana Maissa Antunes

4.3 Database Structure

The database consists of 11 tables that ensure the significant data of excavation and objects are stored. 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 object images, 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.

The table `necropolis` is the top-level table and contains general information about the site. The funerary enclosure or mausoleum is represented by the table `mausoleum`, which stores information such as *dimensions* and *construction_materials* and references the corresponding *id* in `necropolis`. The tomb within the mausoleum is represented by the table `tomb` and has a foreign key *id* referencing the associated mausoleum. While the table `tomb_belonger` links tombs via its *id*. The table `object` stores all information of each object, with 27 attributes describing each artifact. Moreover, table `object_intervention` stores data about interventions performed by VICARTE, including *images_path_b_interv* and *images_path_a_interv*, representing images of the object before and after the intervention. This table references the *id* in the table `object`. Each object also has an associated table `location`, encompassing the coordinates of each object. Finally, the table `excavation` contains excavation information, with two child tables: `excavation_protection` and `excavation_area`, inheriting the *id* of `excavation`.

In Unity, only the following attributes are retrieved: from `object`, *id*, *name*, *material*, *provenance*, and *dimensions*; from `object_intervention`, *images_path_b_interv* and *images_path_a_interv*.

The detailed structure, including relationships and attributes, is illustrated in Figure 4.2.

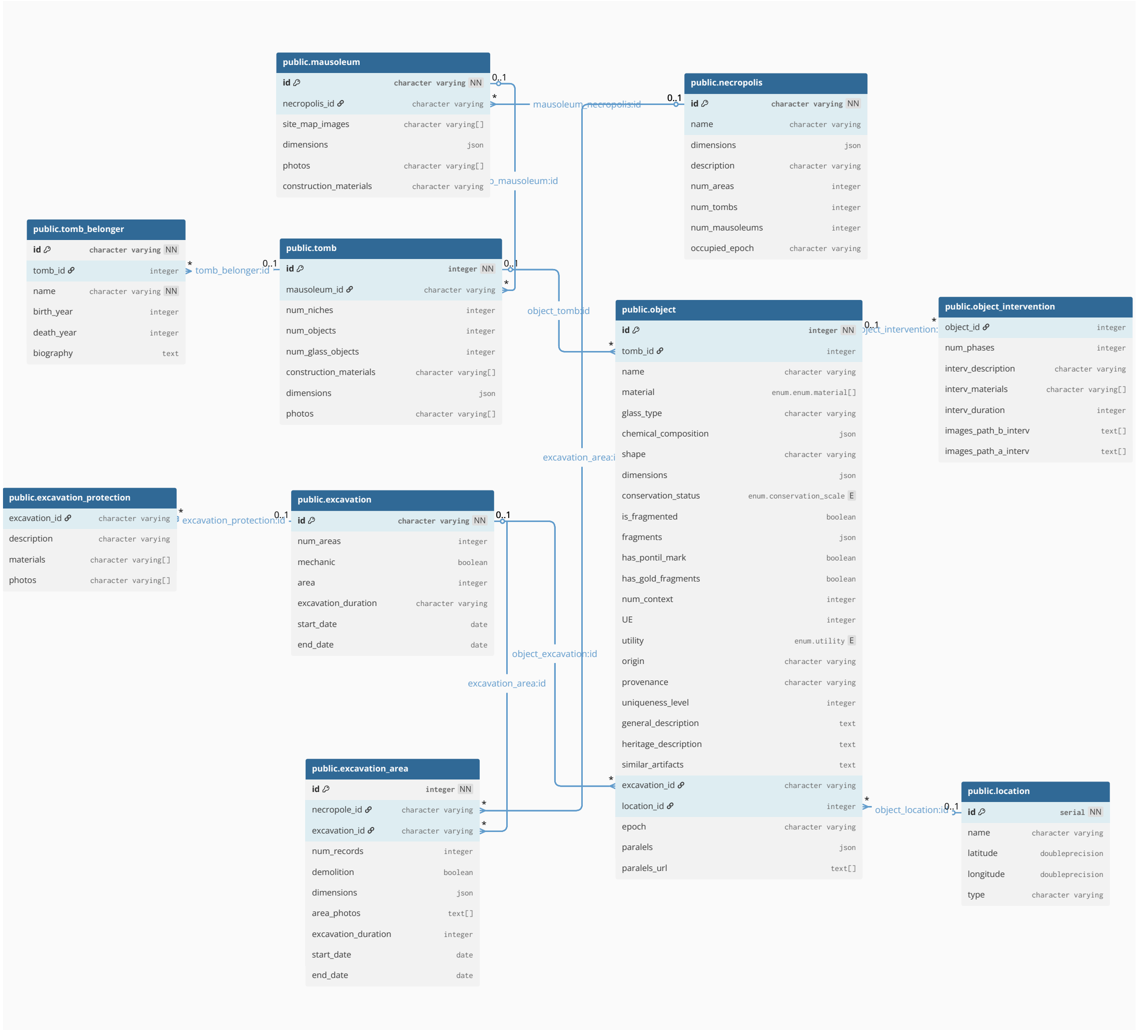


Figure 4.2: Relational Database Model.

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.

4.4 Discussion

Given the diverse requirements of this project, the primary focus was on developing an immersive VE, prioritizing 3D models and VR functionalities for exploring glass artifacts within the tomb. Although interactive map features were included, they were implemented with a lower level of detail. At the beginning of the dissertation, the development of the VR environment and the database proceeded in parallel. Once the base database structure was implemented, the main focus was on the construction of the VE. The initial idea was to implement the map using JavaScript and the Leaflet.js[3] 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 allowed users to walk across the map as if in reality, while simultaneously visualizing the 3D models accurately positioned in space.

The implementation began with the integration of the map into Unity. Then, the model of the funerary enclosure was positioned on the map. Following, the functionalities were implemented, such as 3D model visualization and map navigation, as outlined in Section 4.1. Users can also grab objects, and interact with panel menus that displayed data retrieved from the database. A database was created to store significant data, including artefact and excavation data, with updates during development when needed. For interaction inside the tomb, two glass objects were chosen as the primary focus.

To enable communication between Unity and the database, a backend was implemented. Unity sent requests to the backend, which then queried the database and returned the requested information. A *dropdown menu* was created in the VE to fulfill requirement "Contextual Overlay", allowing the user to select an artefact ID and access the corresponding textual and visual data. Two request types were defined: (i) retrieval of all available ID from the "object" table, and (ii) retrieval of associated textual and image data, combining information from the "object" and "object_intervention" tables. For the layer toggle requirement, a photograph of the actual site was integrated, providing a stronger sense of presence for the user. Perspective switching was supported through photographs provided by specialists of the funerary enclosure architecture materials.

The artefact reconstruction requirement was simplified: instead of reconstructing fragmented models, an illustration of the original object texture was simulated through the *Object Slider* functionality. As a result, users could enter the tomb and experience an immersive interaction with two glass relics, fulfilling the requirements of the VR environment. Additional points of interest were distributed across the map to enrich the user experience.

Each functionality was tested individually, which was useful for correcting errors. After implementation, system testing evaluated the usability of the functionalities implemented to accomplish these requirements.

[3] https://leafletjs.com/

5

Implementation Details

This chapter begins with an introduction to the technologies used for the implementation in Section 5.1. Subsequently, in Section 5.2, all the implementation processes and features are described in detail.

5.1 Adopted Tools and Tecnhologies

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

5.1.1 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)**[1]. 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 used.

For the backend implementation, comprising the Node.js server and the database, **Visual Studio Code (VSCode)**[2] was used.

The version control system used initially for project management was **GitHub**[3], 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**[4] tool was employed as an alternative solution for managing these system.

[1] https://visualstudio.microsoft.com/
[2] https://code.visualstudio.com/
[3] https://github.com/
[4] https://www.diversion.dev/

5.1.2 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 Virtual Environments (VEs). Unity also offers a community forum and repositories available in **Unity Asset Store**[5] where developers can access resources and adapt them for their projects.

For this study, Unity was selected for developing the VR environment. The C# programming language used within Unity facilitates the management of game objects and user interactions in the VE. Its integration enables users an immersive experience while interacting with 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**[6] - This package provides a collection of diverse clickable sounds, designed to provide an immersive and complete UX.
- **Simple Pie Menu**[7] - A radial menu system implemented as the main menu of the project. Further details on its functionality are provided in Section 5.2.2.1.
- **White & Black GUI**[8] - 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.

5.1.3 Tools

Blender[9] 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[10], 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.

[5] https://assetstore.unity.com/
[6] https://assetstore.unity.com/packages/audio/sound-fx/free-ui-click-sound-pack-244644
[7] https://assetstore.unity.com/packages/tools/gui/simple-pie-menu-radial-menu-asset-270056
[8] https://assetstore.unity.com/packages/2d/gui/icons/white-black-gui-by-gamertose-168805
[9] https://www.blender.org/
[10] https://www.gimp.org/

5.1.3.1 Photogrammetry

The software used to process digital images and generate the 3D model of the funerary enclosure was *Agisoft Metashape*[11]. 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 the archaeologist responsible for this site, Inês Vaz Pinto. Based on these images, a 3D model of the funerary enclosure was generated, as described in Section 5.2.3.4. As part of the collaboration with the institutions, two already built models of artefacts, were provided by Sofia Pires.

5.1.4 Backend & Data Management

This section includes the backend and database repository technologies choices.

5.1.4.1 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 mediate the communication between Unity and the database repository.

Express.js[12] is the most popular Node.js web application framework, widely used for building web applications and APIs, with a minimal and flexible design. In this study, the web server Express.js was used to expose the REST[13] endpoints.

5.1.4.2 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 data querying.

5.1.5 XR Components and Plugins

This section comprises the main plugins and components used to support the custom implementation.

[11] https://www.agisoft.com/
[12] https://expressjs.com/
[13] https://www.ibm.com/think/topics/rest-apis

5.1.5.1 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.

5.1.5.2 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.

5.1.5.3 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.

5.1.5.4 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.

5.2 Implementation

This section starts with some explanation of the implementation made from Unity to the Database. After that, it contains the implementation process of all functionalities developed within the VE. The following is the method explanation of the three fundamental techniques. Finally, testing and debugging methodologies were applied during the dissertation.

5.2.1 Communication between Unity and Database

The **UnityWebRequest** class was used to send HTTP requests to the Node.js server, supporting both options retrieval (Section 5.2.1.1) and object data retrieval (Section 5.2.1.2).

To acquire the desired data retrieval, only three data structures were required:

1. **Artifact** – representing an individual artifact and containing all attributes from the `artifact` table described in Chapter 4, Section 4.3.
2. **Dimensions** – a substructure of **Artifact**, storing three measurements: weight, height, and width.
3. **Artifact List** – a collection of **Artifact** structures to manage multiple objects retrieved from the database.

5.2.1.1 Dropdown Options Retrieval

This implementation retrieves all the IDs of the available artifacts, to fulfill the requirement of the user to view the desired object's textual and image information. The artifacts returned from the database are stored in a list structure, which is then iterated to populate the dropdown `options` list, as illustrated in Listing 5.1.

Listing 5.1: Method used to load artifact IDs and define as options in the Dropdown.

```
  IEnumerator GetOptionsIds(string url)
{
   // Send HTTP GET request to the given URL
   UnityWebRequest www = UnityWebRequest.Get(url);
   ...
   if (www.result == UnityWebRequest.Result.Success)
   {
      ...
```

```
            ArtifactList artifactList = JsonUtility.FromJson<ArtifactList>(wrappedJson);

            List<TMP_Dropdown.OptionData> options = new List<TMP_Dropdown.OptionData>();
            ...
            // Iterate through all artifacts and add their IDs to options List
            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);
        }
    }
```

5.2.1.2 Object Data Retrieval

This method, shown in Listing 5.2, retrieves all data of objects necessary to present in the VE. It sends a `GET` request to obtain the complete information, including images before and after intervention, which are then passed to `GetImages()`, explained in the section below.

Additionally, textual data is retrieved. Once the request is successful, the JSON response is parsed into an `Artifact` object using Unity's `JsonUtility.FromJson<Artifact>()` method. From this structure, the following relevant fields are extracted: *id*, *name*, *material*, *epoch*, *provenance*, and *dimensions*. The *dimensions* field is a nested JSON structure containing *height*, *width*, and *weight*.

Finally, a formatted string is created to display the object's details in the UI panel.

Listing 5.2: Method used to load object data from the database.

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

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

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

            string material = artifact.material.Replace("{", "").Replace("}", "");

             displayText += $"ID: {artifact.id} | Name: {artifact.name} \nMaterial: {
                 material} | 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);
        }
        ...
    }
```

5.2.1.3 Object Images Retrieval

The GetImages method iterates over the array of image paths retrieved from the "object_intervention" table. The array passed to this method may be either "images_path_b_interv", containing the object images before intervention, or "images_path_a_interv", after the intervention. For each image, a component is created and positioned appropriately within the gallery.

The implementation of this process is presented in Listing 5.3.

Listing 5.3: Method used to load artifact images and to display them in the Images Gallery.

```
     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;
```

```
            }
            ...
        }
        x_pos = 1.5f;
    }
    else
    {
        Debug.LogWarning("Couldn't␣load␣Images␣for␣Object␣ID" + id);
    }
}
```

5.2.1.4 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 5.4. 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, described in Section 5.2.2.3. 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 5.4: Example of defining an API endpoint in Node.js.

