DEPARTMENT OF
COMPUTER SCIENCE

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Bachelor in Computer Science and Engineering

3D ACQUISITION, CLASSIFICATION AND VISUALIZATION OF ROOM SCALE SPACES AND OBJECTS FOR MUSEUMS

MASTER IN COMPUTER SCIENCE AND ENGENEERING

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Abstract

The usage of Virtual Environments and 3D Scanning has become commonplace in many industries, with many museums incrementally integrating these technologies into their educational and promotional material. In this thesis we will be looking into the area of 3D classification (documentation and cataloguing) and visualization and acquisition. With one of the problems we seek to study being, the poor classification and annotation of 3D models, as it can make the models more susceptible to being lost or losing data related to the original artifact they are based on. The classic method for visualizing 3D models inside Virtual Environments also has issues, as it limits the user's ability to view the models by leaving them in a static position, leading to portions of the models becoming concealed behind blind-spots. We would also like to confirm the use of 360° Images as replacements for 3D Environments as a cost saving measure.

In hopes of showcasing some solutions to these problems, an application was developed to further study the classification of 3D models, 3D visualization and the use of 360° Images as replacements for 3D Environments. This application allows a user to create and explore Virtual Tours for museums. The users can be the staff of a museum, who will work as the editors of these Virtual Tours, or the average person, who wants to visit these virtual experiences.

We used a 3D model of the *Forte da Trafaria* and artifacts from the *Academia das Ciências de Lisboa* as case studies because of their high cultural value. This also opened up the opportunity for us to study the 3D model pipeline from acquisition to visualization.

Through testing and the development of the application we confirmed that museums currently only use the simplest annotations possible, those being name and description for their virtual exhibits, and through a user study we were able to observe that users prefer Virtual Tours around 3D models over 360° Image based Virtual Tours when given both options.

Keywords: 3D Scanning, 3D Visualization, Annotations, Virtual Environment, Virtual Tour, Museum, Cultural Heritage

Resumo

A utilização de Ambientes Virtuais e Digitalização 3D tornou-se comum em muitas indústrias, com muitos museus a integrarem gradualmente estas tecnologias no seu material educativo e promocional. Nesta tese iremos olhar para a área da classificação 3D (documentação e catalogação) e da visualização e aquisição. Onde um dos problemas que procuramos estudar é a má classificação dos modelos 3D, pois pode tornar os modelos mais suscetíveis à perda ou perda de dados relacionados com o artefacto original em que se baseiam. O método clássico de visualização de modelos 3D dentro de Ambientes Virtuais também tem alguns problemas, pois limita a capacidade do utilizador de visualizar os modelos, deixando-os numa posição estática e fazendo com que partes dos modelos fiquem ocultas atrás de ângulos mortos. Gostaríamos também de confirmar a utilização de imagens de 360° como substitutos para ambientes 3D como medida de redução de custos.

Na esperança de apresentar algumas soluções para estes problemas, foi desenvolvida uma aplicação para estudar a classificação de modelos 3D, a visualização 3D e a utilização de imagens 360° como substitutos de ambientes 3D. Esta aplicação permite ao utilizador criar e explorar Visitas Virtuais para museus. Os utilizadores destinados são os funcionários do museu, que trabalharão como editores destas Visitas Virtuais, ou a pessoa comum, que deseja visitar estas experiências virtuais.

Utilizámos um modelo 3D do Forte da Trafaria e artefactos da Academia das Ciências de Lisboa como casos de estudos pelo seu elevado valor cultural. O que nos deu a oportunidade de estudar a *pipeline* de modelos 3D desde a aquisição até à visualização.

Através dos testes realizados e do desenvolvimento da aplicação, confirmámos que atualmente os museus utilizam apenas anotações simples (nome e descrição) nas suas exposições virtuais, e através de um estudo de utilizadores, pudemos observar que os utilizadores preferem Visitas Virtuais baseadas em modelos 3D em vez de Visitas Virtuais baseadas em imagens 360° quando dadas ambas as opções.

Palavras-chave: Digitalização 3D, Visualização 3D, Anotações, Ambientes virtuais, Visitas Virtuais, Museus, Património Cultural

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Introduction

Many industries and technologies nowadays rely on Virtual Environments, also called 3D Environments, and 3D Scanning in order to run more efficiently, to the point these techniques have become indispensable, an example of this can be seen in the Architecture Industry through the usage of the BIM process [5].

The acquisition and visualization of such models are well-known processes, but the methods for classification of 3D models are rarely talked about, as we noticed while writing Chapter 2, specifically how to document a 3D model through annotations and how to catalogue various 3D models. We define 3D classification as the pairing of a 3D model with the documentation of an object's annotations (such as Description, Tags, Images) and the cataloging of a group of models.

Museums, in specific, are becoming more reliant on immersive experiences such as Virtual Tours to publicize their exhibitions and attract new visitors [26, 44]. However, it is hard to differentiate the immersive experiences of various museums when they all use the same technology, based around the use of 360° Images, seen in the Google Arts & Culture initiative[1]. This approach is also not very good to preserve and document information on individual objects, a core concern for any museum.

There are several other solutions for Virtual Tours. One of them is the use of Virtual Environments and 3D models of artifacts. Virtual Environments are networked applications that allows a user to interact with both the computing environment and the work of other users [7], but for this thesis we will be referring to 3D scans of real environments. 3D classification can also supplement this solution by documenting and cataloguing the various 3D models, providing a more long term method of preserving artifacts. However, we understand most museums might not have the capacity and time to 3D Scan everything, so we will consider the use of 360° Images as a possible substitute to Virtual Environments as well.

[1] Google Arts & Culture, website link for the Google Arts & Culture About Page, https://about.artsandculture.google.com/, last access 11/2023

1.1 Motivation

The field of 3D acquisition is well studied [21, 14], while the area of 3D classification and visualization are areas with much more space for study and development of new solutions to be made, as it will be seen in Chapter 2.

UNESCO lists 56 World Heritages (40 cultural and 16 natural) currently in danger in 2023[2]. This is a problem museums must also deal with as they mainly deal with artifacts and sites of Cultural Heritage. Meaning that with this ever looming possibility, that one day items or sites of high cultural value could erode into an unrecognizable state. Maintaining quality records of them becomes a high priority task. 3D Scanning these objects and locations of cultural value is a good solution to preserve their image in a detailed and versatile three dimensional format as part of their documentation.

The lack of research into 3D Classification leads to the usage of inefficient methods, causing a poor archival of 3D models and increasing the chances of them being lost. This can be in the literal sense or because the people who stored them are no longer present so the search for the models becomes extremely time consuming. Examples of this can happen with real life artifacts. The British Museum has announced that Gold coins, silver necklaces and 540 pieces of pottery are among the hundreds of their historical artefact that have gone missing[3]. The importance of good documentation, especially for Cultural Heritage, motivates us to contribute to the research on 3D Classification.

In a survey of many museums, they found that the largest museums typically only display about 5% of their collection at any time[4]. The referenced article goes deeper into how this limited showing can affect specific artists that end up having none of their pieces on display. This is where 3D Virtual Tours could step in, as they are versatile and would allow a museum to run multiple exhibits at the same time or quickly be able to create and deploy new exhibits.

While conducting the literature research (Section 2.3) it became apparent that there is a lack of 3D Virtual Tours, especially for museums, as they rely on 360° scanned virtual tours, which are the cheapest method for creating virtual tours, but are very inflexible as they use 2D images. Once the photos are taken they will see none or almost no changes throughout their use cycle. This motivates us to make 3D Virtual Tours more appealing to museums by making them easier to set up and manage.

Lastly, Virtual Environments allow for flexible and dynamic manipulation of objects and spaces, however once set up into a Virtual Tour they become static, meaning certain angles of an object will become very hard or impossible to observe by a visitor, diminishing one of the advantages of a 3D models, the ability to observe something thoroughly in all

[2]UNESCO - List of World Heritage in danger by region, https://whc.unesco.org/en/list/stat/#s9, last access 02/2024

[3]Hundreds of items "missing" from British Museum since 2013, https://www.theguardian.com /culture/2023/aug/24/hundreds-of-items-missing-from-british-museum-since-2013, last access 02/2024

[4]Museums are keeping a ton of the world's most famous art locked away in storage, https://qz.com/583354/why-is-so-much-of-the-worlds-great-art-in-storage#: :text=Much %20of%20the%20world's%20great,their%20collection%20at%20any%20time, last access 02/2024

three dimension and angles. For this reason, we intend to explore 3D Visualization of objects to elevate the Virtual Tour experience in Virtual Environments even more.

1.2 Objectives and Research Questions

Ultimately, we sought to create an application to aid in the creation and exploration of Virtual Tours for museums. This application should allow for the:

- Classification and Annotation of 3D models
- Quick search of items inside a catalogue
- Interactive Visualization of 3D models
- Substitution of 3D Environments with 360º images

To do this we initially followed the 3D model acquisition pipeline by scanning environments and objects, then grouping the created 3D models to their respective annotations. Afterwards we considered possible improvements that could be done to the 3D model management system, whilst also looking into new features to be added, such as a system that allows for the visualization of the 3D models inside a virtual environment while exploring it and a system that allows the creation of 360° Image based Virtual Tours where the images are used as a substitute for 3D models of room spaces.

With these objectives we looked to answer three related questions by the end of this thesis. The questions center around the documentation process and user experience, with a focus on their practical aspects, as those allow us to reach more direct answers.

- Question 1 - Is an interactive visualization tool better than viewing an object inside a Virtual Environment?

  Viewing objects inside a Virtual Environment can limit a user's ability to fully take advantage of a 3D model's detail by fixing the angles from which a user can look at the model, leading to areas of an object not being visible to the user. It's because of this limitation that we wanted to test if an interactive visualization tool could be used as an option to enhance a user's ability to experience a Virtual Tour.

- Question 2 - Can 360° images be used as a substitute to 3D models of room spaces?

  Considering the financial limitations museum have, creating a 3D Model of various rooms or even a whole building is not always a possibility. On the other hand taking a 360° photo is much cheaper and faster. While still using 3D models of objects we sought to test if 360° Images could be used as a replacement for 3D Models of Room Spaces.

- Question 3 - What information should be stored as a 3D model's annotation?

Some basic information usually comes to mind, such as name, description and images. However not all information is useful and giving users the ability to add custom information might not be a good decision either when considering possible storage space and cost concerns, since museums usually lack those kinds of resources. Meaning that an efficient selection of core data to be stored is imperative.

1.3 Proposed Solution and Contributions

The solution we proposed was the creation of an application to aid in the creation and exploration of Virtual Tours for museums by extending the work done in a previous thesis [46], which we used as a base while implementing the features we wanted to study in this thesis. The main features that we worked on will be presented in this section.

Annotations A 3D model by itself can't tell the entire story of the real life object the model was scanned from. Annotations can link that missing information to a 3D model, enriching the 3D model and connecting it more closely to it's documentation. Annotations can also be useful to lower the time spent searching for a model and used in tandem with the creation of an exposition.

Search Bar We proposed to add a Search Bar that allows the user to search with text for a specific item inside the application's catalogue. The main purpose of this function would be to reduce the time spent searching for a specific item, since when used in a real life setting the application that has been developed is expected to have many dozens of items, turning a manual search into a very time consuming process while creating a Virtual Tour. In addition, by taking advantage of annotations, searching for a 3D model can be done much more elegantly through the use of tags.

Interactive Visualization Tool We also sought to add a new visualization option that also integrates annotations. It can be used while exploring a virtual tour, removing the limitations of static pre-built virtual tours where certain angles of a 3D model are not visible to the user. This tool also has the ability to add annotations to a 3D model, these annotations are set to a specific point on the 3D model, expanding the ways a user can interact with a 3D model and it's annotations.

Implementing 360° Images in a 3D Environment Lastly, we had to find a way to use 360° Images in a 3D Environment, that not only allows the user to place the images in the 3D Environment but that also allows for the movement between two different images while exploring a Virtual Tour. The solution we proposed was to use the 360° Images as textures for spheres, where the full image is visible from inside the sphere, and to connect the spheres we came up with the idea of using arrows that users can click to be sent to the next image.

We used 3D models that we had scanned ourselves during the preparation stage of this thesis from the *Academia das Ciências de Lisboa*. Annotations were acquired by asking museum staff and copying information present in an item's exposition. This way we showcased the steps that can be taken to create a long lasting, versatile and dynamic Virtual Tour with documented, easily searchable 3D models.

Two user studies were also contributed, which can be read in Section 5.3 and 5.5, where we tested the developed application and collected the participant's opinions on the features that were implemented.

1.4 Document Structure

This chapter served as an introduction to this thesis and the work done throughout it.

Chapter 2 will look into the state of the art of the technologies that will be used in this thesis, starting with the 3D scanning process, from the techniques available to the cameras used, followed by a view into 3D objects, methods of classifying and visualizing them plus how Virtual Environments are used in various industries, ending with a look into various kinds of virtual tours.

Chapter 3 describes the developed solution on a theoretical level, starting by explaining the problem, case study and requirements needed. After having explained the prerequisites we can begin talking about the methodology used and about the data that was collected to gather the assets used in this thesis. Lastly, we will discuss the design for each new feature we planned to add.

Chapter 4 covers the actual development of the application. The first sections cover the application's architecture and features that were propose and whose design was discussed in the previous chapter, with the last two sections covering two additional functions that were added during the development of the application.

Chapter 5 details the two user studies that were ran to test the application and answer some of the proposed research questions. It also showcases and analyzes the results gathered from both studies and the improvements that were done in response to the results from the first user study.

Chapter 6 concludes this dissertation, answering the propose research questions and discussing the possible routes for work that can be done with the developed application in the future.

2

State of the Art

In this chapter we will investigate the current state of the research and various technologies related to the topics of 3D Scanning, Virtual Environments and Virtual Tours. The order by which we will talk about each topic will be the same as the steps taken in order to create a Virtual Tour. Firstly, we will approach the topic of 3D scanning, the starting point in the acquisition of 3D models of real-life entities, covering the scanning process and the three most popular scanning methods (Photogrammetry, LiDAR and 360° Scanning). Followed by Virtual Environments, a product of various captures or an original creation, the different areas where they can be used and how. Lastly Virtual Tours, which take the 3D models and virtual environments we have talked about to create the experience of visiting a real space but in a controlled virtual replica, various existing tours will be referenced to give us a view of the various ways they can be achieved.

2.1 3D Scanning

Buildings and artifacts do not last forever, they erode over time in various ways, this in turn also makes them become fragile and hard to move around. 3D Scanning fixes this issue by saving it's digital twin, so it can be shared countless times unchanged by the passage of time. Many initiatives already do this by digitalizing various items of cultural heritage, like the 3D Silk Road initiative, from the Department of Computer Science of Lublin University of Technology in Poland[1]. To this end there has been vast research on the topic of 3D Scanning, which has created various methods of recreating real life entities in a digital format. The most popular methods and the general scanning process will be covered in this section.

2.1.1 Scanning Process

3D Scanning is a large process with many steps. We will exemplify scanning an object to run through those steps and talk about them.

[1]3D Silk Road, website link for the 3D Silk Road initiative, https://silkroad3d.com/, last access 10/2023

Registration First is the Global Registration of multiple point cloud scans of the object, covering it's surface and background, these scans might not yet be correctly positioned in relation to each other. Registration is the process of estimating the transformation matrix between two-point cloud scans [21], the various techniques that can be used to achieve this have been explored by Dong's et al. [14].

This is followed by the erasure of unnecessary objects and backgrounds from the scans, this step can be either done automatically or manually.

The cleaned-up scans are then aligned together into a common coordinate system so that they can be integrated into a single 3D model, most of the time this step asks the user to determine matching feature points in two or more scans, it's automation is still an active area of study.

A new Global Registration is done to save the new transformation matrix between the various point clouds with the aligned scans. The remaining background is then erased. Optionally there can also be a 3D noise removal before moving to the next step. An Example of a mapped/aligned 3D point cloud can be seen in Figure 2.1.

Fusion The Fusion step uses the organized scans to begin creating the 3D model/mesh by triangulating the points from the aligned point clouds. This is an open area of study that keeps receiving new techniques for combining data and using it to create a 3D model [1, 33]. Once the model is complete it is filtered for any remaining noise which might have been created during the Fusion step. The generated model from the point cloud seen in the previous example can be seen in Figure 2.2, we can see it still has some imperfection and might need to be refined more, which can be done in the next stage.

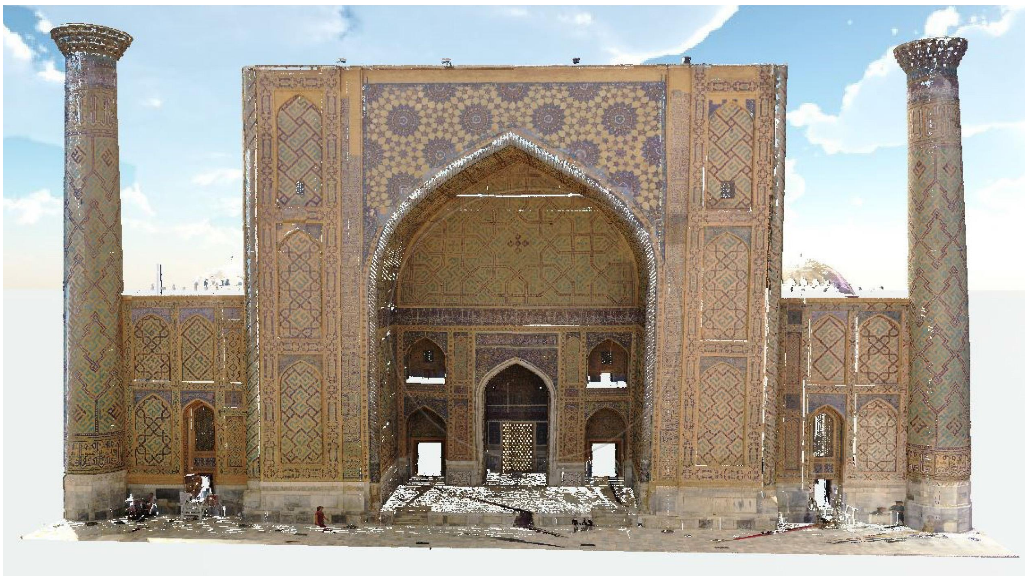

Figure 2.1: A view of a fragment of a 3D point cloud mapping the front of the Ulugh-Bega madrasah in the Registan Ensemble, taken from Milosz et al. [37]

Figure 2.2: Base model generated from the point cloud, taken from Milosz et al. [37]

Postprocessing Now we enter the postprocessing stage, it usually begins with the Mesh simplification in order to reduce the number of polygons the model has, making it less complex and occupy less space.

This can then be followed by another clean-up of the model just to make sure no new artifacts exist and to smooth out the surface of the simplified mesh.

Finally, the Texturing step, where a texture is applied to the model, there are many possible methods to achieve this, one of them simply using the colors recorded in the original scans to apply the texture. The Texturing step is not required to consider the 3D scanning complete [6].

2.1.2 Photogrammetry

Photogrammetry is a technique that uses a series of photographs taken from different angles to create a 3D model, a representation of this can be seen in Figure 2.3. It is well suited for scanning outdoor environments, large structures and creating detailed 3D models of cultural heritage artifacts, but it has many drawbacks. Firstly, it needs a large number of images to achieve high accuracy, which means the capturing process can be very time-consuming. Secondly is the difficulty in obtaining images with sufficient overlap and coverage, this issue is most prevalent when trying to capture complex shapes or objects with reflective or transparent surfaces. Photogrammetry can also be sensitive to changes in lighting and shadows, leading to inaccuracies in the final 3D model. The last drawback is that the process of stitching images together and generating the 3D model can be computationally intensive and require powerful software and hardware [25].

Even so Photogrammetry is still a widely used technology, even in big projects like the most recent Star Wars game made by EA[2], where it was used to create the maps for their

[2]EA Website - Presentation about the use of Photogrammetry in Star Wars: Battlefront,

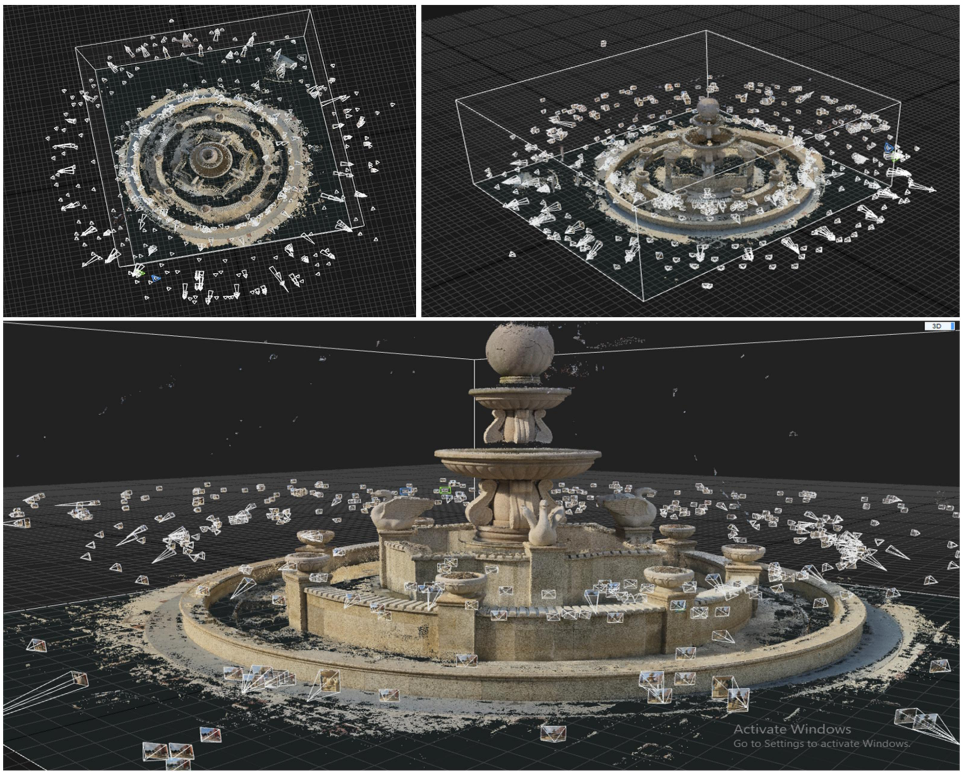

Figure 2.3: 3D model reconstructed using photos, taken from Cheng and Ch'ng [12]

levels of the different ecosystems and to take various real life props (masks, clothes, etc) and make 3D models of them.