```
1 //GET endpoint that retrieves object data by ID
2 app.get('/get-objects_data/:id', async (req, res) => {
3   const id = req.params.id;
4
5   try {
6     // Query to the database: select all object data present in 'object' and '
        ↪ object_intervention' tables by ID
7     const result = await pool.query('SELECT␣*␣FROM␣object␣inner␣join␣
        ↪ object_intervention␣on␣object.id␣=␣object_intervention.object_id␣WHERE␣
        ↪ object.id␣=␣$1', [id]);
8     res.json(result.rows[0]);
```

```
    } catch (error) {
        console.error(error);
        res.status(500).send('Server␣Error');
    }
});
```

5.2.2 Virtual Environment

The initial step was to place the 2D map on the ground plane, using the 1-meter default grid scale of Unity to ensure the precise real-world dimensions. With this in place, it was only necessary to adjust the scale of the funerary enclosure to match its position on the map. It is also important to mention that the two objects in the environment were carefully measured using virtual rules.

In the VE, a set of functionalities was implemented. They are described in this section, in the following order: the Main Menu in Section 5.2.2.1, the Panel UI in Section 5.2.2.2, the Image Gallery in Section 5.2.2.3, object interaction starting with the Slider in Section 5.2.2.5, the Outline in Section 5.2.2.6, and Grab and Release in Section 5.2.2.7, and Points of Interest in Section 5.2.2.4. Furthermore, funerary interaction is described in Section 5.2.2.8, and navigation logic in Sections 5.2.2.9 and 5.2.2.10.

5.2.2.1 Main Menu

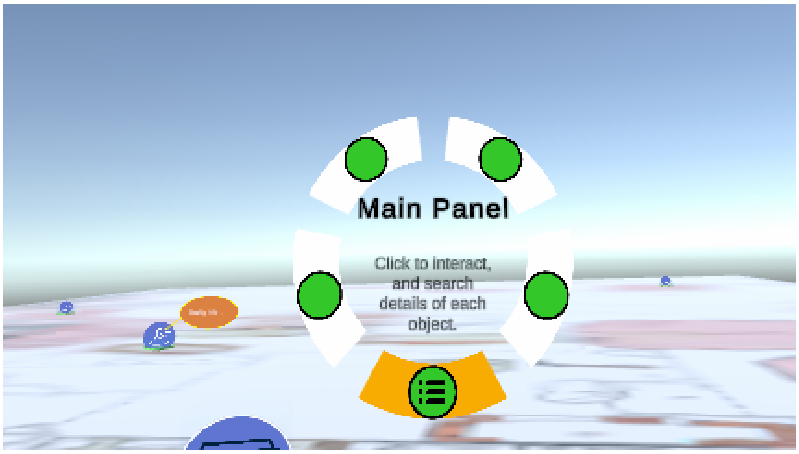


Figure 5.1: Main Menu Interaction, with the option of the Main Panel selected.

The main menu, displayed in Figure 5.1, was built with the support of the **SimplePieMenu** asset. However, it was restructured and adapted for use with VR controllers, since the original implementation was developed for Unity 3D without VR handling. The menu can be opened or closed with the trigger button of the right controller. The menu follows the user through the position of the right controller attributed in the "Follow_Controller" script. Additionally, to select an option, the user points at it with the ray and selects it using the right controller's select button. To detect which menu option is being targeted, a **Raycast** operation is performed based on the current position of the right controller ray, as illustrated in Listing 5.5.

Currently, the menu contains only one functional option, represented by a menu icon. This option performs a single action: activating or deactivating the **Panel UI** menu.

Listing 5.5: Method used to acquire the position that was pointed at by the controller ray.

```
public Vector2 GetPosition(Vector2 anchoredPosition, Transform controllerTransform)
{
    // Create a ray starting from the controller's position, pointing forward
    Ray ray = new Ray(controllerTransform.position, controllerTransform.forward);
    /Ray to detects collisions with the main menu
    if (Physics.Raycast(ray, out RaycastHit hit, 50f, LayerMask.GetMask("Default")))
    {
        Vector3 screenPoint = Camera.main.WorldToScreenPoint(hit.point);

        // Return the point relative to the center of the screen
        return new Vector2(
            screenPoint.x - Screen.width / 2f,
            screenPoint.y - Screen.height / 2f);
    }
    return Vector2.zero;
}
```

5.2.2.2 Panel UI

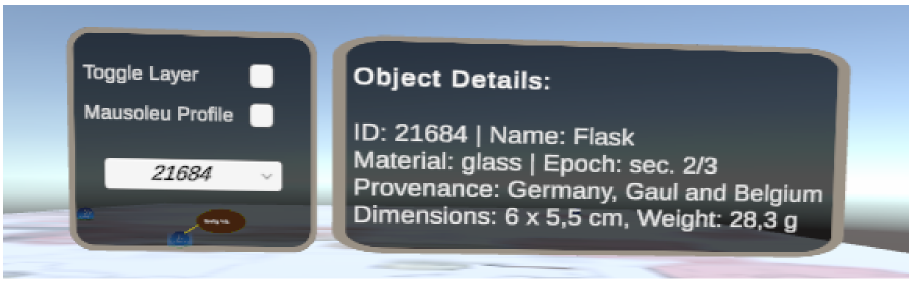


Figure 5.2: Panel UI Interaction.

The UI includes a canvas where users can interact with and explore object data, as shown in the left panel of Figure 5.2.

In this example, the object ID selected from the dropdown menu is "21684," and the textual data associated with this object is displayed in the right panel. This panel is initially empty and populates with the relevant object details after a selection is made.

The UI contains three interactive elements: the "Toggle Layer" and "Mausoleum Profile" checkboxes, and the "Dropdown Menu".

The first element, **Toggle Layer**, is a checkbox that controls the visibility of the ground plane. By default, the base plan is represented by a partial drawing of this archaeological site, which includes the burial enclosure under study. When the user activates the

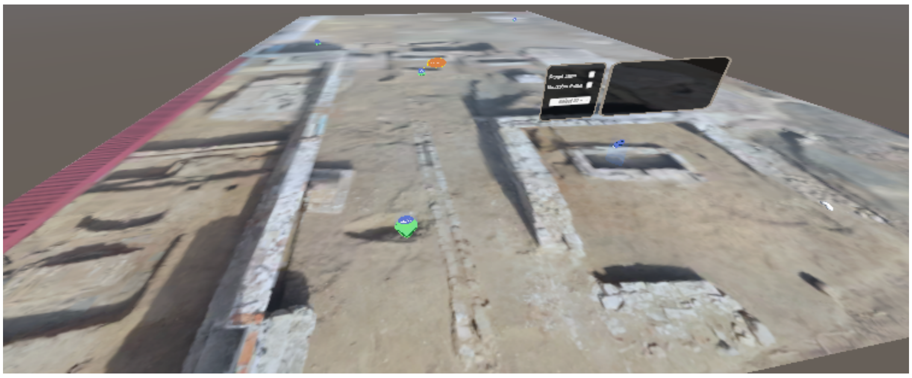


Figure 5.3: Toggle Layer to a photo of the Site Occidental part.

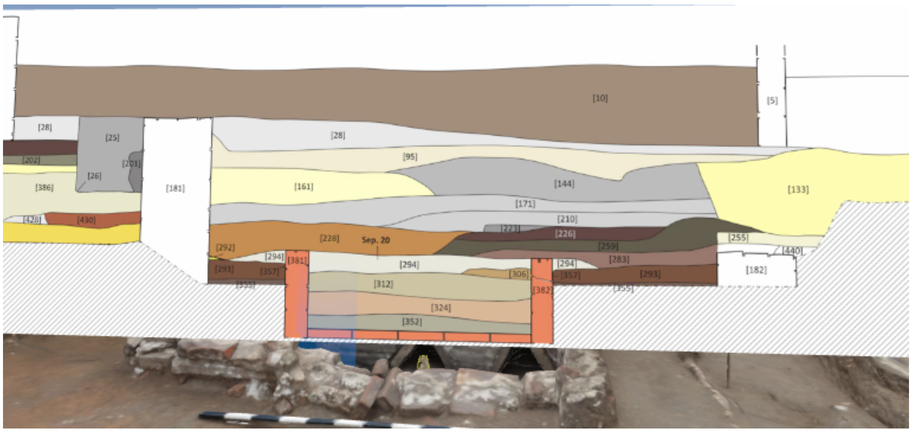


Figure 5.4: Funerary Enclosure Profile constructions layer view.

checkbox, the plan switches to a photograph of the actual site, offering a more realistic view and a stronger sense of presence. This feature is illustrated in Figure 5.3. The user can at any time toggle the view in the checkbox to view the pretended plan.

The second element, the **Funerary Enclosure Profile**, demonstrated in Figure 5.4, works similarly. However, in this case, it opens a profile image of the mausoleum wall, displaying the different material types and layers of construction.

The third element, the **Dropdown Menu**, allows the user to select an object by its identification number (ID). Once selected, the corresponding textual data and intervention images are retrieved from the database. Besides this interaction panel, on the right side of the interface is the place where the textual data related to the selected Object ID is displayed.

The Images Gallery interaction, displayed on the left side of the map, is described below.

5.2.2.3 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 intervention. Users can switch between these states by hovering the controller ray over the gallery arrow. In this manner, they can

Figure 5.5: Image Gallery with object images before intervention.

view the images of a concrete object, compare the visual differences, and acquire a clearer understanding of the intervention's impact on each object.

5.2.2.4 Points of Interest

Figure 5.6: Exemplified point of interest with an aggregated tooltip.

Diverse points of interest were placed in key areas across the plane.

Users can teleport directly to a point of interest by selecting a blue anchor (implemented with the default *Teleportation Anchor* component) within the plan. These points are designed to draw the user's attention to notable features or artifacts, with the most relevant point for the current study located inside the tomb within the funerary enclosure. Figure 5.6 illustrates one of these anchors.

In the future, the idea is to expand to other points and create interactive features as the 3D funerary enclosure model.

5.2.2.5 Object Slider

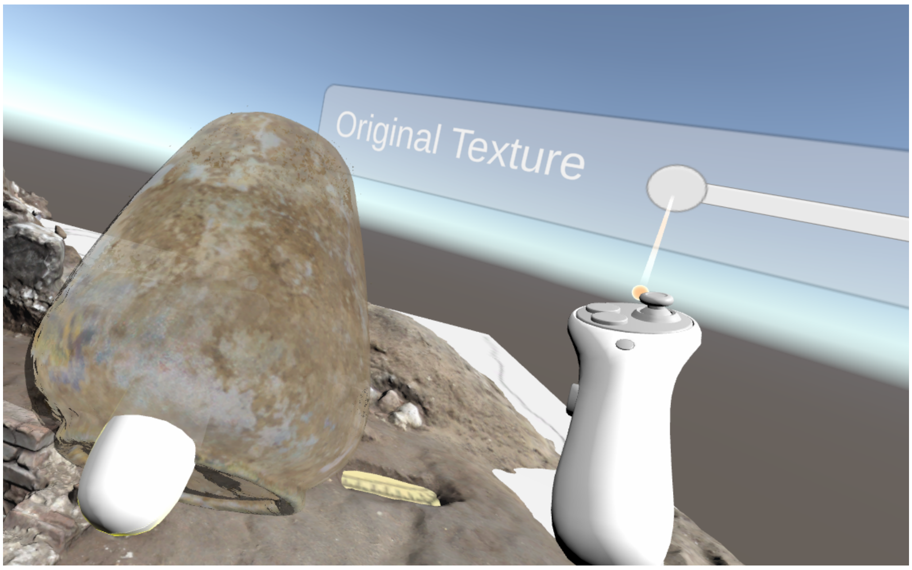


Figure 5.7: Object Slider Interaction.

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.

This functionality is illustrated in Figure 5.7, where the user holds the object with the left controller while manipulating the slider, named "Original Texture," with the right controller. The texture initially displayed corresponds to the post-excavation state, and as the user moves the slider to the right, it gradually transitions to the original glass texture. 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, written in Unity High-Level Shader Language (HLSL) for the Universal Render Pipeline (URP)[14]. This approach provided more control over the material's appearance compared to Unity's built-in shaders. The shader was constructed using key URP shader libraries, including those for lighting and

[14] https://docs.unity3d.com/Manual/urp/writing-custom-shaders-urp.html

shading calculations[15] , reflection probes[16] , shadow integration[17] , camera operations[18] , and transformations[19].

This version accepted two texture inputs: the original appearance of the object (input variable `_DecayTex`) and its current state (input variable `_RestoredTex`). Besides the texture inputs, the shader provides the following adjustable material properties: *Blend Factor*, *Smoothness*, *Fresnel Power*, *Specular Color*, and *Reflection Intensity*, enabling precise control over how the textures blend and the visual appearance of the material. These properties can be modified directly through the Unity Inspector.

A **Lerp function**[20] is a methodology that performs a linear interpolation between two values, based on an interpolation factor. In this case, it was used to interpolate between the two textures, considering their `Albedo`, `Alpha`, and `Smoothness` attributes, as shown in Listing 5.6. In this case, the interpolant factor is *_BlendFactor*, the input value that changes when the user moves the slider bar.

To enhance realism, additional lighting and reflection techniques were integrated into the shader, including the **Fresnel Effect**[21] to model light behaviour based on the angle between the surface normal (`normalWS`) and the view direction (`viewDirWS`), and adjustments to **specular**, **diffuse**, and **environment lighting** properties. These calculations were performed independently for each component, as illustrated in Listing 5.7, before being aggregated into the final `finalColor`. This shader enabled a more faithful representation of the object's original appearance.

Listing 5.6: Partial Fragment shader for blending original and restored textures.

```
half4 frag(Varyings IN) : SV_Target
{
    half4 decayAlbedo = SAMPLE_TEXTURE2D(_DecayTex, sampler_DecayTex, IN.uv);
    half4 restoredAlbedo = SAMPLE_TEXTURE2D(_RestoredTex, sampler_RestoredTex, IN.uv);

    float3 normalWS = normalize(IN.worldNormal);
    float3 viewDirWS = normalize(IN.viewDirWS);

    float fresnel = CalculateFresnel(normalWS, viewDirWS, _FresnelPower);

    half3 finalAlbedo = lerp(decayAlbedo.rgb, restoredAlbedo.rgb, _BlendFactor);
    half finalAlpha = lerp(decayAlbedo.a, restoredAlbedo.a, _BlendFactor);
```

[15] https://docs.unity3d.com/Packages/com.unity.render-pipelines.universal@14.0/manual/use-built-in-shader-methods-lighting.html

[16] https://docs.unity3d.com/Manual/urp/use-built-in-shader-methods-indirect-lighting.html

[17] https://docs.unity3d.com/6000.1/Documentation/Manual/urp/use-built-in-shader-methods-shadows.html

[18] https://docs.unity3d.com/Manual/urp/use-built-in-shader-methods-camera.html

[19] https://docs.unity3d.com/Manual/urp/use-built-in-shader-methods-transformations.html

[20] https://docs.unity3d.com/6000.2/Documentation/ScriptReference/Vector3.Lerp.html

[21] https://docs.unity3d.com/Packages/com.unity.shadergraph@6.9/manual/Fresnel-Effect-Node.html

```
        half finalSmoothness = lerp(_GlassSmoothness, _RestoredSmoothness, _BlendFactor);
        ... Populate Data...

        half3 glasslitColor = CalculateGlassLighting(surfaceData, inputData, fresnel);
        half enhancedAlpha = lerp(finalAlpha, finalAlpha * 0.5, fresnel * 0.5);

        return half4(glasslitColor, enhancedAlpha);
    }
```

Listing 5.7: Lighting Glass Texture Partial Calculation.

```
float3 CalculateGlassLighting(SurfaceData surfaceData, InputData inputData, float fresnel)
{
    Light mainLight = GetMainLight(inputData.shadowCoord, inputData.positionWS, inputData.shadowMask);
    ...

    float3 specular = specularTerm * mainLight.color * _SpecularColor.rgb * surfaceData.smoothness;
    ...

    float3 diffuse = lerp((surfaceData.albedo * mainLight.color * NdotL * 0.1), surfaceData.albedo, _BlendFactor);
    ...

    float3 environmentReflection = GlossyEnvironmentReflection(reflectionVector,
        inputData.positionWS, surfaceData.smoothness, 1.0) * _ReflectionIntensity;

    float3 finalColor = diffuse + (specular + environmentReflection * fresnel);

    return finalColor;
}
```

5.2.2.6 Object Outline

This functionality was implemented to improve the visibility of objects within the tomb and to distinguish them from the surrounding funerary ground. It essentially consists of an outline shader and a complementary script that manages its parameters. The shader highlights objects when targeted with the controller ray, as illustrated in Figure 5.8

The shader includes the following input parameters: *Outline Color*, *Outline Width*, *Outline Power*, and *Outline Softness*. Similar to the shader described for the Object Slider functionality in Section 5.2.2.5, this shader also relies on the Fresnel effect to control outline intensity and appearance.

The rendering of each object includes two materials: a primary material representing its texture and a secondary material responsible for the outline effect. When the user

Figure 5.8: Outline effect applied when an object is hited with the controller ray.

points at the object, the parameter `OutlineColor` is switched from yellow to blue. But if the object is not being grabbed (`if(!select)`), the outline disappears. This behavior is handled through hover events, as shown in Listing 5.8. By accessing the second material of the object via `meshRenderer.materials[1]`, the shader updates the outline color.

The fragment shader logic for the glowing outline is presented in Listing 5.9. It computes the Fresnel term with the Outline Power attribute, and applies a `smoothstep()` to achieve a soft personalized outline. This mechanism ensures that the objects are easily identifiable.

Listing 5.8: Partial class with Outline Color changed when the object is Hovered.

```
    public class GlowingObject : MonoBehaviour
{
    private MeshRenderer meshRenderer;
    private bool select = false;
    Color Yellow = new Color(65, 65, 0, 1);
    Color Blue = new Color(0, 59, 49, 1);
    ...
    public void OnHoverEnter()
    {
        meshRenderer.materials[1].SetColor("_OutlineColor", Blue);
    }

    public void OnHoverExit()
    {
        if(!select)
            meshRenderer.materials[1].SetColor("_OutlineColor", Yellow);
    }
    ...
}
```

Listing 5.9: Partial Fragment shader for creating an outline effect to the object.

```
      float4 frag(v2f i) : SV_Target
      {
         float3 N = normalize(i.normalWS);
         float3 V = normalize(i.viewDirWS);

         float fresnel = pow(1.0 - saturate(dot(N, V)), _OutlinePower);

         float edge1 = 1.0 - _OutlineWidth;
         float edge2 = edge1 + _OutlineSoftness;
         float outlineFactor = smoothstep(edge1, edge2, fresnel);

         return _OutlineColor * outlineFactor;
      }
```

5.2.2.7 Grab and Release Object

The artefacts can be grabbed with the lateral button of the controllers. When the object is grabbed or released, the corresponding event in Listing 5.10 is triggered.

The proximity of the controller's ray to the object determines how close the object appears to the user's view. Releasing the object is achieved simply by releasing the button. Small objects are automatically zoomed when hovered over or grabbed (operation `transform.localScale = zoomScale`), improving clarity and visibility during interaction.

Additionally, two other behaviors are implemented. The colliders that might interfere during grabbing are reactivated upon release, except when the user is inside the tomb, in which case a coroutine (`StartCoroutine`) is executed. During `OnGrab`, and as illustrated in Figure 5.7, the object slider is repositioned depending on whether the object is grabbed with the left or right controller, controlled by the `CompareTag` method.

Listing 5.10: Partial Fragment of objects onGrab and onRelease events.

```

   private void OnGrab(SelectEnterEventArgs args)
   {
      transform.localScale = zoomScale;
      args.interactableObject.colliders.ForEach(collider => { collider.enabled = false; });
      ...
      var interactor = args.interactorObject.transform;
      if (interactor.CompareTag("left"))
      {
         follow.targetOffset = new Vector3(sliderRightxPos, follow.targetOffset.y, follow.targetOffset.z);
      }
```

```
        else if (interactor.CompareTag("right"))
        {
            follow.targetOffset = new Vector3(sliderLeftxPos, follow.targetOffset.y, follow.targetOffset.z);
        }
    }