Furthermore with the rise in digital photography the time-consuming capturing process is drastically reduced, this can be seen in the well-known paper by Agarwal et al. [2] "Building Rome in a Day" where they took all the photos they could find of Rome from a popular photo-sharing website and tried to create the best 3D model possible from them within 24 hours, the results were impressive, especially for the points of biggest interest in the city as those were also the ones with the biggest amount of pictures taken from various angles.

2.1.3 LiDAR

LiDAR or Light Detection And Ranging is a remote sensing method for determining ranges/distances by targeting an object or a surface with a laser and measuring the time it takes for the reflected light to be returned to the receiver. LiDAR scanning or 3D laser scanning is when lasers are used to scan multiple directions.

A fully functional LiDAR system is made of four major subsystems namely the laser range-finder, beam deflection, power management, and master controller units. The range finding unit is the core of the LiDAR system, within which are present the components required to generate, transmit, and receive short laser pulses.

https://www.ea.com/frostbite/news/photogrammetry-and-star-wars-battlefront, last access 12/2023

The beam deflection unit is responsible for acquiring spatial information in 2D and 3D, otherwise in it's absence the LiDAR system can only acquire spacial information in 1D. The control unit handles basic signal processing, control signal generation, and communication with the host PC.

LiDAR instruments are usually classified using the types of information-capturing functionality it offers namely spatial, spectral, and temporal.

Spacial information can be captured in one (1D), two (2D) and three (3D) dimensions. 2D and 3D spatial information is gathered with the aid of optical deflecting systems.

The spectral information of a material is usually captured by value of the laser return intensity (LRI). LRI refers to the reflectance in the interaction between the laser and the target material. An LRI value is characteristic to a specific material type, making it potentially useful in the identification of surface properties, but to avoid ambiguities in LRI readings, at least two wavelengths of laser are required.

Temporal information is used to understand dynamic processes such as plant growth and soil erosion. The repeated LiDAR technique can be used to collect this data by collecting temporal data of a target environment over a finite period of time [41].

Practical use of LiDAR scanning can be seen in the mining industry [16] where the use of explosives is common, leading to unpredictable results after the explosions. Miners can use this technology to help measure and evaluate the size distribution of blasted rocks in a quicker and more precise way than before, helping them prepare for subsequent excavation and loading operations as well as indicates the success of the blasting process.

In 2000, the British Geological Survey (BGS) became the first organization outside of the mining industry to use Terrestrial LiDAR Scanning (TLS) as a tool for measuring change, TLS is the use of LiDAR technology to measure distances from XYZ coordinates. The BGS still uses TLS to this day on various activities such as generating digital models of historic buildings, to create virtual outcrop models (VOM) of geological structures, to detect cracks and wet spots in the clay-lined caps of landfill sites, to monitor long-term ground movement due to shrink-swell clays, to measure the loss of glacial volume and to study coastal evolution [24]. We can also see from Figure 2.4 TLS being used to create elevation models, as scans can be taken from high places or in the air in order to get terrestrial information.

2.1.4 360° Scanning

360° images are nothing new, and their usage can be seen in our daily lives when using Google Map's Street View[3] to simulate driving through a street and in the Google Arts & Culture initiative[4] to create Virtual Tours of various museums.

[3]Google Street View, website link for the Google Street View Page, https://www.google.com/streetview/, last access 11/2023

[4]Google Arts & Culture, website link for the Google Arts & Culture About Page, https://about.artsandculture.google.com/, last access 11/2023

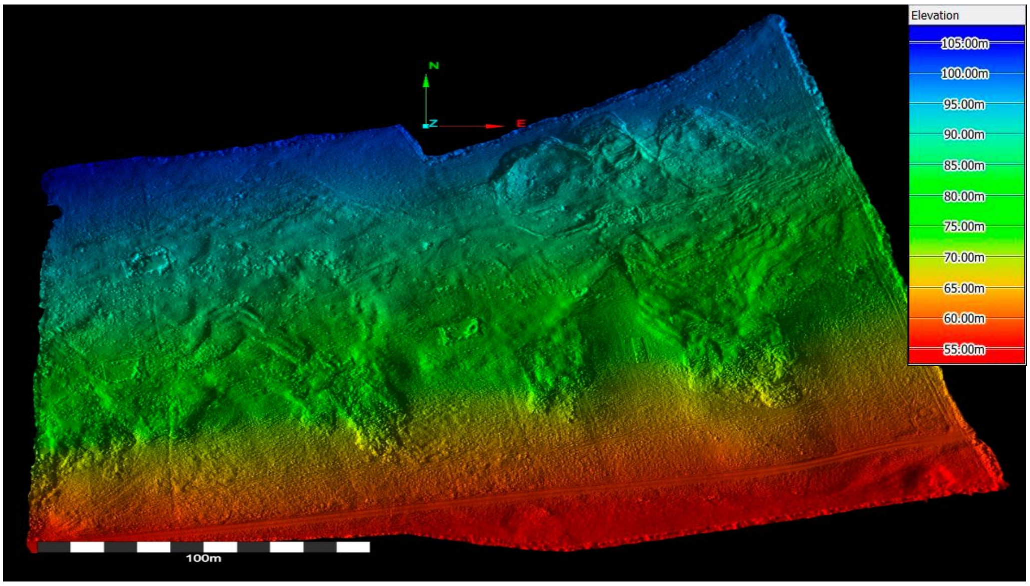

Figure 2.4: Elevation model of initial TLS survey of the Hollin Hill landslide, taken from Jones and Hobbs [24]

As already seen in Section 2.1.2, we can use images to create 3D models, however 360° images have their own peculiarities, which can be more easily noticed when looking at an equirectangular projection (ERP) of a 360° image and the distortions such a projection creates, as seen in Figure 2.5, making the usage of regular algorithms not a straightforward process, an example of this can be seen when trying to infer depth from a 360° image [45]. This makes it so 360° images are not usually used to scan 3D objects, but rather to create viewing experiences akin to the ones already talked about from Google, which are used instead of 3D scans and 3D models because of their lower price and processing time.

Figure 2.5: 360° video projected as an equirectangular, taken from Tarek El-Ganainy's paper [15]

2.1.5 Cameras

In this section we will be dividing cameras into 4 types (basic, 360°, triangulation/SLAM and LiDAR) in order to discuss them.

Basic Cameras We consider Basic cameras to be those used to take simple 2D photographs, such as cellphone cameras. These cameras might not seem very useful, but they can still be used to create 3D models with Photogrammetry with decent quality as seen in "Building Rome in a Day" [2]. There exist techniques that also allow these cameras to create 360° images and calculate depth in a 2D, but those methods are not as accurate or quick as simply using a camera more suited for the task, that being the reason why they are not mentioned often.

360° **Cameras** With a quick search one can find a broad list of 360° cameras with varying prices and shapes, from a more traditional shape to a globe/ball format. There are also many brands that sell 360° cameras, but Matterport, a brand we have experience with, has a wide line of 360° cameras that take 360° pictures that can then be used to create what they call virtual clones, which are a fusion/collection of 360° images done through Matterport's software that can be traveled through in a similar fashion to Google Street View.

Triangulation/SLAM Cameras SLAM or Simultaneous Localization and Mapping, is the use of visual and/or inertial sensors to estimate the camera's position and scene structure [23], it can be used to scan 3D models as seen with the Matterport Pro 2[5] camera, seen in Figure 2.6, that has 3 cameras, two of them to act as it's visual sensors and the remaining one to do the image capturing.

LiDAR Cameras There can already be found some specialized cameras that integrate LiDAR technology in their scanning process in order to create 3D models, like with the Leica RTC360 3D Laser Scanner[6] where they call it laser scanning, there are also cameras that use LIDAR technology to help in the camera's evaluation of it's distance relative to it's surroundings or in other words depth measurement, like with the Matterport Pro 3 Camera[7], seen in Figure 2.7, where the laser is used to enhance the quality of the camera's 360° scans.

[5]Matterport, website link for the Matterport Pro 2 Web Page, https://matterport.com/pro2, last access 01/2024

[6]Leica RTC360 3D Laser Scanner Product Website, https://leica-geosystems.com/products/laser-scanners/scanners/leica-rtc360, last access 12/2023

[7]Matterport Pro 3 Camera Product Website, https://matterport.com/pro3, last access 12/2023

Figure 2.6: Matterport Pro 2, source: (https://matterport.com/pro2), last access 01/2024

Figure 2.7: Matterport Pro 3, source: (https://matterport.com/pro3), last access 01/2024

2.2 3D Objects and Virtual Environments

A good Virtual Environment is one that immerses the User and makes them feel as if they are in a real Environment. 3D Objects also play a critical role in immersing the user, as environments of interiors would feel unnatural if left empty.

There have been many studies on how to create and maintain this illusion, like in Russel et al. [47] where their tests showed that an object's perceived size can change depending on the other objects surrounding them in a 3D environment, or as expressed in Lease et al. [28], where they noted the importance of lighting in the production of realistic and immersive virtual environments, as lighting can be used to simulate different times of day in a room or to best simulate the time at which the room was scanned, by properly processing the shadows of the surrounding 3D objects, enhancing the Virtual Environment's realism.

Virtual Environments can be used in many industries for different purposes, some of those will be covered in this section through the Entertainment, Commerce and Tourism industries. Methods for showcasing a list of 3D objects, their individual visualization and annotation will also be reviewed in this section.

2.2.1 3D Catalog Presentation

There is very little to no serious literature around how to catalog a series of 3D Objects/Models. However, this is something that is frequently done in the Video Game Industry. We will look into some examples of video game inventories and how they are used to communicate information about an item and how it is supposed to look like. This is in line with the concept of classification of 3D Models in this thesis, as a correct classification will lead to a better user experience when trying to look up a certain Model.