    private void OnRelease(SelectExitEventArgs args)
    {
        transform.localScale = originalScale;
        args.interactableObject.colliders.ForEach(collider => { collider.enabled = true; });
        ...
        if (r.isInsideTomb)
        {
            StartCoroutine(DisableColliderRoutine(5f));
        }
        ...
    }
```

5.2.2.8 Funerary Enclosure Interaction

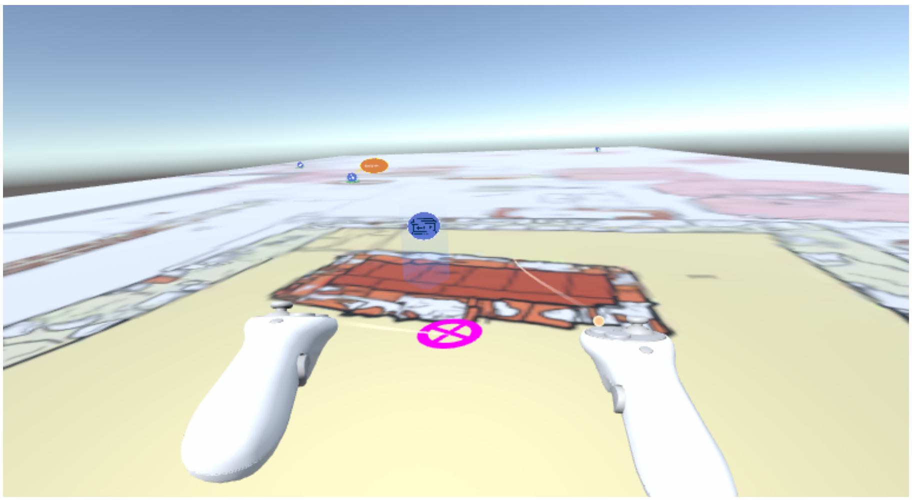


Figure 5.9: Funerary Enclosure Activation Reticle in the default ground plan.

The system provides the possibility to activate or deactivate the 3D model of the funerary enclosure. This functionality is triggered using the trigger button of the left command. When the user points to the funerary enclosure area in the map, a purple reticle appears, indicating that the enclosure can be activated, as illustrated in Figure 5.9. This interaction can be performed at any point during the experience.

To ensure realism, the funerary enclosure is implemented with a default *Mesh Collider* combined with an aggregated *Rigidbody*. This configuration prevents the user from crossing the enclosure walls and accurately reproduces the surface levels of the original structure, thereby enhancing the immersive experience.

An exception occurs when the user is inside the tomb. In this case, the funerary enclosure collider is temporarily disabled, allowing the user to descend naturally to the ground without obstruction. Once the user exits the tomb, the collider is restored to maintain consistent collision detection.

5.2.2.9 User Navigation

The user can navigate in the environment with the controllers. These allow two modes of movement: continuous walking, which simulates real-world locomotion, and teleportation, providing a faster way to reposition within the scene.

There are two types of teleportation available in the environment. The first allows the user to teleport freely to any position on the environment's ground plane (default *Teleportation Area* component). The second restricts teleportation to specific points of interest, marked with blue icons (anchors).

In addition to locomotion, users can switch their perspective inside the environment, using the controllers, moving laterally with the right joystick. Both continuous movement and snap turning can also be performed physically, without controllers, within the limits of the real-world space.

The overall movement system is managed by the *Character Controller* component, which also ensures accurate collision detection. In particular, the collider associated with the user interacts with the collider of the funerary enclosure, preventing the user from passing through walls and thereby preserving realism in the experience.

Further refinements and a dynamic management of movement behavior were introduced in the script "CustomMovement", where two key methods were implemented within Unity's default `Update()` function. The first method continuously updates the center of the character controller to reflect the user's current position during locomotion. The second manages custom movement behaviors by dynamically controlling gravity. Depending on the context, gravity may either be applied or disabled. When active, it influences the user's velocity over time, and its intensity can be adjusted dynamically.

5.2.2.10 Tomb Navigation Logic

To access the tomb, the user may either walk in continuous movement toward its interior or use teleportation by clicking on the blue anchor located in that area. Upon entering, the user will have a view similar to the one shown in Figure 5.11. The tomb contains triangular areas, that was the place where the majority of the objects were discovered. It's important to note that the artifacts are presented in the exact positions in which they were found during the excavations. During the dissertation process, different techniques were implemented and tested to address navigation and visualization challenges inside the tomb.

Figure 5.10: Tomb Exterior View with blue anchor inside.

Figure 5.11: Tomb Interior View with Objects positioned.

Plan Removal

The first approach used a collider placed inside the tomb. When the user collided with it, the ground plane was removed, revealing the full interior of the tomb.

This, in the end, caused conflicts because the interior collider overlapped with the collider responsible for activating the funerary enclosure.

To handle this issue, the limits of the tomb were defined manually. With this method, the plane disappears when the user enters that space and reappears once the user exits it. In Figure 5.10, the outside view of the tomb is depicted. As illustrated, the plane is disabled, providing full visibility of the tomb's interior.

Vertical Descend

Another challenge was ensuring that users could navigate naturally within the tomb while maintaining clear visibility of objects and architectural details inside. Standard gravity alone was insufficient, as it did not allow reliable interaction with objects located in triangular areas. To address this, the "TombNavigation" script was developed, introducing controlled vertical displacement along the y-axis.

Initially, a Raycasting approach was tested, directing rays toward the front and the floor of the tomb. When a collision was detected, the user's position was adjusted and lowered by a few centimeters. Although functional, this method is unreliable, as it heavily depends on the user's viewing direction, extracted from the camera position.

The final implementation instead defined the tomb interior using axis-based boundaries. When the user entered this delimited area, they were automatically displaced downward. Upon exiting, the user's position was restored to its correct height, ensuring they did not remain unnaturally below the expected level. This approach allows the user to enter and exit the tomb by simply walking.

During development, two alternative exit mechanisms, a block and a ladder, were added. However, these were later deactivated, as they were unnecessary with the finalized gravity-based solution and occupied additional space in the relatively small tomb environment. Nevertheless, both alternatives remain available for reactivation if required in the future.

5.2.3 Key Techniques

This section describes the main techniques implemented during the development process. The first two techniques focus on optimizing UX and improving system performance by significantly reducing the complexity of the funerary model, while preserving essential detail. The last two techniques detail the methodologies used to generate the glass material and the funerary 3D model.

5.2.3.1 Light Technique

There is a main directional light that illuminates the entire environment, simulating reality. However, it was understood that depending on the angle, the user might see the tomb and objects as 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.

5.2.3.2 Funerary Enclosure Model Reduction

The resolution of the burial site model was significantly reduced in *Agisoft Metashape* software through the "Decimate Model" property. This adjustment was necessary due to warnings of potential collision issues arising from 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.

5.2.3.3 Generating the Glass Texture

The process of generating the glass texture consisted of two phases.

First, the material was modeled in Blender using a node-based shader structure. The desired glass effect was achieved by combining the `Glossy BSDF` and `Refraction BSDF` nodes. It also received a `Fresnel` node as input[22]. This structure is represented in Figure 5.12.

After having the node structure, a UV unwrapping[23] was made to prepare the 3D object surface for texture mapping, process illustrated in Figure 5.13. Finally, a baking process[24] was performed using the Cycles render engine. With these materials, a "Combined" texture was baked and imported to Unity as a .png file.

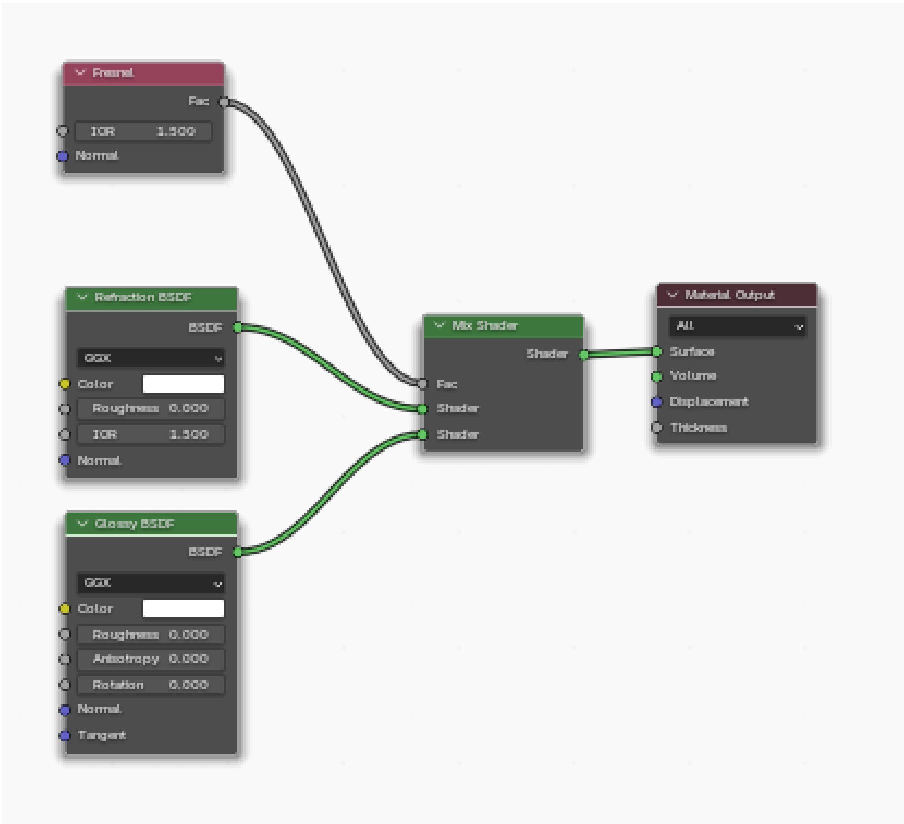


Figure 5.12: Glass Material Nodes Blender.

In Unity, one **Reflection Probe** for each object was added to simulate the environment's reflection on the glass surface. Additionally, the four attributes *_GlassSmoothness*, *_FresnelPower*, *_SpecularColor*, and *_ReflectionIntensity*, used in the slider shader in Section

[22] https://docs.blender.org/manual/en/latest/render/shader_nodes/index.html
[23] https://docs.blender.org/manual/en/latest/modeling/meshes/uv/unwrapping/
[24] https://docs.blender.org/manual/en/latest/render/cycles/baking.html

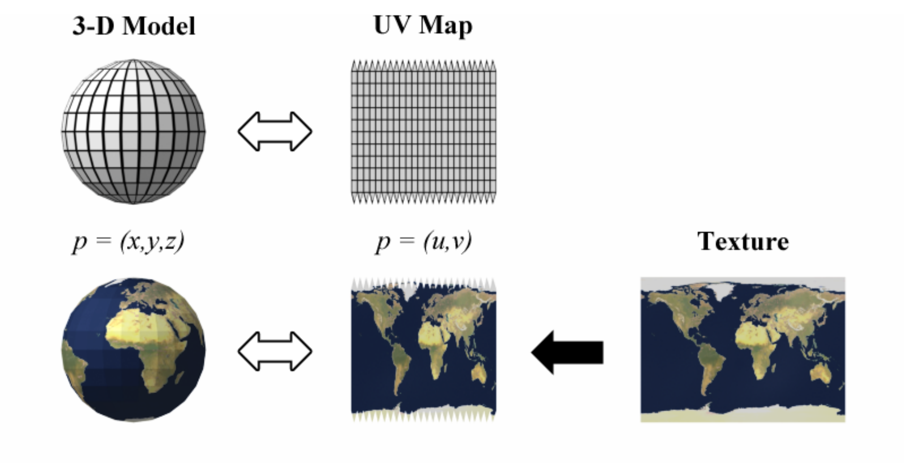


Figure 5.13: UV unwrapping process with corresponding mapped texture.

5.2.2.5, can be adjusted to control the pretended reflections in the glass. The final glass texture exemplifying one object is illustrated in Figure 5.14.

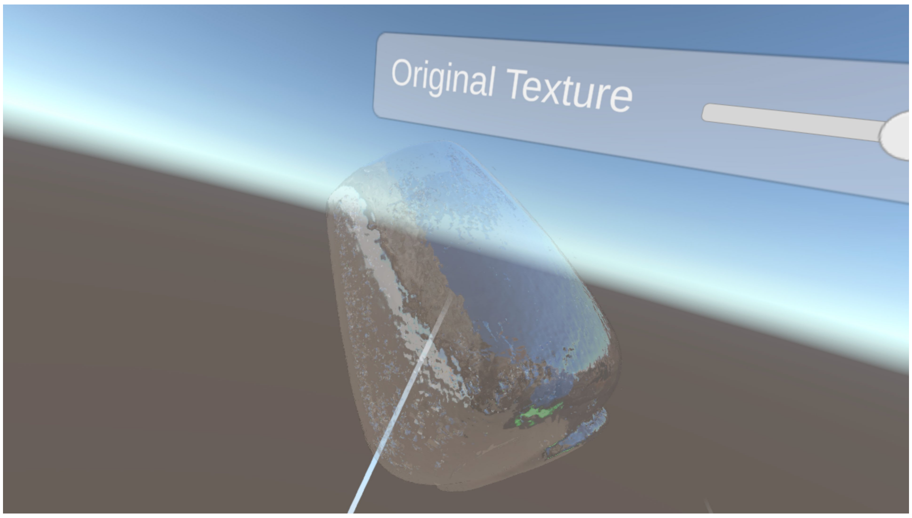


Figure 5.14: Glass Texture of Object with ID 21684.

5.2.3.4 Generating the Funerary 3D Model

The funerary enclosure model was generated with the support of the photogrammetric survey and subsequently imported into the *Sketchfab* viewer for intuitive interaction. Within the grave, three open triangular areas were identified, containing the precious artefacts of the deceased, as shown in Figure 5.15 below.

This phase used the *Agisoft Metashape* to stitch together photographs and capture the geometry, texture, and visual characteristics of the physical funerary structure.

The workflow began with the Align Photos operation, which produced 91,053 tie points. Then, a dense point cloud was generated to refine the level of detail, followed by the creation of a 3D mesh. The resulting model comprised 1,910,026 faces, for which a texture was mapped. Finally, the model was exported in `.obj` format, and grouped with `.png` texture files, and imported into the Unity VR environment.

Figure 5.15: 3D Model in Sketchfab.

5.2.4 Testing and Debugging

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.

During the development, the functionalities within the environment were tested in real-time using the *MetaLink* app. However, when connected via Wi-Fi, the environment did not load correctly. This issue was resolved by employing a wired connection.

Additionally, debugging was performed with the Visual Studio debugger and Android Debug Bridge (adb). This second tool enabled a in-depth troubleshooting and the identification of issues in the interaction with the headset by accessing detailed system logs through the `adb logcat` command. The logs proved useful for tracing errors and understanding their source during testing.

6

User Evaluation

This chapter introduces the user evaluation conducted in the scope of this dissertation. Section 6.1 describes the methodology and procedures adopted for the evaluation, while Section 6.2 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.

6.1 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 6.1, 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 6.1, the average time spent was around 10 minutes, with the exception of faster users and three cases where the application had to be restarted after users fell out of the environment, which increased the experience time.

6.1.1 User Testing Setup

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.

After the initial setup with a USB connection, an **Android build** was generated in Unity, producing an *.apk* file that allowed the application to run natively on the headset without requiring a cable. This provided greater flexibility during the evaluation. The *Meta Quest Developer Hub* application was then used to transfer the *.apk* file to the headset.

Figure 6.1: User Testing the VR Environment with the HMD and controllers.

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.

6.2 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.

Table 6.1: Registered Times spent by each Participant to Execute the provided Tasks.

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

6.2.1 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.

The bar plot in Figure 6.2 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 6.3.

In the pie chart of Figure 6.4, 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.

In Figure 6.5, a horizontal bar plot illustrates the distribution of participants' technical backgrounds. The areas are ordered in descending frequency, with priority given to those

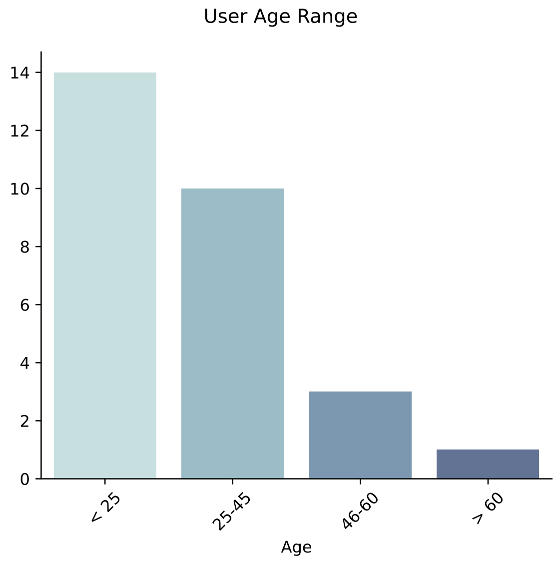


Figure 6.2: Age Distribution of the Test Participants.

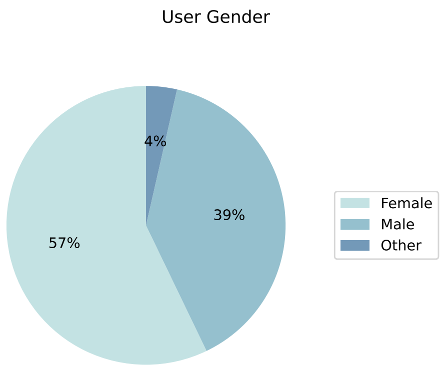


Figure 6.3: Gender Distribution of the Test Participants.

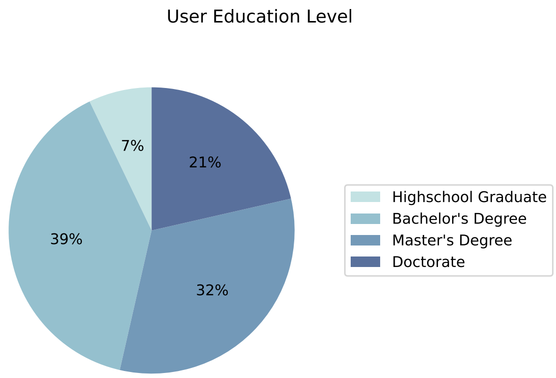


Figure 6.4: Education Level Distribution of the Test Participants.

most relevant for this thesis. This results in a meaningful sample, comprising mainly technology developers, specialists in conservation and restoration, and archaeologists

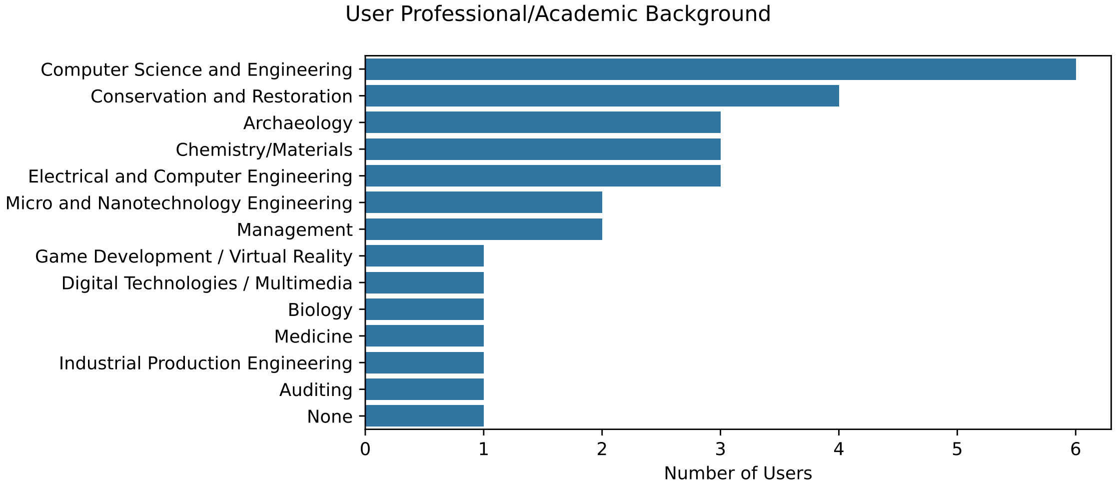


Figure 6.5: Distribution of Training Levels among Participants.

working in contexts comparable to the site under study.

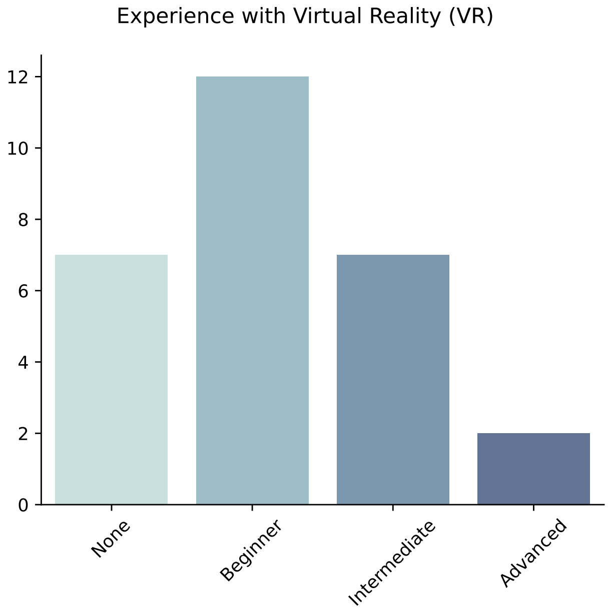


Figure 6.6: VR Experience Levels among Participants.

As illustrated in Figure 6.6, it is evident that the majority of the participants have prior experience with VR, while only a small portion are experts.

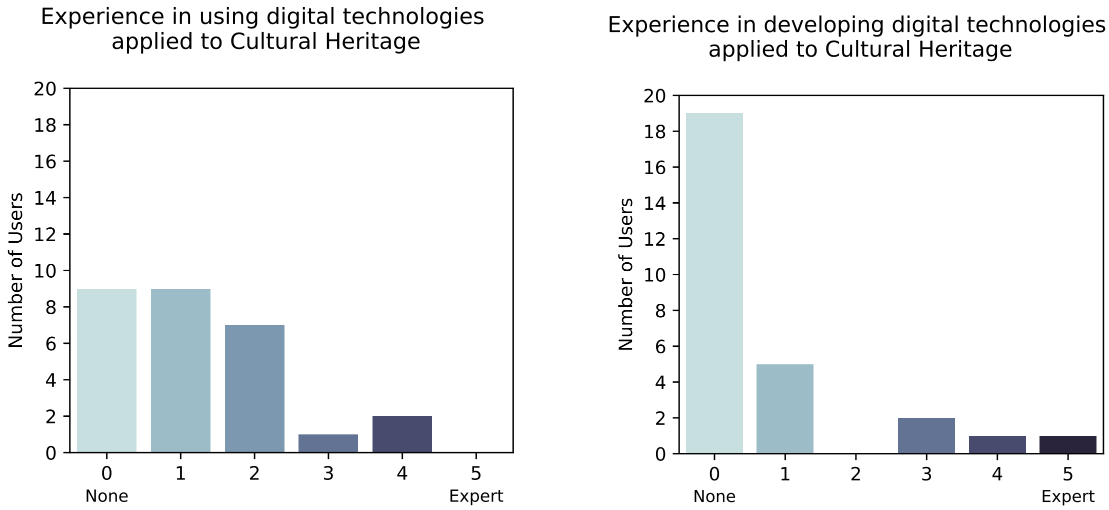


Figure 6.7: Participants' Experience with Digital Technologies Applied to CH.

The two distributions in Figure 6.7 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.

6.2.2 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.

Analyzing the graph in Figure 6.8, 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 6.3.1.

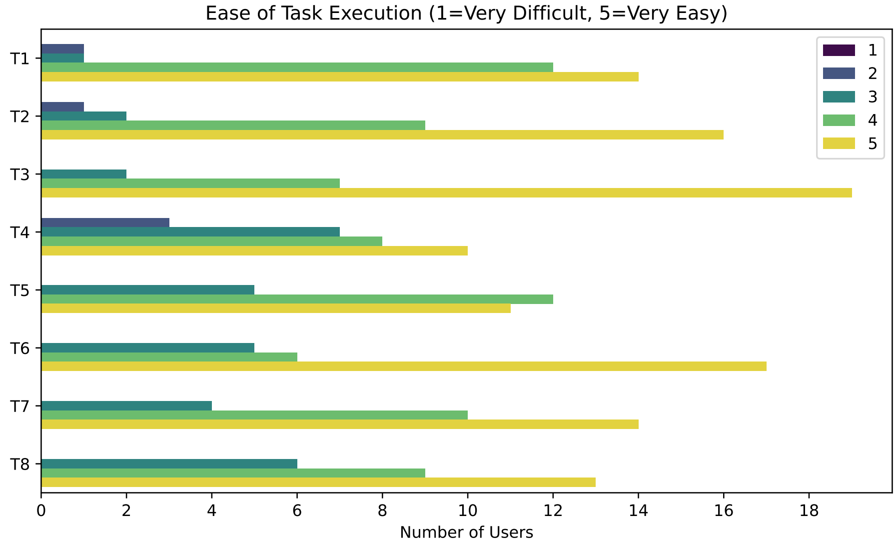


Figure 6.8: Perceived Task Ease among Participants.

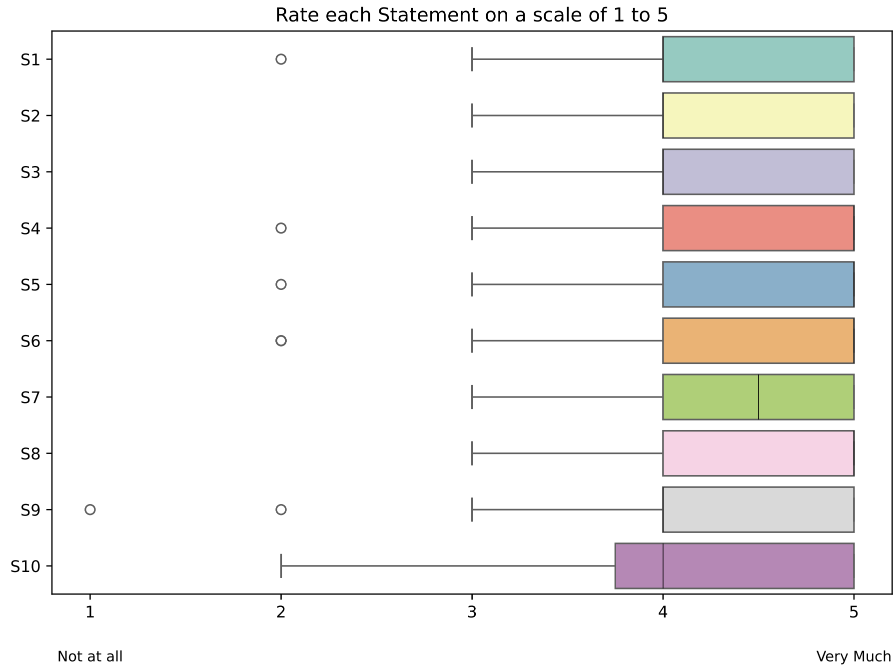


Figure 6.9: Participants' Agreement with Task-Related Statements.

The results shown in Figure 6.9 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.

6.2.3 Presence Questionnaire (PQ)

The evaluation of presence was conducted using the Portuguese validated version of the Presence Questionnaire, adapted by Vasconcelos-Raposo et al. [46] 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. [51] 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.

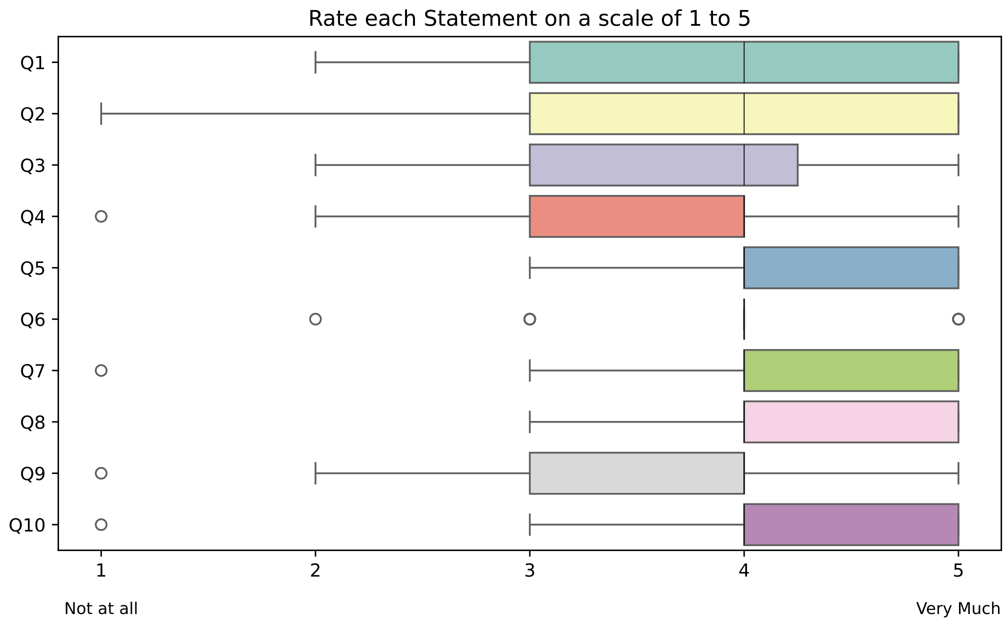


Figure 6.10: Perceived Sense of Presence among Participants.

It is represented in Figure 6.10 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 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.

6.2.4 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

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

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. [39]. These items are grouped into two meta-dimensions, illustrated in Figure 6.11: 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.

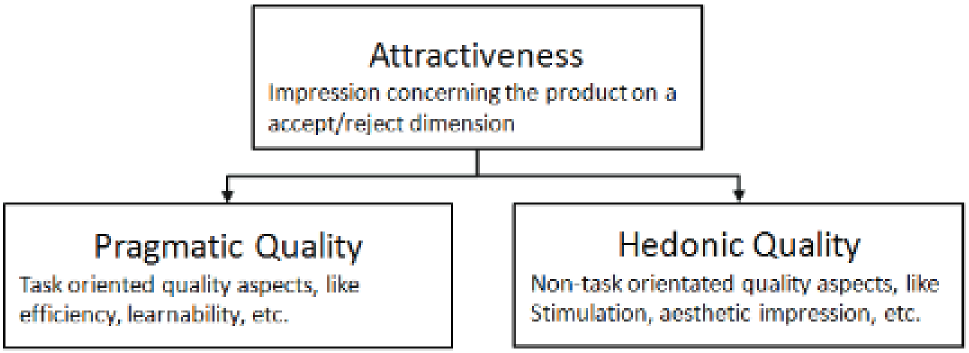


Figure 6.11: Grouping of the two quality attributes [35].

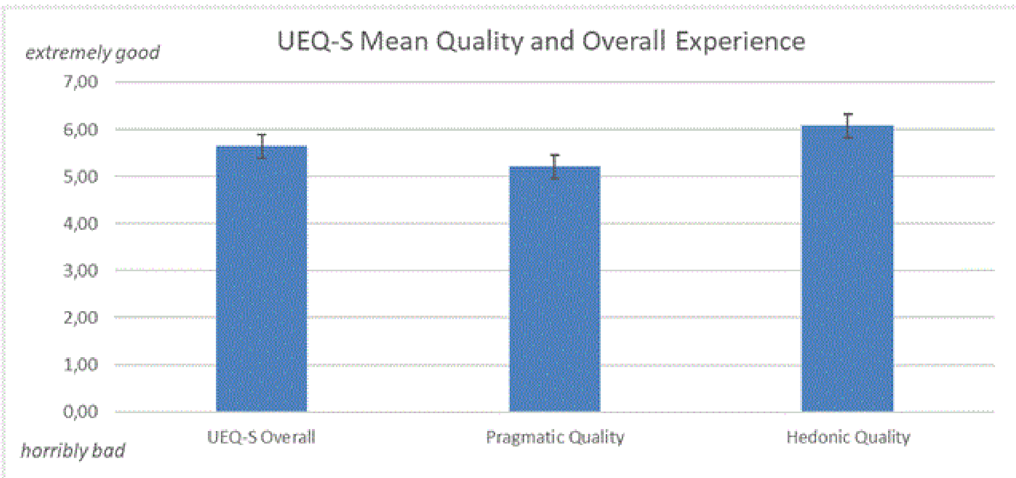


Figure 6.12: Overview of the UEQ Evaluation Distribution among Test Participants.

The UEQ results, as demonstrated in Figure 6.12, 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 6.13 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: Pragmatic or Hedonic Quality. Table 6.2 supports this graphic with this and more relevant

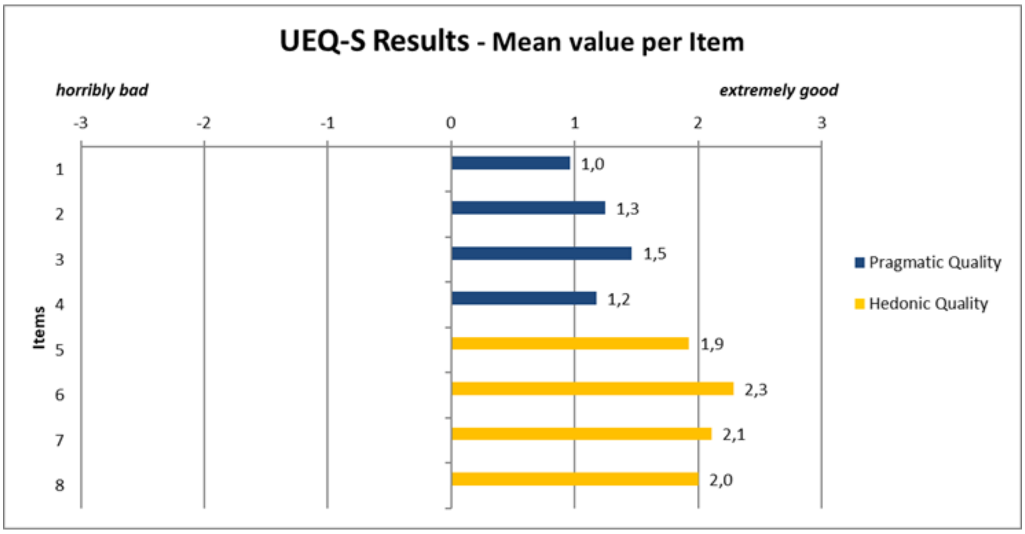


Figure 6.13: Mean value of UEQ Items of the Participants' Experience.

Table 6.2: UEQ Items, their Mean responses, Standard Deviations, and the corresponding Opposite Pairs by Scale.

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

information of the UEQ used.

6.2.5 Graphics Comparison

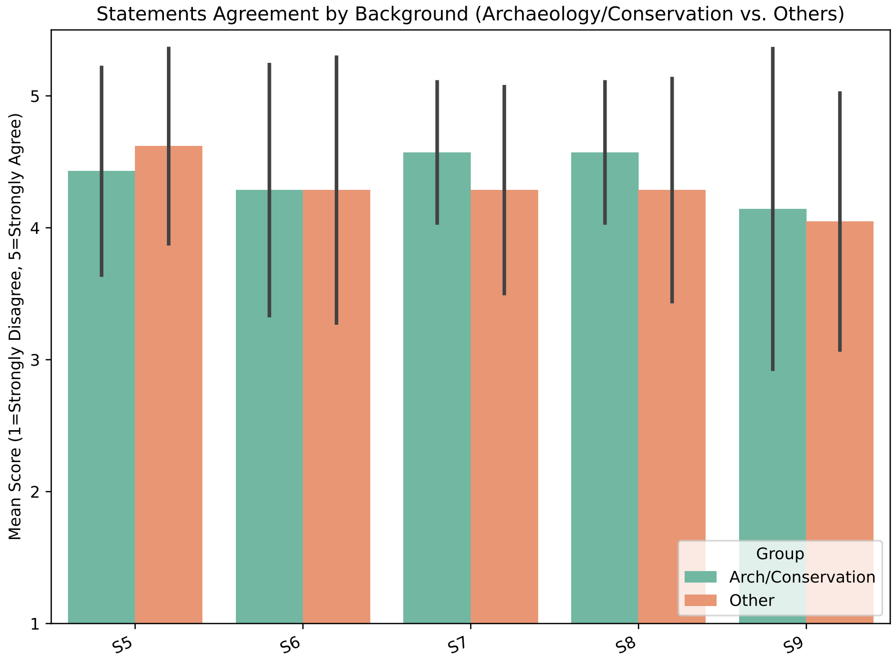


Figure 6.14: Comparison between Participant Groups, regarding Agreement with Statements about their Experience.

The graph illustrated in Figure 6.14 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 6.9, 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.

The results presented in Figure 6.15 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

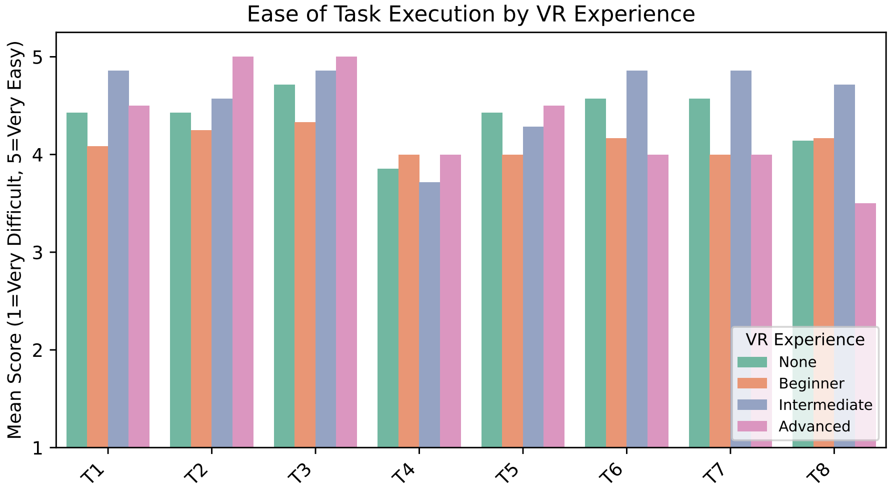


Figure 6.15: Ease of Task Execution according to Participants' VR Experience.

in T1, T6, T7, and T8). This outcome may be explained by the fact that, as illustrated in Figure 6.6, only two participants were classified as "Advanced", representing a very small sample that may not provide fully reliable results.

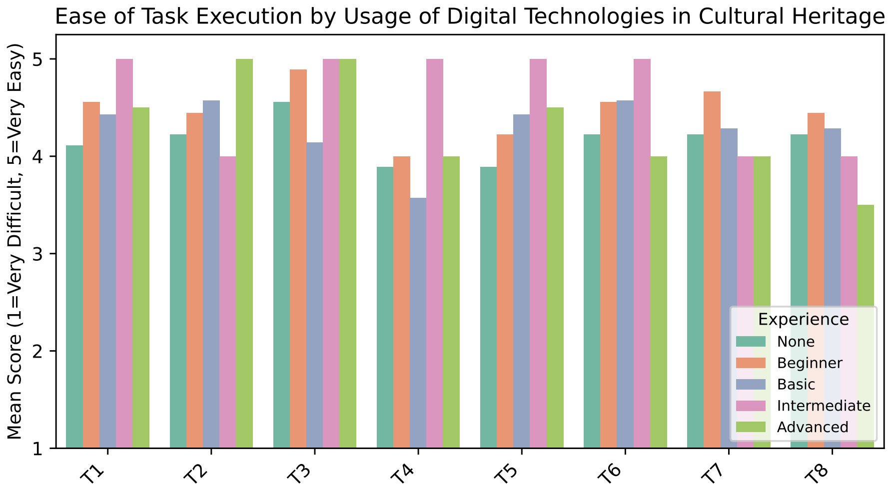


Figure 6.16: Ease of Task Execution according to Participants' Experience with Technologies applied to CH.

The bar chart in Figure 6.16 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 6.17, 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.

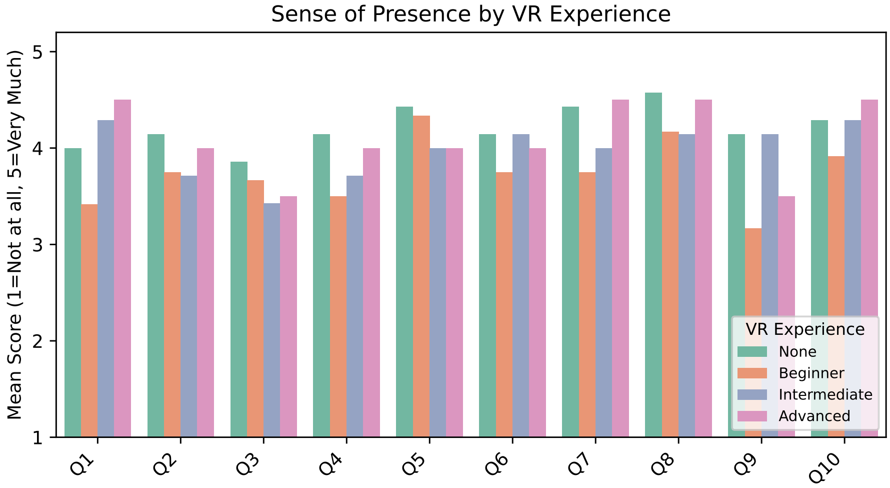


Figure 6.17: Participants' reported Sense of Presence according to their VR Experience.

6.3 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 6.8. 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 6.2.5, 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.

6.3.1 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.
- Original Glass Texture Improvements: Adjusted parameters for object ID 2676. Enhanced the realism of the texture by adding a slight blue tint, as experts indicated that these Roman glasses tended to have a bluish hue.
- Tomb Interaction: Improved the definition of the tomb limits, increasing the coordinate precision on both sides.

7

Conclusions

The last chapter begins with a conclusion of the results achieved and functionalities developed, and their alignment with the intended goals, in Section 7.1. Section 7.2 then enumerates possible future improvements, identifies limitations, and new ideas that could further evolve the system and provide a more complete user experience.

7.1 Final Overview

The system was developed with careful attention to the special Cultural Heritage artifacts and monuments of the archaeological site of Troia. The concept of a Digital Twin was considered throughout the project, aiming to provide a virtual representation of real objects and, in the case of the funerary enclosure, a reconstructed immersive space within the tomb that preserved the context of the artifacts. Another important outcome of this project was the dissemination of developments: a short paper has been written and will be published soon. The system provided an engaging user experience by displaying informative content through data panels. It also offered interactive features, such as grabbing objects, map teleport and exploration, and navigating within the realistic 3D funerary enclosure. Users often perceived the experience as finished after these interactions, even before opening the *Panel UI* for additional exploration.