Within the games medium there has been a wide variety of ways creators have used to implement and inventory system [19] and gamify it, usually by turning it into a puzzle, however most of those are done for a 2D environment or do not focus on the visual representation of the 3D Models. The games that do focus on informing their players of an item's visuals usually either divide them into lists while showing the selected item, seen in classic games such as Skyrim and very commonly seen in FPS/shooter games such as Overwatch[8] or Apex Legends, seen in Figure 2.8, where the player is also given the ability to rotate and zoom the weapon skin they are previewing, or the other popular method of listing items is in a grid, visible in Figure 2.9, where we can see a preview of how the item will look when held by the game character. These are the most popular and standard methods of cataloguing objects in the Games Industry, as it seems that communicating visual information about an object is a complex task that requires an adequate amount of space and control from the user.

[8]Overwatch Golden Weapons Preview, https://www.youtube.com/watch?v=Nmy05erEPkc, last access 01/2024

Figure 2.8: Apex Legends Weapon Skin Preview, source: (https://answers.ea.com/t5/General-Feedback/Real-Time-Weapon-skin-change-in-Firing-range-Concept-idea/td-p/11388316), last access 01/2024

Figure 2.9: The bow and arrows inventory section in LoZ: BotW (2017), taken from Glasell et al. [19]

2.2.2 3D Object Visualization

The research on 3D Object Visualization is broad and varied, as some focus on creating a more immersive visualization through VR, while others want to create high quality viewings through a 2D screen.

In the area of cultural heritage dissemination there have been found 3 groups of solutions for the visualization of 3D Objects [37]. Firstly, objects viewed individually "in space", the already seen method of having an object exist in an empty environment where it can be rotated by the user. Secondly, interactive animations using 3D elements, image backgrounds, and other multimedia elements. Thirdly, there is also the use of 360° images, but this is not real 3D as it uses 2D images to simulate an omnidirectional experience.

In the realm of VR researchers are trying to harness the potential this technology has to allow new ways of visualization, which would increase the speed and effectiveness of visualization when compared to the traditional 2D methods. VROffice [43] was an attempt at doing this by creating a 3D virtual office where through VR allows the user to interact with 3D objects, by observing, free-hand manipulating, inspecting details and object location in a 3D georeferenced space. It also allows interaction with 2D data, as a user can "organize datasets, perform analysis between different types of objects, combine characteristics, and interpret data in a Geographic Information System (GIS) environment".

There are also those who seek to try more unorthodox approaches to capitalize on VR's potential. This can be seen in DataDancing [32] a study on the design space for visualization view management. A user study was ran in order to test different combinations of interaction techniques and space use in VR, Figure 2.10 shows some images from the user study, the combinations where made up pairs of different display formats such as Wall Display, Tabletop Display, Cockpit Display, Body-fixed Display and Floor Display this last one being the one that stands out the most and whose data was reviewed more thoroughly. Even though during the user study they found that users took more time and mental effort to do tasks due to not being used to Floor Displays, the final results found that foot interaction is natural and easy to learn but is less effective than hand interaction for primary tasks, meaning foot interaction should see better results when in support of the user through simpler interaction such as panning and zooming, freeing up for the user's hands and eyes.

The two previous studies show that there is still untapped potential in VR, which could be studied in another thesis. For the rest of this thesis we will focus on the visualization of 3D objects through a screen, as it is the method that will be applied in this thesis's prototype. As this method of visualization is lacking in innovation, we will take a look at some specialized use cases.

We have already seen in the previous subsection how some video games showcase 3D objects to their players, allowing them to zoom and rotate the objects, usually in only one axis.

To aid in teaching about the human anatomy to medical students Maclean et al. [35]

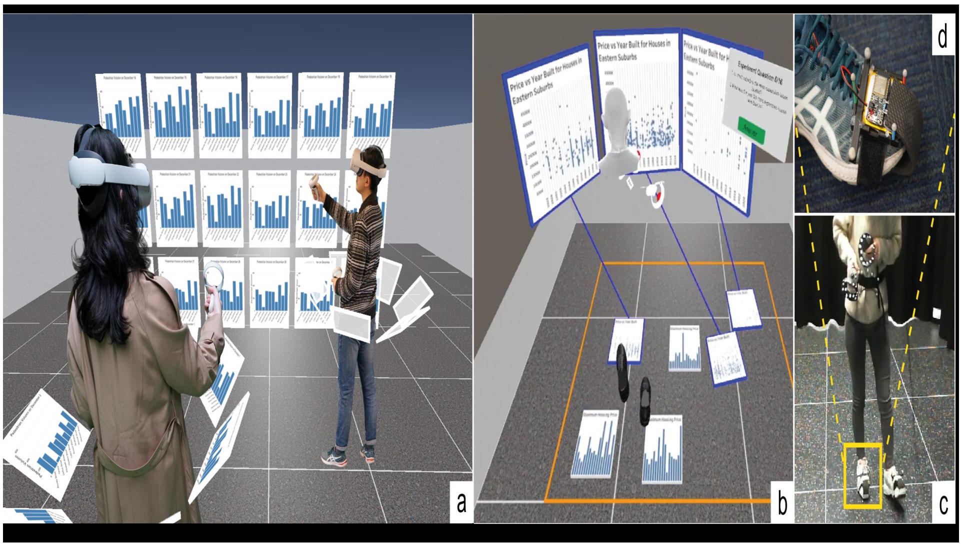

Figure 2.10: (a) A hybrid prototype demonstrating interaction possibilities of the DataDancing design space for visualization view management. (b) One of four prototypes evaluated in a qualitative user study with a body-fixed large display and a floor display with novel foot interactions. (c) The third-person front view of one participant "dancing" with views on the virtual floor in VR (synchronized with scene b). (d) A novel foot device used in the user study for each participant foot with reflective trackers and a pressure sensor system., taken from Liu et .al [32]

created a web-based education application for anatomical and neurophysiological concepts, allowing users to see specific parts of the human anatomy in a 3D plane with 360° rotations. It also allows users to "decompose" or in other words disassemble certain body parts such as the skull, letting the user separate certain or all parts/sections of the skull apart.

In the realm of engineering History in Motion (HiM) [48] was created as a visualization tool to help CAD (Computer-Aided Design) designers explore the history of 3D CAD models, it works as an educational tool but also as a creation tool that lets users to create or modify already existing models. It's main feature is the animation and visualization of the modeling process of pre-established 3D CAD models, which is divided in steps that can be freely browsed by the user while they "play" with the models by rotating or changing their transparency. The user can also choose to only follow the creation process for only one specific piece within a model as a whole, assisting in a more detailed analysis. These features allow for the user to learn a variety of important aspects in the making of a high-quality CAD model and with the additional editing tool they can also use it to create and fix their own models.

These visualization tools give us some ideas of how to enhance a basic visualization screen. Animations and decompositions are interesting concepts that could be played with depending on the item being exposed, maybe we could animate a dinosaur's skeleton moving or allow user to deconstruct and reconstruct an old broken pot. These concepts could be added to the basic zoom and rotation actions in visualization tools, but they also would require a lot more work and might not work for all models and exhibits.

2.2.3 Annotations

The use cases for annotations have been expanding over the years, now annotations do not only exist to serve people but also the machines they use, these annotations that serve to inform both humans and machines are referred to as Semantic Annotations [30]. Annotations can also have many kinds of formats and annotate various items, images and 3D models can be annotated by text, images or a more complex format with more than one kind of media. Likewise, Annotations can either be linked to an item as a whole or be linked to a specific coordinate or area within an item.

The field of Cultural Heritage is already starting to use Semantic Annotations in order to aid it's creation of digital information systems [13], which link external data to the geometric representation of an artifact, where tags are one of the most common type of annotation used.

However, having to annotate every item manually has been seen as a limiter in this area, leading to the study of automated ways to annotate items such as 2D images [8, 11] through the use of Artificial Intelligence, to more efficiently be able to classify them on a large-scale.

Nevertheless, manual annotating is still highly valued, to the point tools are being created to make this process easier and faster for users. An example of this can be seen in Lai et al. [27], where they proposed a technique for automatically annotating charts according to a textual description, where well timed annotations can help enhance their presentation and discussion to an audience. This technique turns an image and textual description into a series of vivid well annotated animations and the process only takes a few seconds, saving the presenter's time and effort while crafting their presentation.

Within this spectrum, the developed application will mostly focus on using normal Annotations, which are only intended to be read by humans. These annotations will come in all formats from textual to visual and even some more complex formats. The only annotations that we could consider semantic would be the tags that will be used to help document and search for the 3D models in the application. There are also no plans to automate the creation of these annotations.

2.2.4 Entertainment

It is already a well-known fact that the modern big budget movie and games industries thrive with the usage of Virtual Environments in their products, be it in order to more easily integrate actors in certain environments with the usage of CGI and green screens or when used to create open world experiences in games, but the same technology can be used to assist in other field which some might have not considered before.

One example is in the comic books industry, that has seen a new wave of artist now leveraging Virtual Environments to save time in drawing backgrounds[9], this has created

[9] A comic artist's debut made possible with 3D software - Blog Article, blog.sketchup.com/article/a-comic-artist-s-debut-made-possible-with-3d-software, last access 12/2023

Figure 2.11: Photo by Francois Duhamel of the LED panel set for The Mandalorian, source: (https://www.icgmagazine.com/web/a-new-hope/), last access 01/2024

a new market for artists to sell Virtual Environments almost like stock images.

Coming back to the movie industry, 3D Printing[10] can be used to take the Virtual Environments or 3D Objects they already use and bring them to the real world, a whole set could be made with 3D Printing.

In Disney's recent show The Mandalorian they have started using a new filming technique which allows them to film actors while also having a virtual Environment running in the background[11], they use LED panels to allow them to have dynamic Virtual Environments that they can change on the fly. This technique also helps actors by giving them context on the scene and location they are in and saves post production time by already integrating the backgrounds in the filming stage, a lot of big advantages when compared with green screen technology.

These are some interesting ways Virtual Environments are being used to aid the professionals in the Entertainment Industry, they can be used to help guide us in possible evolutions in future iterations of this thesis's prototype, being able to promote museums through an artistic medium or through the creation of models to support people with visual impairments could be an interesting topic to be looked into.