Among the implemented features, the *Object Slider*, which allowed a gradual transition control in a slider bar between the original and restored states of an object, is one of the most innovative features of this work. This combination of immersion in an environment with artifacts, map layers, and cultural learning of the system fosters a meaningful engagement with heritage content.

As this dissertation represents the beginning of a broader project, there was some freedom in defining the primary focus of this study. The implementation concentrated on developing functionalities that enhanced immersion and interaction within the VR environment. The development in Unity was the tool that was dedicated the most time during the implementation phase. The custom scripts focused primarily on user navigation within the plane, including tombstones, interaction with objects, and interaction with the data panels containing images before and after the intervention, as well as text, and interaction with the dropdown and checkboxes. The repository was designed as a parallel focus. A base structure with 11 tables was created, although only two tables, “object” and “object_intervention”, were used in this study. The communication between Unity and the Postgres database was established through a *Node.js* backend, which implemented two requests. These enabled data exchange between Unity and the database using `UnityWebRequest`. The artifact attributes stored in the database were ensured to be technically correct with conservation and restoration specialists.

Some external tools supported the technical pipeline and imported them to Unity. The *AgisoftMetashape* was employed in two key moments. At the beginning of the implementation, to generate the funerary enclosure 3D model with its associated texture. And at the end of the development phase, to perform the "Decimation", and to optimize the model size for efficiency. Additionally, the use of the *Blender* tool was a challenge for designing a simulation of the original glass texture, given the limited references and experience.

The user evaluation and feedback played a crucial role in validating the system. Moreover, several minor improvements were made after the user evaluation phase. These modifications focused on aspects of the UI and subtle interaction details that only became evident through user testing. Also, receiving feedback from domain experts was essential. The evaluation results, analyzed with supporting graphics in Chapter 6, confirmed a generally positive experience, and users gave interesting suggestions for future environment improvements.

7.2 System Limitations and Future Work

As this dissertation represents a first step toward a broader project, several future improvements are interesting. Some were identified during development, while others emerged from user feedback during the evaluation phase. These ideas are summarized below:

User Interaction

- **Hand Tracking vs Controllers:** Possibility to replace the controller-based interaction with hand tracking to provide a more natural and immersive experience, which would be particularly helpful for users less familiar with controllers.

- **Object Proximity Control:** Introduce a mechanism that allows users to control the distance they want when an object is grabbed. Currently, the distance is determined by how close the controller ray is when the user grabs the object.

- **Object Identification:** In the future, it would be interesting if, when grabbing an object, it would display object data when an object is grabbed, which would be more intuitive and easier to understand. An implementation had been tried, but not concluded, that consisted of showing the object's measurements in 3D when grabbed.

- **Tomb Navigation Control:** Add, for example, a button that explicitly places the user inside or outside the tomb to avoid the user entering the tomb when it is not wanted.

- **Plan Limits:** Add some warning safety bay, or a safety sign, or disable gravity outside the plan, to prevent users from falling off the plan.

User Interface

- **Dynamic Panels:** Allow Panel UI and Main Menu to open relative to the user's position and be repositioned dynamically, instead of remaining static. Additionally, the possibility for the user to move the Panel to another side if they desire.

- **Main Menu Improvements:** Expand the menu with additional options and improve usability.

- **Panel UI:** Possibility to view more details data, returning more information already stored in the database, adding more backend requests to the system. Additionally, integrate in the Panel UI a link to related excavation findings or museum artifacts. This feature was developed and is working, but an additional paid library, such as 3D WebView[1] would be needed to open the link to the parallel museums with these findings. With the implementation made, the link only opens in the computer browser.

- **Search and Filter Features:** Add users search and filter objects details feature based on fields, such as time period, shape, and provenance.

Environment & Immersion

- **Expand Environment:** Add more 3D object models and have further points of interest with 3D models across the map.

- **Sound Design:** Provide a more complete experience with sounds, such as footsteps, ambient audio, and UI interaction effects. It already exists in some functionalities, but it is very little because it was not a priority.

- **Geospatial Data Integration:** Incorporate GIS layers, and georeferencing for richer spatial context, for example, in the excavation process, or objects location.

- **Extended Map Interaction:** Extend and improve map interaction, such as uploading an object after clicking on a position in the map and saving it in the "Location" table,

[1] https://developer.vuplex.com/webview/overview

or an Algorithm to find the best route for the visit and provide directions, such as using direction arrows to guide users to historically significant locations.

Repository & Data Management

- **Document Upload/Download:** Allow contributors to upload images, videos, or excavation reports of the archaeological intervention.
- **Digital Preservation:** Add the usage of standard formats for the CH information stored in the database, such as the CIDOC-CRM, approached in the Chapter 2, Section 2.5.1.

Bug Fixes

- **Reticles Bug:** Address the issue of duplicate pink reticles appearing in the headset when the user is looking forward.

Bibliography

[1] Academia das Ciências de Lisboa. *Academia das Ciências de Lisboa inaugura visita virtual interativa*. https://www.acad-ciencias.pt/2024/09/04/academia-das-ciencias-de-lisboa-inaugura-visita-virtual-interativa/. Accessed: 2025-01-20. 2024 (cit. on p. 26).

[2] D. Arca, D. Z. Seker, M. Alkan, S. Karakıs, C. Bayık, and H. Acar. "Development of web-based GIS for the cultural heritage of safranbolu, Turkey". In: *International Journal of Environment and Geoinformatics* 5.3 (2018), pp. 368–377 (cit. on p. 22).

[3] J. Baqersad, P. Poozesh, C. Niezrecki, and P. Avitabile. "Photogrammetry and optical methods in structural dynamics – A review". In: *Mechanical Systems and Signal Processing* 86 (2017), pp. 17–34. DOI: 10.1016/J.YMSSP.2016.02.011 (cit. on p. 12).

[4] M. Campanha. "Developing Support for Digital Representations of Heritage Artefacts in Cultural Exhibitions". MSc Dissertation in Computer Science. Universidade NOVA de Lisboa, 2024 (cit. on pp. 25, 27).

[5] R. Carey. "The virtual reality modeling language explained". In: *IEEE MultiMedia* 5.3 (1998), pp. 84–93. DOI: 10.1109/93.713310 (cit. on p. 23).

[6] J. Coimbra. "Designing and implementing a museum Virtual Tour". MSc Dissertation in Computer Science. Universidade NOVA de Lisboa, 2024 (cit. on pp. 25, 26).

[7] M. Cota, J. Thomaschewski, M. Schrepp, and R. Gonçalves. "Efficient Measurement of the User Experience. A Portuguese Version". In: *Procedia Computer Science* 27 (2014-12). DOI: 10.1016/j.procs.2014.02.053 (cit. on p. 68).

[8] E. Dezen-Kempter, D. L. Mezencio, E. D. M. Miranda, D. P. De Sãi, and U. Dias. "Towards a digital twin for heritage interpretation". In: *RE Anthr. Des. Age Humans: Proc. 25th Int. Conf. Comput. Archit. Des. Res. Asia, CAADRIA 2020*. Vol. 2. 2020, pp. 183–191. DOI: 10.1007/978-981-99-0337-5_35 (cit. on p. 7).

[9] M. Doerr, C.-E. Ore, and S. Stead. "The CIDOC conceptual reference model-A new standard for knowledge sharing ER2007 tutorial". In: *26th international conference on conceptual modeling (ER 2007)*. 2007. DOI: 10.13140/2.1.1420.6400 (cit. on p. 18).

[10] O. Eide, A. Felicetti, C. E. Ore, A. D'Andrea, J. Holmen, et al. "Encoding cultural heritage information for the semantic web. procedures for data integration through cidoc-crm mapping". In: *EPOCH Conference on Open Digital Cultural Heritage Systems*. 2008, pp. 1–7 (cit. on p. 17).

[11] European Commission. *EU Policy for Cultural Heritage*. Accessed: 2025-01-30. URL: https://culture.ec.europa.eu/cultural-heritage/eu-policy-for-cultural-heritage (cit. on p. 5).

[12] European Commission. *European Digital Heritage*. Accessed: 2025-01-30. URL: https://culture.ec.europa.eu/cultural-heritage/cultural-heritage-in-eu-policies/european-digital-heritage (cit. on p. 5).

[13] N. Faria. "Web Integration of Virtual Museum Tours and 3D Media Visualization". MSc Dissertation in Computer Science. Universidade NOVA de Lisboa, 2024 (cit. on pp. 25, 26).

[14] A. Ferreira, C. Wohlmuth, A. Rodrigues, and N. Correia. "Plataforma Multimédia Interativa: Experiência imersiva da Paisagem Sonora Histórica de Évora". In: ed. by V. de Sá, R. de Paula, A. F. Conde, and A. Gouveia. Vol. I. húmus, 2021-04, pp. 313–335. ISBN: 978-989-755-688-3. URL: https://research.unl.pt/ws/portalfiles/portal/44478809/Sonoridades_Eborenses.pdf (cit. on p. 25).

[15] S. Gonizzi Barsanti, G. Caruso, L. Micoli, M. Covarrubias, and G. Guidi. "3D Visualization of Cultural Heritage Artefacts with Virtual Reality devices". In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W7 (2015-08), pp. 165–172. DOI: 10.5194/isprsarchives-XL-5-W7-165-2015 (cit. on p. 23).

[16] M. Grieves and J. Vickers. "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems". In: *Transdisciplinary perspectives on complex systems: New findings and approaches* (2017), pp. 85–113 (cit. on p. 7).

[17] M. Haindl and M. Sedláček. "Virtual reconstruction of cultural heritage artifacts". In: *2016 International Workshop on Computational Intelligence for Multimedia Understanding (IWCIM)*. 2016, pp. 1–5. DOI: 10.1109/IWCIM.2016.7801178 (cit. on p. 15).

[18] K. S. Hale and K. M. Stanney. *Handbook of virtual environments: Design, implementation, and applications*. CRC Press, 2014, pp. 23–24, 33, 293–304, 932–933 (cit. on pp. 7, 8, 17).

[19] J.-C. Hocquet. *Fish and Ships. Production et commerce des" Salsamenta" durant l'Antiquité, Actes de l'atelier doctoral, coll.«Bibliothèque d'archéologie méditerranéenne et africaine»*. 2015 (cit. on p. 2).

[20] S. Islam, M. S. Tanvir, M. Habib, T. Tashrif, M. A. Ahmed, T. Ferdous, M. Arefin, and S. Alam. "Autonomous Driving Vehicle System Using LiDAR Sensor". In: *Hemanth, D.J., Pelusi, D., Vuppalapati, C. (eds) Intelligent Data Communication Technologies and Internet of Things*. Singapore: Springer, 2022. DOI: 10.1007/978-981-16-7610-9_25 (cit. on pp. 13, 16).

[21] P. Jouan and P. Hallot. "Digital twin: Research framework to support preventive conservation policies". In: *ISPRS International Journal of Geo-Information* 9.4 (2020), p. 228. DOI: doi.org/10.3390/ijgi9040228 (cit. on p. 8).

[22] B. Laugwitz, T. Held, and M. Schrepp. "Construction and Evaluation of a User Experience Questionnaire". In: vol. 5298. 2008-11, pp. 63–76. ISBN: 978-3-540-89349-3. DOI: 10.1007/978-3-540-89350-9_6 (cit. on p. 67).

[23] N. Li, C. P. Ho, J. Xue, L. W. Lim, G. Chen, Y. H. Fu, and L. Y. T. Lee. "A progress review on solid-state LiDAR and nanophotonics-based LiDAR sensors". In: *Laser & Photonics Reviews* 16.11 (2022), p. 2100511. DOI: 10.1002/lpor.202100511 (cit. on pp. 13, 14).

[24] W. Linder. *Digital Photogrammetry: A Practical Course (4th ed.)* Springer, 2016. ISBN: 978-3-662-50463-5 (cit. on p. 12).

[25] J. M. Lourenço. *The NOVAthesis LaTeX Template User's Manual*. NOVA University Lisbon. 2021. URL: https://github.com/joaomlourenco/novathesis/raw/main/template.pdf (cit. on p. i).

[26] T. Luhmann, C. Fraser, and H.-G. Maas. "Sensor modelling and camera calibration for close-range photogrammetry". In: *ISPRS Journal of Photogrammetry and Remote Sensing* 115 (2016), pp. 37–46. DOI: 10.1016/j.isprsjprs.2015.10.006 (cit. on p. 13).

[27] J. McCarthy. "Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement". In: *Journal of Archaeological Science* 43 (2014), pp. 175–185. DOI: 10.1016/j.jas.2014.01.010 (cit. on p. 12).

[28] P. Milgram and F. Kishino. "A taxonomy of mixed reality visual displays". In: *IEICE TRANSACTIONS on Information and Systems* 77.12 (1994), pp. 1321–1329 (cit. on p. 11).

[29] M. Murphy, E. Mcgovern, and S. Pavía. "Historic building information modelling (HBIM)". In: *Structural Survey* 27 (2009-08), pp. 311–327. DOI: 10.1108/02630800910985108 (cit. on p. 7).

[30] T. Nunes. "Creating an improved and immersive visitor experience for museums". MSc Dissertation in Computer Science. Universidade NOVA de Lisboa, 2023 (cit. on p. 27).

[31] U. S. G. A. Office. *Geospatial Information: OMB and Agencies Need to Make Coordination a Priority to Reduce Duplication*. Accessed: 2025-02-09. 2012-11. URL: https://www.gao.gov/products/GAO-13-94 (cit. on p. 16).

[32] Permanent Delegation of Portugal to UNESCO. *Roman Production Centre of Fish Salting and Conservation in Troia*. Accessed: 2025-02-09. 2017. URL: https://whc.unesco.org/en/tentativelists/6223 (cit. on p. 2).

[33] I. V. Pinto, A. P. Magalhães, and P. Brum. "A reassessment of the fish-salting workshops 1 and 2 of Tróia (Portugal): the ceramic contexts". In: *Rei Cretariae Romanae Fautorum Acta* 45 (2018), pp. 153–162 (cit. on p. 2).

[34] I. V. Pinto, A. P. Magalhães, and P. Brum. "Ruínas Romanas de Tróia: A valorização de um património singular". In: *Musa Mus. Arqueol. E Outros Patrimónios* 4 (2014), pp. 29–40 (cit. on p. 2).

[35] M. Rauschenberger, M. Schrepp, M. Cota, S. Olschner, and J. Thomaschewski. "Efficient Measurement of the User Experience of Interactive Products. How to use the User Experience Questionnaire (UEQ). Example: Spanish Language Version". In: *International Journal of Interactive Multimedia and Artificial Intelligence* 2 (2013-03), pp. 39–45. DOI: 10.9781/ijimai.2013.215 (cit. on p. 68).

[36] A. Rodrigues and N. Correia. "Using technology in digital humanities for learning and knowledge dissemination". In: *Revista EducaOnline* 15.2 (2021), pp. 27–44 (cit. on p. 25).

[37] J. Rosário and et al. "A Responsive Platform for the Auditory Atlas of Évora". In: *Paisagens Sonoras históricas*. Ed. by A. F. Conde and et al. Publicações do CIDEHUS, 2021. DOI: 10.4000/books.cidehus.17810. URL: https://doi.org/10.4000/books.cidehus.17810 (cit. on p. 25).

[38] J. Schindling and C. Gibbes. "LiDAR as a tool for archaeological research: a case study". In: *Archaeological and Anthropological Sciences* 6 (2014-12). DOI: 10.1007/s12520-014-0178-3 (cit. on p. 16).

[39] M. Schrepp, A. Hinderks, and J. Thomaschewski. "Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S)". In: *International Journal of Interactive Multimedia and Artificial Intelligence* 4 (2017-01), p. 103. DOI: 10.9781/ijimai.2017.09.001 (cit. on p. 68).

[40] W. R. Sherman and A. B. Craig. "Chapter 5 - Output: Interfacing the Virtual World With the Participant(s)". In: *Understanding Virtual Reality (Second Edition)*. Ed. by W. R. Sherman and A. B. Craig. Second Edition. The Morgan Kaufmann Series in Computer Graphics. Boston: Morgan Kaufmann, 2019, pp. 258–396. ISBN: 978-0-12-800965-9. DOI: 10.1016/B978-0-12-800965-9.00005-2 (cit. on pp. 10, 11).

[41] N. G. Society. *GIS (Geographic Information System)*. Ed. by E. E. Jeannie Evers. 2024. URL: https://education.nationalgeographic.org/resource/geographic-information-system-gis/ (cit. on p. 15).

[42] J. Soler-Dominguez, C. de Juan Ripoll, M. Contero, and M. Alcañiz Raya. "I walk, therefore I am: a multidimensional study on the influence of the locomotion method upon presence in virtual reality". In: *Journal of Computational Design and Engineering* 7 (2020-04), pp. 1–14. DOI: 10.1093/jcde/qwaa040 (cit. on p. 10).

[43] A. Spreafico, F. Chiabrando, and C. Della Coletta. "3D WEBGIS APPLICATIONS FOR DIGITAL HUMANITIES STUDIES: THE TURIN 1911 PROJECT". In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLVIII-M-2-2023 (2023-06), pp. 1501–1508. DOI: 10.5194/isprs-archives-XLVIII-M-2-2023-1501-2023 (cit. on pp. 11, 21).

[44] R. Stone and T. Ojika. "Virtual heritage: what next?" In: *IEEE MultiMedia* 7.2 (2000), pp. 73–74. DOI: 10.1109/93.848434 (cit. on p. 7).

[45] L. Tolley. "UH Research Team Uses Airborne LiDAR to Unveil Possible Honduran Archaeological Ruins". In: (2012-06). URL: https://www.uh.edu/news-events/ (cit. on p. 16).

[46] J. Vasconcelos-Raposo, M. Melo, L. Barbosa, C. Teixeira, L. Cabral, and M. Bessa. "Assessing presence in virtual environments: adaptation of the psychometric properties of the Presence Questionnaire to the Portuguese populations". In: *Behaviour & Information Technology* 40.13 (2021), pp. 1417–1427. DOI: 10.1080/0144929X.2020.1754911. eprint: https://doi.org/10.1080/0144929X.2020.1754911. URL: https://doi.org/10.1080/0144929X.2020.1754911 (cit. on p. 67).

[47] J. Vilar. "Sistema para Criação e Exploração de Narrativas Interativas e Jogos". MSc Dissertation in Computer Science. Universidade NOVA de Lisboa, 2022 (cit. on p. 25).

[48] J. Vilar, A. Rodrigues, and N. Correia. "An Extended Reality Platform for Cultural Gaming: Enabling Interactive Narratives in Spatial Contexts". In: *J. Comput. Cult. Herit.* 17.4 (2024-12). ISSN: 1556-4673. DOI: 10.1145/3702484. URL: https://doi.org/10.1145/3702484 (cit. on p. 25).

[49] A. R. Willis and D. B. Cooper. "Computational reconstruction of ancient artifacts". In: *IEEE Signal processing magazine* 25.4 (2008), pp. 65–83. DOI: 10.1109/MSP.2008.923101 (cit. on p. 14).

[50] F. Windhager, P. Federico, G. Schreder, K. Glinka, M. Dörk, S. Miksch, and E. Mayr. "Visualization of Cultural Heritage Collection Data: State of the Art and Future Challenges". In: *IEEE Transactions on Visualization and Computer Graphics* 25 (2019), pp. 2311–2330. DOI: 10.1109/TVCG.2018.2830759 (cit. on p. 6).

[51] B. G. Witmer and M. J. Singer. "Measuring Presence in Virtual Environments: A Presence Questionnaire". In: *Presence: Teleoperators and Virtual Environments* 7.3 (1998-06), pp. 225–240. DOI: 10.1162/105474698565686. eprint: https://direct.mit.edu/pvar/article-pdf/7/3/225/1836425/105474698565686.pdf. URL: https://doi.org/10.1162/105474698565686 (cit. on p. 67).

[52] E. Wyckoff, M. Ball, and F. Moreu. "Reducing gaze distraction for real-time vibration monitoring using augmented reality". In: *Structural Control and Health Monitoring* 29.10 (2022). DOI: 10.1002/stc.3013 (cit. on p. 11).