2.2.5 Industry and commerce

The Architecture Industry has been evolving and relying more on the usage of Virtual Environments in their representations of the buildings they design, in a process they call

[10]How are 3D prints made in the entertainment industry?, https://www.thereyouhaveit3d.com/post/how-are-3d-prints-made-in-the-entertainment-industry, last access 12/2023

[11]The Virtual Production of The Mandalorian Season One - Video, https://www.youtube.com/watch?v=gUnxzVOs3rk, last access 12/2023

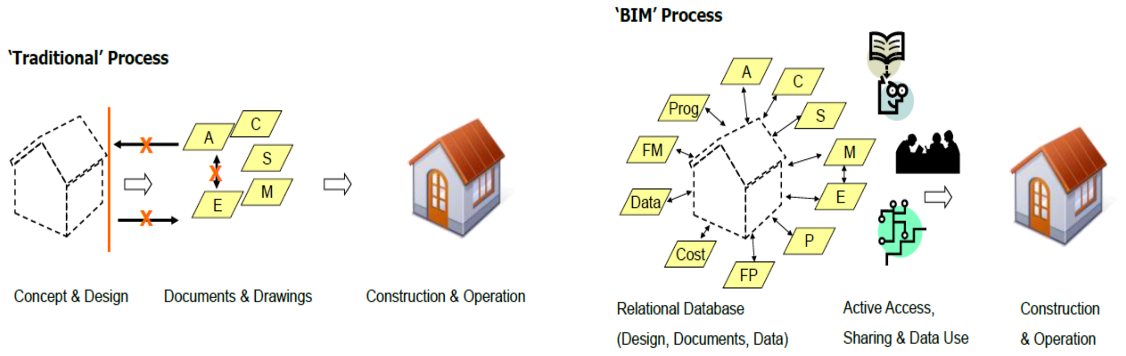

Figure 2.12: A Comparison between "Traditional" and "BIM" Process (Courtesy of: Holder Construction, Atlanta, Georgia, USA), taken from Azhar et al. [5]

Building Information Modeling (BIM) [5] where they connect various elements of the 3D Model to their documentation, something that could not be done before as seen in Figure 2.12. It is also of interest to note that there are studies into the usage of these new methods to enhance the documentation of already existing building [49], which we can link with the concept of preserving Cultural Heritage.

The Interior Design Industry is also one that highly gains from the use of Virtual Environments to simulate the interior design of houses[12], it helps them make more realistic and easy to understand representations for their customers with a more efficient process that also improves cost estimation for the team that will be implementing the design[13], and with the growing number of online CAD libraries such as 3D Warehouse[14]. they get more assets to use in their designs. There have also been recent developments in the creation of applications where the user can design an interior while using augmented reality (AR) or virtual reality (VR) in real time [22].

Virtual Environments can also be used to help industries inform their customers in a way that makes it easier for them to perceive and remember. In Nguyen et al. [40] they discuss a Virtual Environment based on a dairy farm, which can be seen in Figure 2.13, created in order to educate their customer base on the process and guidelines they follow to produce various dairy products. In this Virtual Environments users take a visit to a farm where they can see the animals in different stages of their daily routine while also being able to talk to interactive human agents that provide information about how the farm works and how they produce their dairy products.

The prototype for this Thesis will also aim to educate users with a Virtual Tour through

[12]How to Create 3D Interior Designs - 3D-Ace Blog post,
https://3d-ace.com/blog/how-to-create-3d-interior-design, last access 12/2023

[13]How 3D Visualization Can Revolutionize Your Home Renovation,
https://www.easyrender.com/a/how-3d-visualization-can-revolutionize-your-home-renovation, last access 12/2023

[14]Importance of 3D modeling for interior design by Vincent Sheppard,
https://blog.vincentsheppard.com/importance-of-3d-modeling-for-interior-design-3-reasons, last access 12/2023

a museum where the various objects in exposition will have extra annotations to help inform the user of the object's story.

2.2.6 Tourism

Many tourist attractions live off a unique element that distinguishes them from their competition, while others focus on providing the best experience possible in picturesque locations. Both of these require an advertisement method that shows their distinguishing aspects and Virtual Environments can be an answer to that, since it is a technology not yet used by most tourist spots, it's use already helps to distinguish from the competition.

In Lin et al. [31] a study that compared the 2D versus 3D tourism promotional videos found that 3D videos were shown to be more attractive to respondents than 2D videos, leading to them outperforming 2D videos in terms of intentions to visit. This study shows that there is value to be gained from the early adoption of 3D videos, as they have yet to be seen as the norm, creating more interest in the customer towards the advertised product.

As defined in Gursoy et al. [20] the metaverse is a "collective, persistent, and interactive parallel reality created by synthesizing all virtual worlds to form a universe that individuals can seamlessly traverse", social connections is also a key factor mentioned. As explored in this opinion piece, there has been a surge of interest in the use of the metaverse to promote and create tourism and hospitality experiences. Even though the metaverse cannot yet replace in-person travel and real-life sensations, it is mentioned in the piece that the Japan-based First Airlines has begun offering virtual flights from Tokyo, where the company has reported 100% occupancy for virtual flights to multiple locations, including Hawaii, Rome, Paris and New York. This shows the existence of a market for simulations of attractive touristic spots and the start of the conceptualization, done in Gursoy et al. [20],

Figure 2.13: A captured scene of the developed virtual dairy farm simulation, taken from Nguyen et al. [40]

on how to develop these technologies to answer this demand.

A more common example of Virtual Environments being used to advertise a tourist spot can be seen in Guzman et al. [4], where MNLTour is a 360° image based web application that enables virtual tours of select tourist spots in Manila, Philippines. While both the computer and android versions can access the web application and web page, only the android version can access the VR Mode. The application was created just after the COVID-19 pandemic, with the intent of promoting tourism in Manila and increase awareness on the filipino economy after the severe impact COVID-19 had on it. In the paper they reference a survey done by the Tourism Marketing Agency where they found that 78% of the businesses that used Virtual Tours reported an increase in the awareness of their brand, while 38.20% reported an increase in revenue from the use of Virtual Tours. Guzman et al. [4] is a good showcase of an application with all the expected basic features, that shows an interesting look into the effectiveness of Virtual Tours on a business's revenue and brand awareness.

Using Virtual Environments as a way to protect certain environments, such as buildings with low physical or chemical integrity. This idea links with the concept of preserving Cultural Heritage and can be seen applied in Caciora et al. [10], where a website was made with Virtual Environments based on 3 Wooden churches from Romania. The Virtual Environments were made up of 3D models of the interior and exterior of the churches, with the addition of panoramic images of the churches and 3D models of certain objects. This was done to document the the creation process for such technology, in order to push for the adoption of sustainable tourism, where Virtual Environments are used to reduce social and environmental impact on tourist spots while still offering a quality experience to visitors.

2.3 Virtual Tours

We cannot begin talking about Virtual Tours without mentioning Google Arts & Culture initiative[15], as it already contains a wide number of virtual tours and 3D Objects that anyone can access, while working with many cultural institutions and artists around the world. Google Arts & Culture has defined people's expectations on how a Virtual Tour is supposed to look like, many museums are already using their systems, because they use the cheapest and easiest scanning method (360° scanning) in order to create simple experiences where a user can "walk" through an image of the inside of a museum.

However Aishan Zhang [51] criticizes how Google Arts & Culture changes the way each piece of art is interpreted from the way the original creators meant them to be, be it from the angle photos/videos are taken, image quality, even the addition of a narrator/audio guide or background music to their Virtual Tours, greatly influencing the narration of viewing art. This criticism could also be made towards other Virtual Tour technologies,

[15] Google Arts & Culture, website link for the Google Arts & Culture About Page, https://about.artsandculture.google.com/, last access 11/2023

such as the one used in thesis, however in this thesis we want to give the visitor the most control over how they visualize an object as possible, which should help to answer some of the problem brought up by Aishan.

Nevertheless, Google Arts & Culture's dominance does not mean Virtual Tours are limited to only using 360° scans, as we will be creating a Virtual Tour with the usage of 3D scans and it will also be shown that 3D scans and Virtual Environments are more versatile, allowing various kinds of modifications, which 360° scanning cannot allow as it creates static 360° images.

Technology In a study ran by Adriel and Jean Felipe [42] they found that the quality of the user experience for a virtual tour using 360° images was relatively similar on most devices ("a laptop computer with a mouse, a smartphone," "and a Samsung Gear VR HMD"), except for the Google Cardboard which had a significant worse user experience score when compared to the rest. While in Kyrlitsias et al. [26] their feasibility study between VR and desktop computers they found that even though VR has higher levels of presence and a better experience in comparison to the desktop version, Desktop helped the participants acquire and memorize more information than VR, and both had the same effects in the participant's attitude towards acquiring new knowledge about the location of the virtual tour. Meaning that nowadays there are a wide range of technologies that allow for a quality virtual tour experience where the price does not have a big impact on the experience provided.

2.3.1 Museums

One of the most recognizable uses for virtual tours is in the aid of museums, since they deal with old artifacts that have become fragile and hard to move around, making the creation of a virtual twin a safe method to increase the artifact's visibility and reach. We will be looking into various kinds of virtual tours which differ from the established norm of Google Arts & Culture.

Virtual Reality and Augmented Reality are rarely thought to be used together, however in Ulfatun Nafi'ah et al. [38] a fusion of both was used, or in their own words, a collaboration between Augmented Reality and Virtual Reality in one application was created. This is an android application where the user can visit the Museum of Universitas Negeri Malang, in Indonesia, through a guided video with a virtual guide giving the user a tour through the museum, an example of the application running can be seen in Figure 2.14. The Augmented Reality elements come from the way they present the tour, where there is a contrast between the virtual guide and the museum, while the Virtual Reality elements come from the usage VR technology to achieve this experience, as the user is not actually inside the museum, he is just being shown a virtual representation of it through a VR video format.

There have also been platforms created to allow a customizable experience that any member of the museum staff or team can assist with, seen in Zidianakis et al. [53] they created Invisible Museum, a "user-centric platform that allows users to create interactive and immersive virtual 3D/VR exhibitions", that can be seen running in this video[16], the platform is focused on allowing collaboration between users and being accessible to users with no previous knowledge or experience with this kind of technology. Before making an exhibition the user must upload the objects they wish to showcase, the latest version of the interface can be seen in Figure 2.15, the objects have annotations associated to them, some are required like the title, description, category, dimensions and object type (i.e., text, 3D model, image, sound, video, etc.), but there is also the ability to add custom attributes defined by a key-value relationship. The objects can then be moved, rotated and scaled as the user pleases when put into an exhibition. The exhibitions themselves can be fully customized by having the user adjust the walls in a two-dimensional floorplan, followed by the generation of it's 3D representation and the ability to add more predefined elements like doors, windows, furniture, floor/wall textures and lighting, not forgetting the 3D objects added by the user themselves, the Exhibition Designer can be seen in Figure 2.16. This take on Virtual Tours of museums is very much in line with the application that we want to develop for this thesis, as we also want to enable easy customization of exhibits and guided visits in a 3D virtual environment, with a rich database of 3D objects and their respective annotations.

A metaverse like experience could also be applied to virtual tours, where visitors can communicate with one another and visualize each other's presence through the use of avatars, populating the Virtual Environments and increasing immersion through socialization.