[53] Y. Yao, X. Wang, L. Luo, H. Wan, and H. Ren. "An overview of GIS-RS applications for archaeological and cultural heritage under the DBAR-heritage mission". In: *Remote Sensing* 15.24 (2023), p. 5766. DOI: https://doi.org/10.3390/rs15245766 (cit. on p. 16).

A

Portuguese Version of the User Evaluation Questionnaire

Teste de Usabilidade e Presença no contexto da dissertação: *"Digital Tools for Studying Luxury Glassmaking in Roman Portugal"*

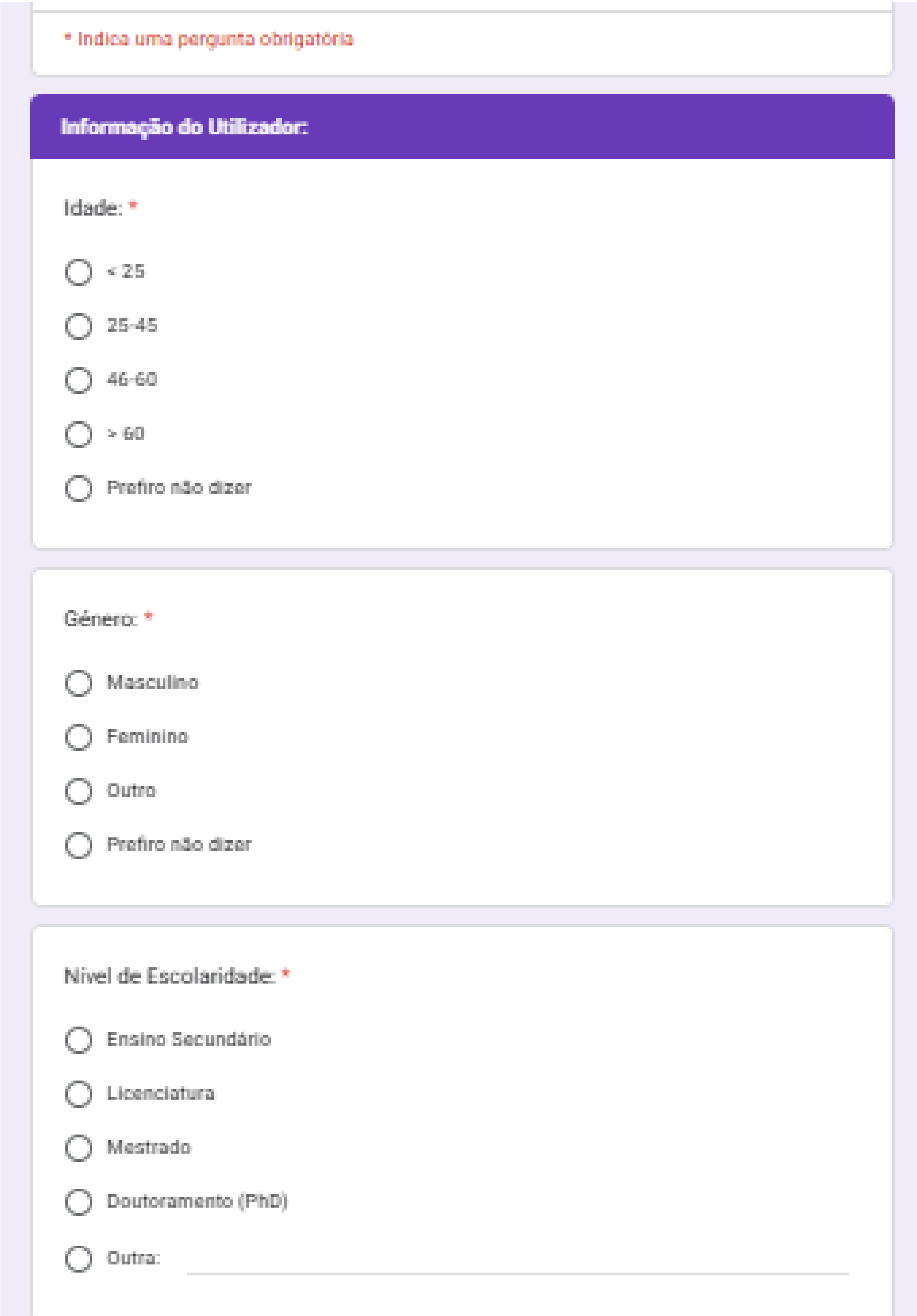
Este estudo procura avaliar a usabilidade de um sistema de **Realidade Virtual** desenvolvido no âmbito da dissertação *"Digital Tools for Studying Luxury Glassmaking in Roman Portugal"*.
Inicialmente, serão recolhidas informações sobre os participantes para fins estatísticos.

De seguida, será convidado(a) a realizar um conjunto de tarefas no ambiente, que representa virtualmente uma parte das **Ruínas Romanas de Tróia**.
Por fim, será solicitada a sua opinião sobre a experiência. O questionário é anónimo e destina-se exclusivamente a fins académicos.

NOVA
NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

Seguinte

Limpar formulário


* Indica uma pergunta obrigatória

Informação do Utilizador:

Idade: *

- < 25
- 25-45
- 46-60
- > 60
- Prefiro não dizer

Género: *

- Masculino
- Feminino
- Outro
- Prefiro não dizer

Nível de Escolaridade: *

- Ensino Secundário
- Licenciatura
- Mestrado
- Doutoramento (PhD)
- Outra:

Área(s) Profissional(ais) ou de Formação: *
(pode selecionar mais do que uma opção)

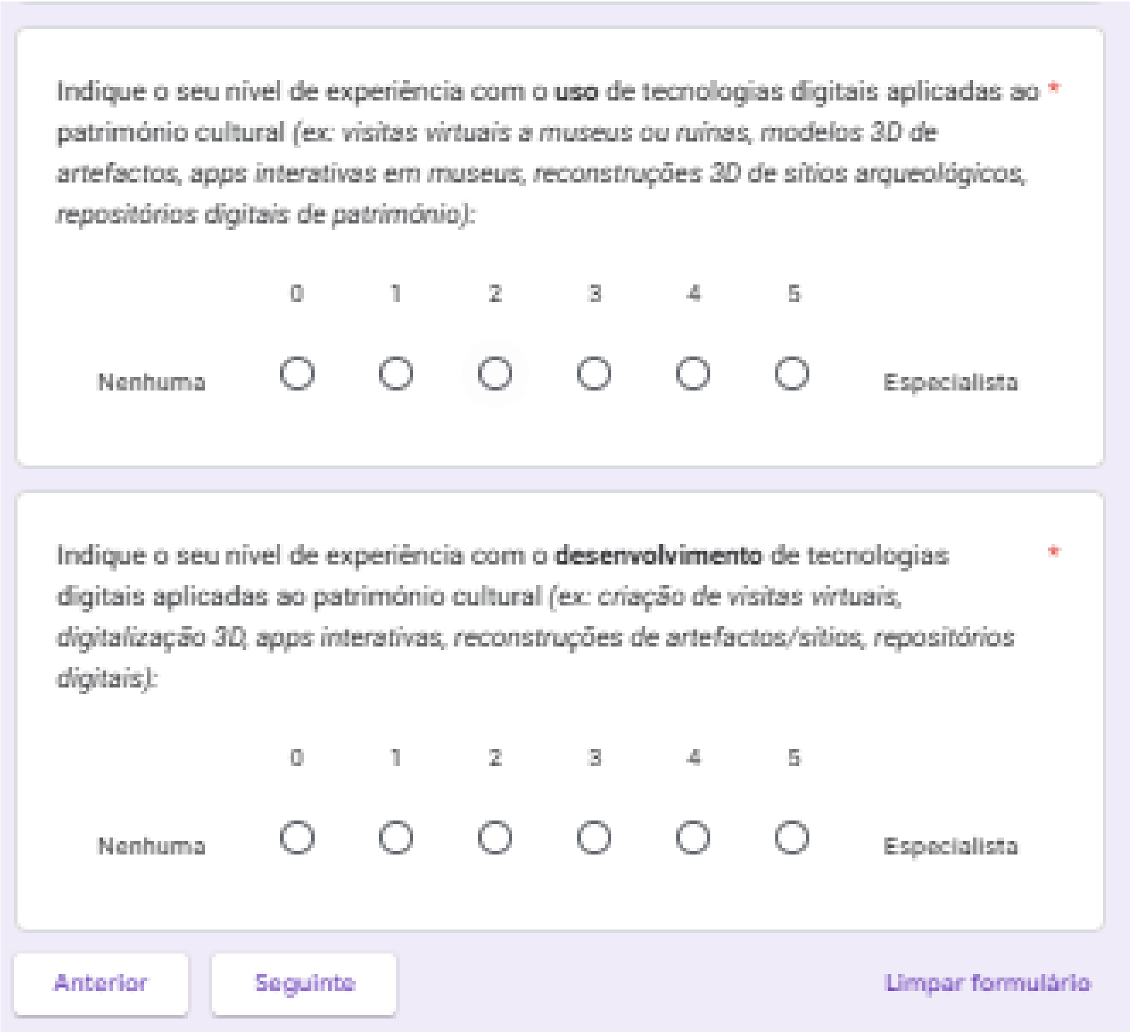
- [ ] Arqueologia
- [ ] Conservação e Restauro
- [ ] Museologia / Património Cultural
- [ ] História
- [ ] Educação
- [ ] Tecnologias Digitais / Multimédia
- [ ] Engenharia Informática
- [ ] Desenvolvimento de Jogos / Realidade Virtual
- [ ] Outra: ____________

Com que frequência joga videojogos ou interage com aplicações em ambientes 3D *(ex: jogos, simuladores, visitas virtuais)*? *

- ○ Regularmente (várias vezes por semana)
- ○ Ocasionalmente (1–2 vezes por mês)
- ○ Raramente (menos de 1 vez por mês)
- ○ Nunca

Experiência com Realidade Virtual (RV): *

- ○ Nenhuma
- ○ Principiante (usou 1-2 vezes)
- ○ Intermédio (usou várias vezes)
- ○ Avançado (usa com frequência)



Indique o seu nível de experiência com o **uso** de tecnologias digitais aplicadas ao património cultural *(ex: visitas virtuais a museus ou ruínas, modelos 3D de artefactos, apps interativas em museus, reconstruções 3D de sítios arqueológicos, repositórios digitais de património):* *

	0	1	2	3	4	5	
Nenhuma	○	○	○	○	○	○	Especialista

Indique o seu nível de experiência com o **desenvolvimento** de tecnologias digitais aplicadas ao património cultural *(ex: criação de visitas virtuais, digitalização 3D, apps interativas, reconstruções de artefactos/sítios, repositórios digitais):* *

	0	1	2	3	4	5	
Nenhuma	○	○	○	○	○	○	Especialista

Anterior Seguinte Limpar formulário

Tarefas

Está prestes a explorar uma reconstrução virtual de um **recinto funerário romano descoberto em Tróia**. Este encontra-se sobre um **plano base**, que contém o desenho duma parte deste sítio arqueológico.

Contexto:

Recinto funerário: Estrutura principal, que inclui a tumba.

Tumba: Parte do recinto, e contém 2 objetos de vidro para explorar.

Artefactos: Dois objetos que pertenciam ao defunto e que podem ser examinados de perto.

Slider: Barra interativa que permite visualizar a transformação do objeto, do estado original até ao atual.

Painel Informativo: Fornece dados textuais sobre os objetos.

Galeria de Imagens: Contém fotografias dos artefactos antes e depois da intervenção de restauro.

Pontos de Interesse (âncoras azuis): Locais destacados que facilitam a navegação e permitem a observação de áreas específicas.

Instruções de Movimento:

Pode deslocar-se no ambiente virtual de duas formas: **movimento contínuo** ou **teletransporte**. Experimente e utilize a que lhe for mais confortável.

1. Movimento Contínuo – Caminhe pelo ambiente com o **joystick esquerdo**.

2. Teletransporte – Use o **joystick direito** girado para a frente, para se mover instantaneamente para um novo local.

Rotação Rápida (Snap Turn) – Altere o seu ângulo de visão movendo o **joystick direito** lateralmente.

Agarrar Objetos (Grab) – Use o **botão lateral** de qualquer comando para agarrar um objeto.

Selecionar – Pressione o **botão A** no comando direito.

Ativar/Desativar o modelo 3D da tumba – Aponte para a área da tumba e clique no **trigger** (botão traseiro) do **comando esquerdo**.

Ativar/Desativar o menu principal – Pressione o **trigger** (botão traseiro) do **comando direito**.

1. Ative o **modelo 3D da tumba.**
2. Caminhe até à tumba ou selecione o seu ícone azul para se teletransportar.
3. Dentro da tumba, aponte para um objeto até ver o **contorno** e **agarre-o**.
4. **Saia da tumba** com o objeto ainda na mão.
5. Com o objeto na mão, use o outro comando para **mover o slider** e visualizar a sua aparência original.
6. **Largue o objeto** ao deixar de pressionar o botão lateral do comando.
7. Teletransporte-se para um **Ponto de Interesse**, selecionando um dos ícones azuis.
8. Ative o **menu principal** e selecione o **ícone** visível com o comando direito.
9. Feche o menu principal.
10. No painel à sua frente, selecione o **Object ID 21684** e visualize as informações apresentadas.
11. Caminhe até ao painel azul e passe o cursor sobre as **setas** para visualizar as imagens do objeto **após da intervenção.**
12. No painel à sua frente, **altere o plano base**, selecionando a opção **"Toggle Layer"**, e explore.

Anterior Seguinte Limpar formulário

Avaliação da Experiência

Para cada uma das tarefas que realizou, indique numa escala de 1 (Muito difícil) a 5 (Muito fácil) quão fácil foi a sua execução. *

	1	2	3	4	5
Visualização da informação textual do objeto	○	○	○	○	○
Visualização da Galeria de Imagens	○	○	○	○	○
Agarrar e manipular artefacto	○	○	○	○	○
Acesso ao menu principal	○	○	○	○	○
Ver aparência original do objeto com o slider	○	○	○	○	○
Mover-se no ambiente (andar/teletransporte)	○	○	○	○	○
Aceder a um ponto de interesse	○	○	○	○	○
Alterar o plano base (do chão)	○	○	○	○	○

Avalie cada afirmação numa escala de 1 (Nada) a 5 (Muito): *

	1	2	3	4	5
A exploração dentro da tumba foi intuitiva.	○	○	○	○	○
A exploração fora da tumba foi intuitiva.	○	○	○	○	○
A navegação para o/os ponto/s de interesse foi clara e acessível.	○	○	○	○	○
O slider foi eficaz a mostrar a transformação do objeto ao longo do tempo.	○	○	○	○	○
Consegui distinguir claramente entre o estado original e restaurado do artefacto.	○	○	○	○	○
As informações apresentadas ajudaram a compreender melhor o artefacto.	○	○	○	○	○
A experiência contribuiu para uma melhor compreensão do sítio arqueológico.	○	○	○	○	○

A experiência ajudou a compreender melhor os artefactos apresentados.

A experiência provocou uma sensação de presença no local histórico.

As tarefas tinham um objetivo claro e foram fáceis de interpretar.

Anterior

Seguinte

Limpar formulário

Presence Questionnaire (PQ) - Avaliação da presença no ambiente virtual

Esta secção tem como objetivo avaliar o seu nível de envolvimento no ambiente virtual.

Indique o seu grau de concordância com as afirmações seguintes: *(1 – muito baixo, 5 – muito alto)* *

	1	2	3	4	5
Quão natural te pareceram as tuas interações com o ambiente?	○	○	○	○	○
Em que medida os aspetos visuais do ambiente te envolveram?	○	○	○	○	○
Quão consistentes te pareceram ser as experiências no ambiente virtual em comparação com as experiências do mundo real?	○	○	○	○	○
Quão bem conseguiste inspecionar ou pesquisar ativamente no ambiente virtual utilizando o tato?	○	○	○	○	○
Quão envolvido estiveste na experiência do ambiente virtual?	○	○	○	○	○

Quão completamente estavam os teus sentidos envolvidos na experiência?	○	○	○	○	○
Houve momentos durante a experiência no ambiente virtual durante os quais te sentiste completamente concentrado na tarefa ou no ambiente?	○	○	○	○	○
Quão facilmente te adaptaste aos dispositivos de controlo utilizados para interagir com o ambiente virtual?	○	○	○	○	○
A informação fornecida através dos diferentes sentidos no ambiente virtual (p. ex., a visão, toque ou audição) foi consistente?	○	○	○	○	○

Anterior Seguinte Limpar formulário

User Experience Questionnaire (UEQ)

A fim de avaliar o ambiente desenvolvido, por favor preencha a secção seguinte.
Marque a sua resposta da forma mais espontânea possível.

Não há respostas "certas" ou respostas "erradas". A sua opinião pessoal é que conta!

Esta questão é constituída por **pares de opostos** relativos às propriedades inerentes ao ambiente desenvolvido. *

		1 2 3 4 5 6 7	
Ex:	Atraente	○ ● ○ ○ ○ ○ ○	Feio

Esta resposta significa que avalia o produto **mais atraente** do que **feio**.

	1	2	3	4	5	6	7	
Obstrutivo	○	○	○	○	○	○	○	Condutor

*

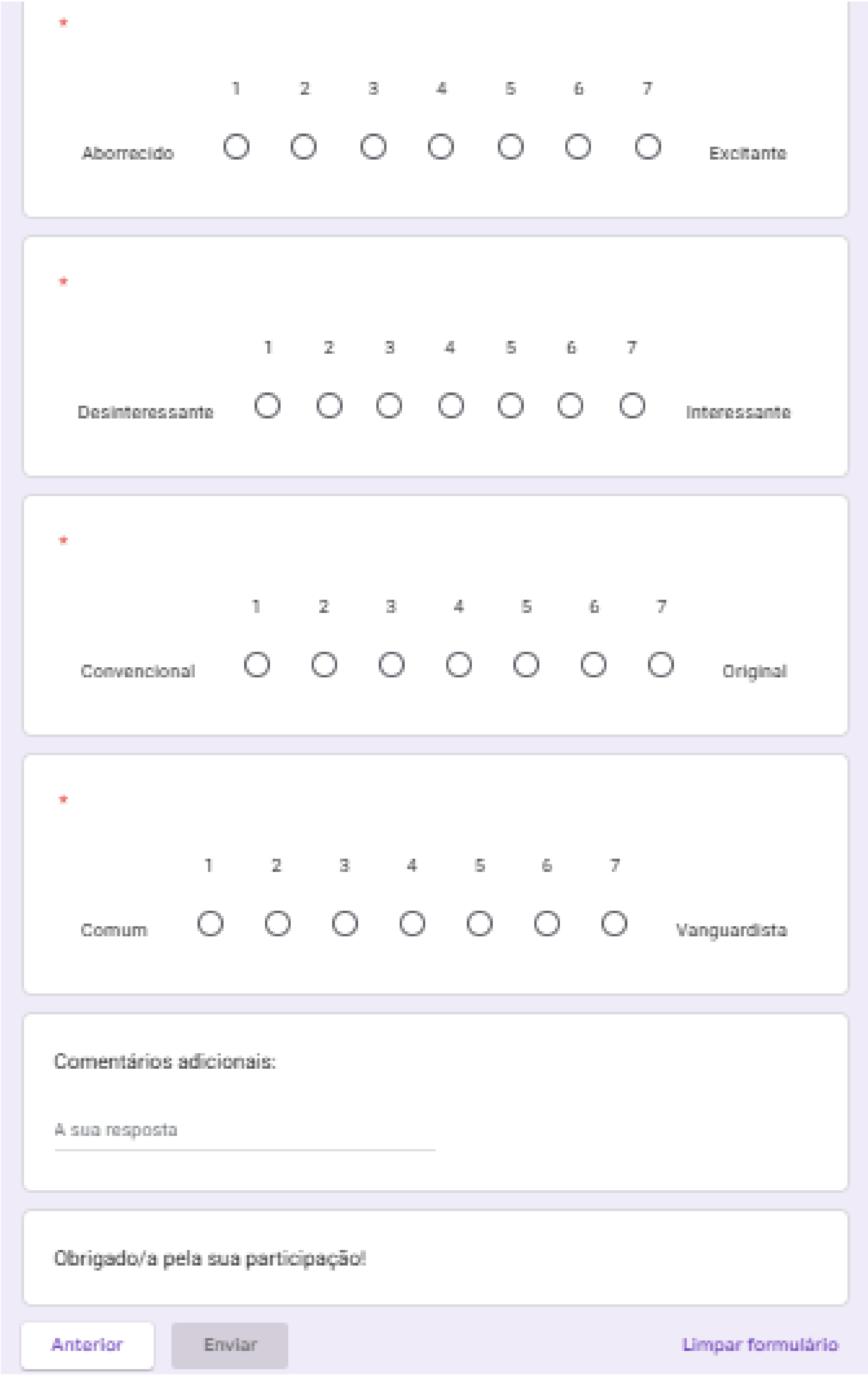
	1	2	3	4	5	6	7	
Complicado	○	○	○	○	○	○	○	Fácil

*

	1	2	3	4	5	6	7	
Ineficiente	○	○	○	○	○	○	○	Eficiente

*

	1	2	3	4	5	6	7	
Confuso	○	○	○	○	○	○	○	Evidente



*

	1	2	3	4	5	6	7	
Aborrecido	○	○	○	○	○	○	○	Excitante

*

	1	2	3	4	5	6	7	
Desinteressante	○	○	○	○	○	○	○	Interessante

*

	1	2	3	4	5	6	7	
Convencional	○	○	○	○	○	○	○	Original

*

	1	2	3	4	5	6	7	
Comum	○	○	○	○	○	○	○	Vanguardista

Comentários adicionais:

A sua resposta

Obrigado/a pela sua participação!

Anterior Enviar Limpar formulário