10 chinese museums have experimented with the usage of Cloud Editing Digital Museum (CEDM), as seen in Yang at al. [50]. CEDM is an application that allows museums to create a digital twin of themselves to a cloud storage, which can then be

[16]The Invisible Museum - Video Showcasing Platform, https://www.youtube.com/watch?v=5nJ5Cewqngc, last access 01/2024

Figure 2.14: Guide Video - Replica of Rector's Desk, taken from Ulfatun Nafi'ah et al. [38]

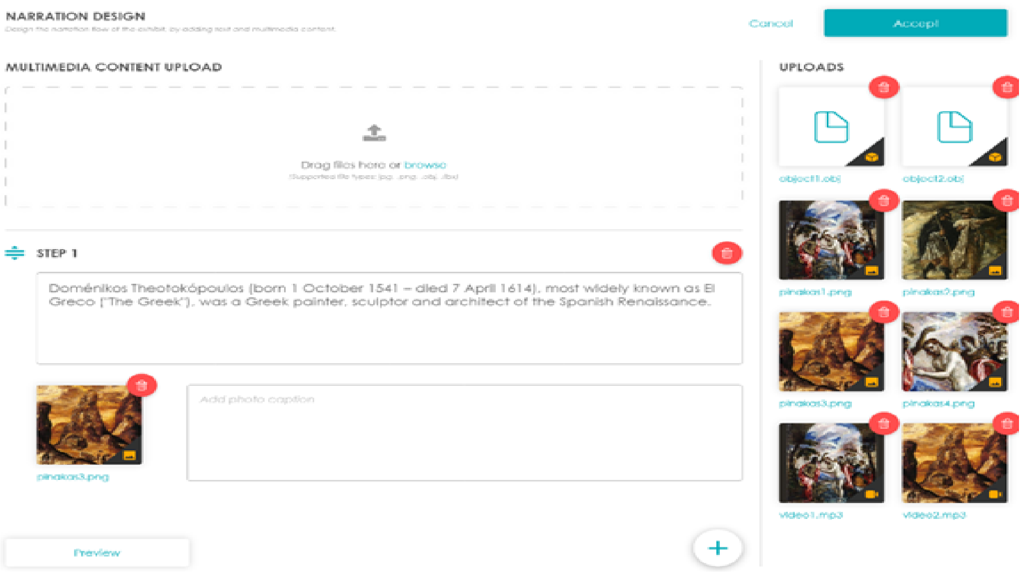

Figure 2.15: Add digital exhibit Menu, taken from Ulfatun Nafi'ah et al. [53]

accessed by visitors in a metaverse like tour that can be experienced with or without Virtual Reality glasses. The Virtual Tours in these museums allow users to represent their presence with an avatar and username above the avatar's head, they can also converse with each other in a text chat inside the application, Figure 2.17 shows us how a Virtual Tour looks inside this application. The paper also mentions "cross-platform cultural digital inheritance activities", that refer to the moments when students share the tours content on social media. The China Silk Museum took the CEDM application and enhanced the interactivity of the "Silkworm Weaving Drawings", a famous painting drawn by Lou Xuan, by creating a dynamic simulation showing the process from farmers raising silkworms to

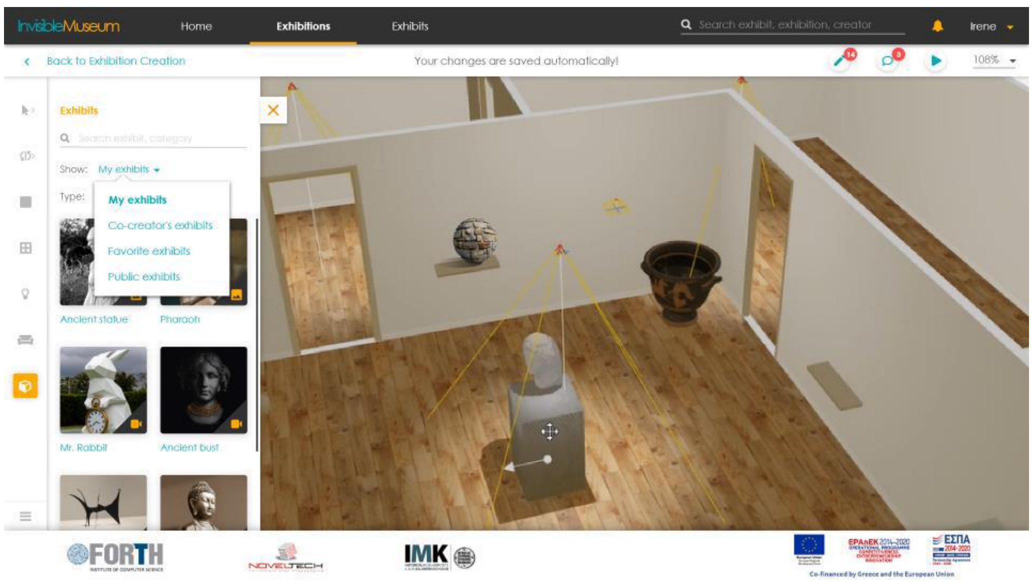

Figure 2.16: Exhibition Designer, 3D design tool, taken from Ulfatun Nafi'ah et al. [53]

Figure 2.17: Students visit the school history museum, taken from Yang et al. [50]

the silk being woven into silk fabric, Figure 2.18 shows a screenshot of a Virtual Tour to this exhibit. This is a very interesting way to take advantage of the digital space in order to immerse and inform visitors about one or more pieces by taking them inside the painting and living through it's narrative.

Both of these last two Museum Virtual Tours are an excellent example of what an application that allows for the creation and tour of virtual museums should look like. They have simple interfaces that allow for the easy addition of new objects, editing of the object's annotations and the virtual environments that represent their expositions.

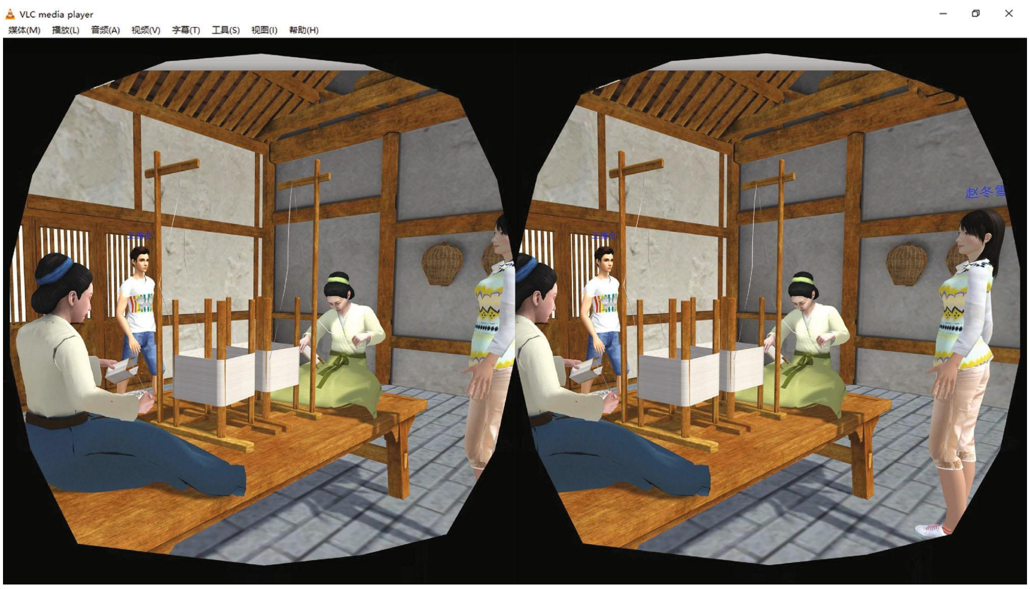

Figure 2.18: Visitor wears Oculus to visit the Silkworm Weaving Drawings Museum, taken from Yang et al. [50]

2.3.2 Educational

The use of Virtual Tours as educational tools is still a debated topic. To help us understand the current state of this discussion we will look into some articles covering this question and testing it's validity.

In Shahab et al. [44] they did a study to see if Virtual Reality could be used to promote visitor enjoyment and learning. They ran an experiment in the VRlab of Deutsches Museum, where participants experienced all four VR exhibits and were interviewed after using the VR about both expectations and post-usage evaluations. Their results found that VR experiences effectively promoted learning among visitors. Entertainment, education, and telepresence were assigned as driving factors behind a pleasant experience with VR, however novelty proved to cause the opposite as people new to VR may be overwhelmed by the device and how to use it, taking focus away from the VR content, worsening their experience. This is important as a correlation was made between better experiences and higher learning effectiveness. In addition, visitors expect a high level of entertainment when experiencing VR, leading the authors to suggest that museums should focus their marketing and developments on the entertainment brought forth from the VR experiences in order to attract and enhance the visitor's experience as a method to promote learning. A limiting factor of this study was the lack of variety in topics, meaning that the effectiveness of VR might be dependent on the topic, but even in this study the finding suggests that topics that may be perceived as less exciting can still benefit from VR.

Another literature review [52] also found that when given only a short period for investigation in a science museum, students using AR demonstrated significantly greater knowledge gains than those who did not. However, another study has contested this by saying that AR games did not necessarily improve learning performance or social interaction when compared to the traditional learning method. Some studies have also reported that AR/VR-assisted museum learning promoted higher-order thinking skills, such as creative thinking, inquiry, and critical thinking skills. Meaning that there is still more research needed in order to confirm the validity of these technologies in the promotion of learning in a museum setting. Fortunately, there has been an increased interest in researching the incorporation of virtual and augmented reality in learning practices.

In Leet et al. [29] they have done experiments with children in order to explore the effects of the Blended Learning Model, which utilizes symbiotic online and offline conversions to enhance learning effectiveness. In this study they created a 5 step learning activity where the children were told to assemble a 3D model of the monument being studied, visualize the model in the AR app, then read information pertaining to the topic from their textbooks, now with AR app they explored a 3D model of the monument's interior where they were asked various question based on the content of their textbook in a gamified manner, and lastly they visited the museum related to the topic, part of this process can be seen in Figure 2.19. The programme was found to be appropriate for elementary school third and fourth graders, that had a very positive response to it. When asked which learning method they preferred, blended versus one-way information delivery (e.g. text and video), the children picked the blended method. The learning effects were confirmed in relation to the children's success in answering the questions made by the AR app.

2.3.3 Cultural Heritage

The use of Virtual Tours to preserve the current state of cultural heritage sites is already being normalized through Google Arts & Culture. However there are many other ways this technology can be used to help the people who maintain these locations, such as with the use of 3D models inside a Virtual Environment, as it can be seen in Ferraz et al.[17]. The same technology used in Virtual Tours can also be used to more efficiently share and explain information, such as changes in the state of the structures between parties.

In Fino et al. [18] they discuss how Virtual Tours of Cultural Heritage sites and the artifacts they create (i.e. 360° panoramic scenes, 3D models) can be used for more than just Virtual Tours. They can also be used to perform assessments on the state of conservation of these structures, safeguarding their tangible and intangible characteristics. Risk Management is also an important factor for these sites, where Virtual Tours can be used to preview escape routes and dangerous paths, which can then be communicated to the visitors through the same medium. The article also explain how they found virtual

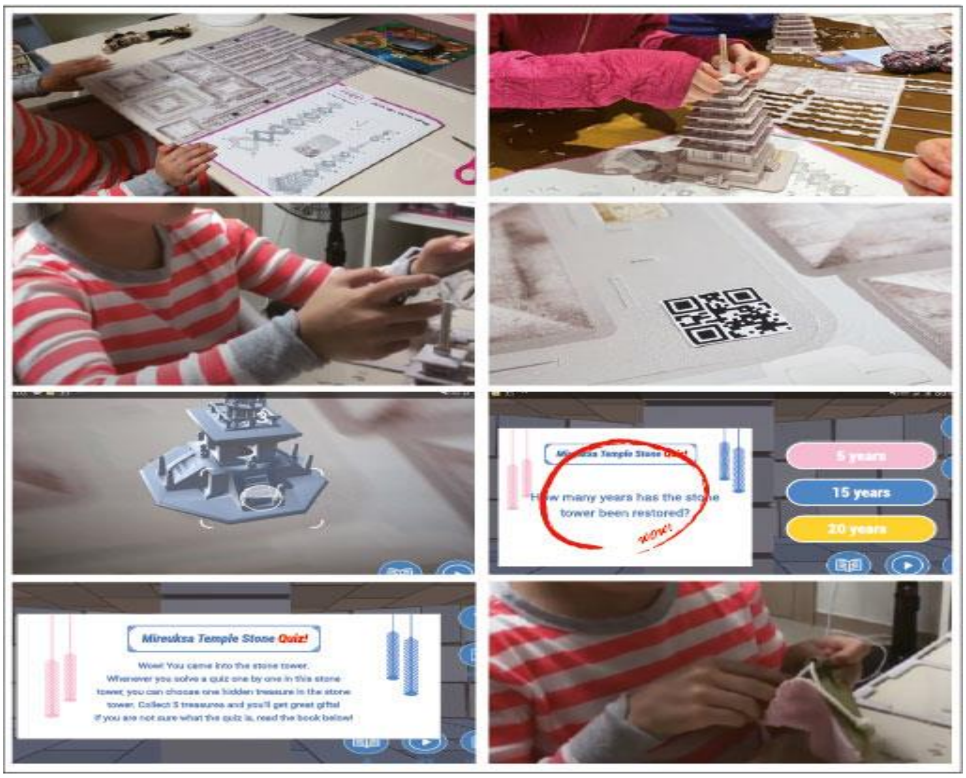

Figure 2.19: Experimental test process, taken from Lee et al. [29]

tours of 360° panoramic scenes to be the more appropriate focus of their attention given their faster acquisition/creation and the tools being lower cost and more user-friendly, however they still mention the usage of 3D models to enrich a virtual tour and how 3D models can play a key role in a more accurate representations, making them a more flexible and scalable solution.

An attempt to lower the cost of 3D models for this use case was done in Napolitano et al. [39], where the solution they came up with was to use 360° panoramic images, chosen for their lower price, faster acquisition speed and smaller file sizes, leading to less resources being spent on data management. The 360° images were supplemented with tools to help visually indicate points of interest and link to outside sources and files, such as 2D maps and older reports. This method was deemed useful but only in an initial stage to begin communications between partners, assessments and documentation, as it does not have as much detail or versatility as a 3D models, where one can have a more complete view of a structure or object.

Nevertheless, the most common use for use for Virtual Tours in the aid of Cultural Heritage sites is still to promote and share these historic locations with the wider public. Even Cultural Heritage sites with bad accessibility or just generally hard to reach can now get a chance to be visited by a much wider audience, as we can see from Kyrlitsias et al. [26], where they created a Virtual Environment which simulates the archaeological site of Choirokoitia in Cyprus, which is a site that does not have good accessibility, but it's settlement is still studied to this day in Cyprus's primary school history curriculum and it is one of the most visited tourist attractions in Cyprus, as it is ranked among the top oldest ruins in the world. So we can see the value in creating a digital replica of this location not just to preserve the cite as Cultural Heritage, but also for educational purposes and this article shows a good step forward towards a well documented high quality recreation of this location that will be able to dynamically adapt to new technologies and the needs of it's users.

3

Analysis and System Design

In this chapter we will be reviewing the problem we seek to solve and the solution we proposed to solve it. We will specifically be covering the requirements we set for the solution, the methodology followed and work done in order to acquire the 3D models of museum objects used in this thesis, ending this section by describing the design for each planned feature and the system's architecture.

3.1 Problem and Case Study

There already exist many Virtual Tours available to the public, however most are based only around the usage of 360° Images, as commonly seen in the Google Arts & Culture initiative[1], making these visits hard to differentiate and lackluster when it comes to the ability to interact with the objects on display. Even so, when there is a 3D model based on some of the objects on display, many times, it requires a third party website or application in order to be interacted with by the user, the model is also disconnected from the various annotations that are on display next to the real life object and the ones shown in the Virtual Tour. Meaning there is a lack of classification (documentation and cataloguing) for these models. Nevertheless, 3D Scanning can be a costly and time consuming activity especially for museums, making them usually just choose the cheaper option of using 360° Scanning technology, even though 3D scans would provide a much more long lasting and dynamic form of simulating and preserving objects of Cultural Heritage.

To solve this problem we proposed an application for creating and exploring Virtual Tours in a 3D Environment, with the focus of this thesis being on adding new features that allows for the classification of 3D models through the use of Annotations, a search bar, a function that allows the creation of 360° Image based Virtual Tours and a built in Interactive Visualization Tool that lets users interact with a 3D model and it's annotations. To build the proposed application we built upon an application that had been developed in a previous thesis [46] as a base. However this application was very simple and had

[1]Google Arts & Culture, website link for the Google Arts & Culture About Page, https://about.artsandculture.google.com/, last access 11/2023

some issues, the biggest one was that it did not allow users to edit Virtual Tours after they were saved to the database, leading to a stressful user experience, where one mistake leads the user to have to remake the Virtual Tour he had already built.

To assist in this solution a case study was needed, using buildings and objects with cultural value would be best since we are focusing on the use cases around museums, additionally we require the buildings to be in either a 3D or 360° Image format, while the objects can only be in a 3D format.

With these requirements we decided to reuse the 3D model for the *Forte da Trafaria*, visible in Figure 3.1 which was already used in the previous dissertation [46] and proved to be in line with the subject of this thesis. The remaining assets required came from the *Academia das Ciências de Lisboa*. They came from various scans that were done to rooms and objects, the 3D models were specifically created from the scans done to a model of a human heart, a frog mask and a model of the human body. For the 360° Images, we used the ones taken while scanning Room 4 from the *Academia das Ciências de Lisboa*. A 3D model of Room 4 was not used, because it and other rooms of the *Academia das Ciências de Lisboa* were only scanned using 360° Scanning techniques, so we could only make use of the 360° Images taken during the scanning process. These assets were used in the User Studies we ran (Section 5.3 and 5.5). We used them to built two small Virtual Tours and as assets that users could use while testing the Editor Interface.

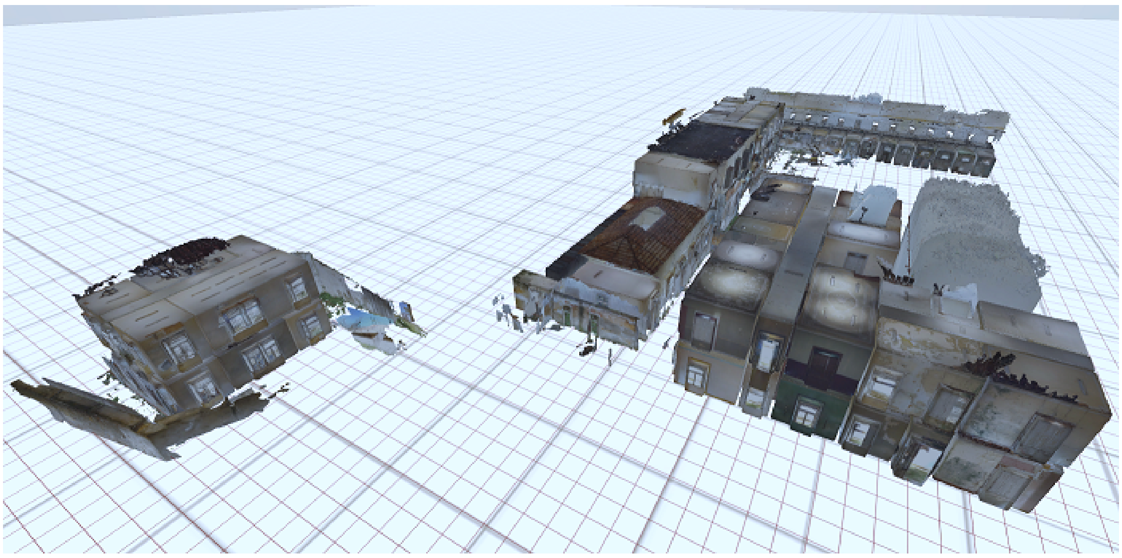

Figure 3.1: *Forte da Trafaria* inside the developed application

3.2 Requirements

As we sought to make an application to aid in the creation and exploration of Virtual Tours for museums and with the problems that have been laid out. This section will present the main requirements for the system design and implementation.

It is required that the system allows the user that creates the Virtual Tours, the Editor, to add and classify 3D models with their respective annotations and use 360° Images as substitutes for 3D Environments. To successfully use 360° Images as Virtual Environments a method for transportation between images is required, the automated linking of these images is also desireable, since 360° Image based Virtual Tours will require the use of tens of images to simulate various rooms and manually linking each and every image would become a very time consuming process for the user. For the item's catalogue we also need to add a search bar to be able to search various items by name or in the case of 3D objects by their annotations too.

On the other hand, for the user that will explore the Virtual Tour, the Visitor, the application should allow the user to explore the Virtual Environment with the newly added 360° Image based Virtual Tours in mind. A new method of visualization and interaction with the various 3D models shown should also be added. This could be achieved through a pop-up window that lets the user rotate, zoom in/out of the object and view the various annotations connected to a given model.

The application needs an update to the inner workings of it's database. The database needs to be updated to add annotations to a 3d model, the various operations related to 3D models, such as the upload and get operations, will also need to be updated and new ones will have to be created with annotations in mind.

The application also needs an update to it's Virtual Tours save feature, as it does not allow a user to edit a Virtual Tour after it has been saved, requiring the creation of a new menu that lets the user call back already saved Virtual Tours so the user can edit them.

In summary, the main requirements for the application are:

- The addition of the ability to add and edit annotations to specific 3D models, which can also be used to better catalogue these models.
- The addition of a search bar, that can search by item name, and in the case of 3D models, also by their annotations.
- Allow 360° Images to be added to the application and correctly displayed in a Virtual Environment.
- Create a method by which a user can move between 360° Images.
- Create a system they will automatically connect nearby 360° Images.
- The creation of an Interactive Visualization Tool.
- Update the current database to add annotations directly to the data about a specific 3D model.
- Update current Virtual Tour save feature to allow for the editing of saved Virtual Tours.

3.3 Methodology

Before covering the development methodology used for the application we will first cover the steps we followed to acquire the 3D model of an object through 3D scanning.

3D acquisition starts by gathering 3D scans of the object that we wish to use. These scans will create a point cloud in the shape of the scanned object, which can then be processed into a solid 3D model and textured with the color data taken while scanning. However, this process is not infallible and getting a good 3D model on a first try is not always possible, leaving us with two options, either rescan the object or fix the imperfections in the postprocessing stage. A lot of time can be spent in this stage, scanning and then rescanning or editing the 3D model until it is up to the desired quality. A more detailed explanation of the 3D Scanning process can be read in Section 2.1.1.

Once the 3D model is complete and up to the desired standards, we can finally upload it to the application by sending the model's files and choosing a name for it to be stored by in a database. A stored 3D model can now be used through the catalogue, where it's annotations can added and the model can be inserted inside the Virtual Environment where the Virtual Tour is being created.

A similar process is also followed in order to add 360° Images of room spaces to the Virtual Environment, where the biggest differences come from the type of camera that needs to be used and that we would be working only in two dimensions, which should make it easier to get the results we want with little to no postprocessing.

A visual representation of the development methodology used can be seen in Figure 3.2. We followed a similar strategy to the Agile methodology[3], but without the deployment step, since the application is not being used commercially.

Initially we planned what features would be required, followed by their design. Once the designs were complete, the features were developed. After all the planned features had been developed we planned and conducted a user study to evaluate the state of the application. Lastly, the results gathered from the user study were reviewed.

This cycle was followed two times, which lead us to conduct two user studies, where the second cycle was used to improve the application based on feedback received from the first user study. It is also worth mentioning that various meeting were had with the advisers during all the steps in these cycles to make sure everything was being done properly.

3.4 Data Collection

It was necessary to scan nearly all the 3D models and 360° Images used for this thesis, most of the work was done during the preparation phase of this thesis by following the steps described in the previous section. All assets used from this process came from the *Academia das Ciências de Lisboa*.

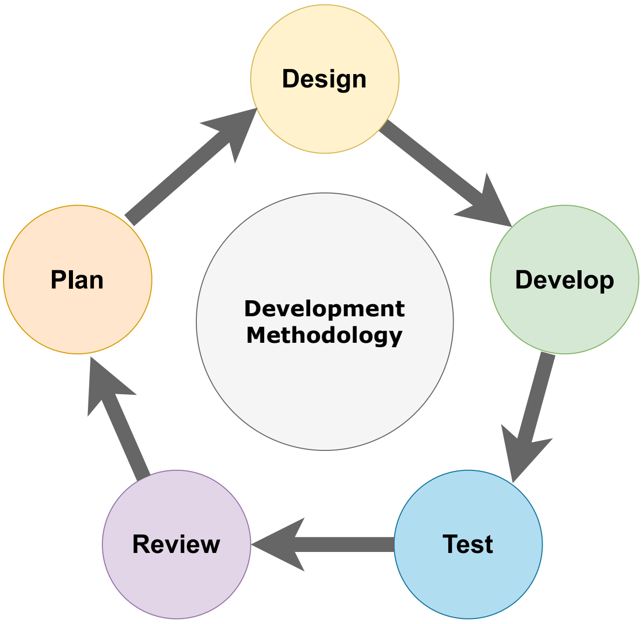

Figure 3.2: Development Methodology Diagram

The first 3D model we obtained was the model of a Frog Mask, the object was scanned and then the resulting point cloud was processed into a light weight model that was used to to run the initial tests. The point cloud and 3D model of the Frog Mask can be seen in Figure 3.3. However this model did not end up being used after the preparation phase, instead a model that was processed by a professional was used, the same is also true for the rest of the 3D models used in this thesis. These professional models are more detailed and more work has been done to fix scanning errors and optimize their size.

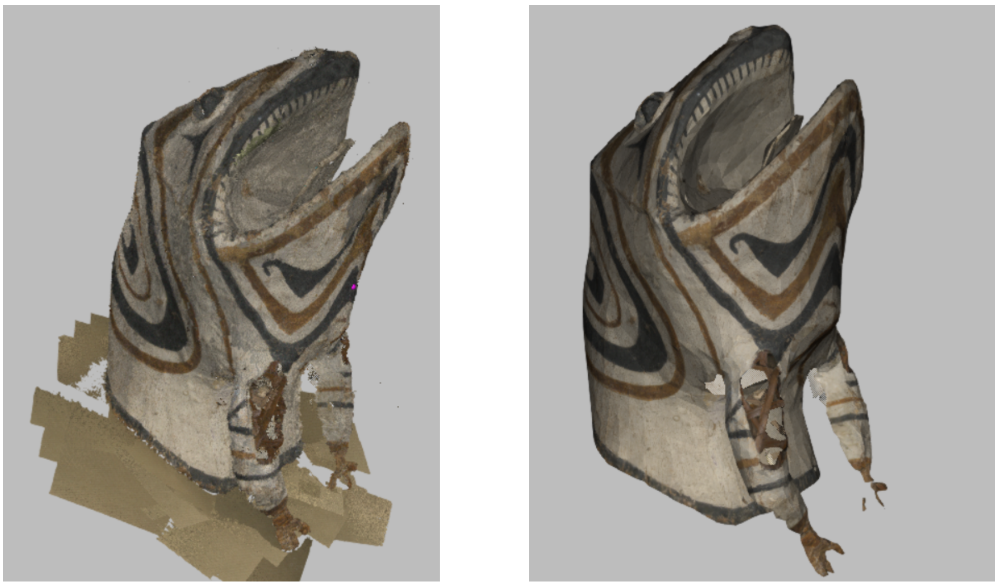

Figure 3.3: **Left** - Frog Mask Point Cloud, **Right** - Frog Mask Finished Model

Figure 3.4: 360° Image of Room 4 from the *Academia das Ciências de Lisboa*

In the case of the 360° Images used, they were gathered through 360° Scanning halfway through the development of the application. No postprocessing was done to the images after being gathered as we deemed it not necessary. An example of the images taken can be seen in Figure 3.4.

While collecting data from the museums, we were also able to see the kind of annotations museums use at the moment in their Virtual Tours, those only being an artifact's name and description. This was found when we received the annotations that the *Academia das Ciências de Lisboa* used for the artifacts that we had scanned.

3.5 Feature Design

In short, we sought to develop an application that allows users to create a Virtual Tour and then visit it. Through various meetings and visits to museums, we decided to focus on developing the aspects of the application that allow for the classification (documentation and cataloging) of 3D models, the use of 360° Images to simulate room spaces in a Virtual Environment and the ability to interact with 3D models for visitors. These feature were chosen for various reason, some of them being their relevance to the topics being studied, their complexity and how long they would take to develop as we had limited time to fully develop all of them. In more detail the main features that we planned to add were:

Annotations The application should allow for an editor to add annotations to a 3D model, such as description, images and tags. There should also be method to add annotations to a specific point of the 3D model. This should be done through a specific interface that we will call annotations window, this window will have all the actions related to annotations, simplifying this feature for the end user. When a 3D model is inside a Virtual Tour it should also be possible for the user to view the model's annotations while they

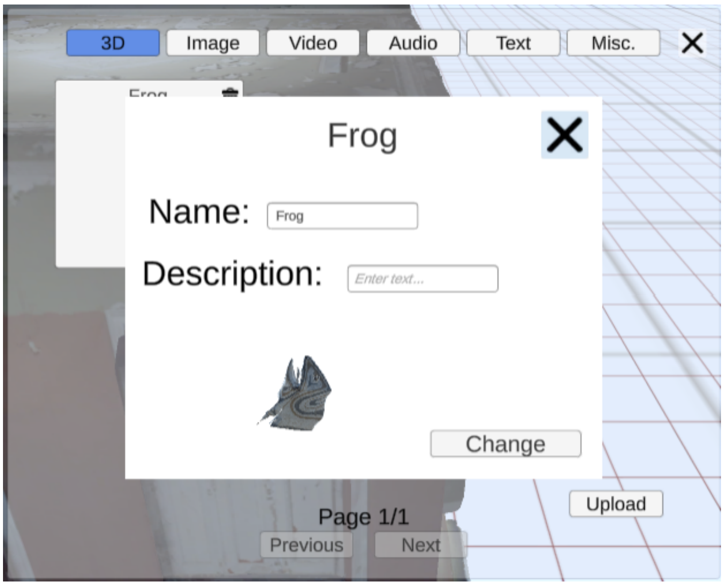

Figure 3.5: Frog Mask Test Annotations Window

visit the Virtual Tour. An early implementation of this feature can be seen in Figure 3.5, developed during the testing phase of this thesis, it served as a way to test adding simple annotations to a 3D model and to begin exploring the design space for the annotations window interface.

This felt like a must have feature when talking about documentation for 3D models. The most important choice made was the kinds of annotations that would be added. Personalized annotations and metadata of the 3D model were considered, but the space they would take up and the complexity they would bring did not seem worth it when thinking of the target audience for this application, which are less tech savvy users, such as the staff of a museum.

Search Bar The search bar should be inside the catalogue, allowing an editor to search for an item by name when inside their respective window. In addition it should be possible to search for 3D models by their annotations, specifically their tags. This additional search method should allow for multiple tags to be used to search at the same time, only showing the 3D models that have all of the tags being searched for.

This feature was decided on after thinking of ways to improve the current application's cataloguing ability, as the catalogue felt too simple and a search bar is a must in any application nowadays.

Interactive Visualization Tool This tool will come in the form of a window that allows a user to interact with a 3D model. The more common types of interaction such as rotating, zooming in/out and moving the model must be present in this tool. In addition, the tool should allow an editor to add annotations to a point in the 3D model and let visitors view the annotations and interact with them to view their contents. We will call these kinds of annotations 3D annotations and they should have a name, description and optionally an image. A drawing of the intended design for the Interactive Visualization Tool can be seen in Figure 3.6, we can see the interactive visualization window with a 3D model that the user can rotate, zoom and move around, and another window to the left with the detail of the 3D annotation that has been added to the 3D model. To access this window visitors should only need to point at the 3D model and click it with their mouse or tap a certain key in their keyboard. On the other hand, for editors this window should be accessible through the annotations window interface.

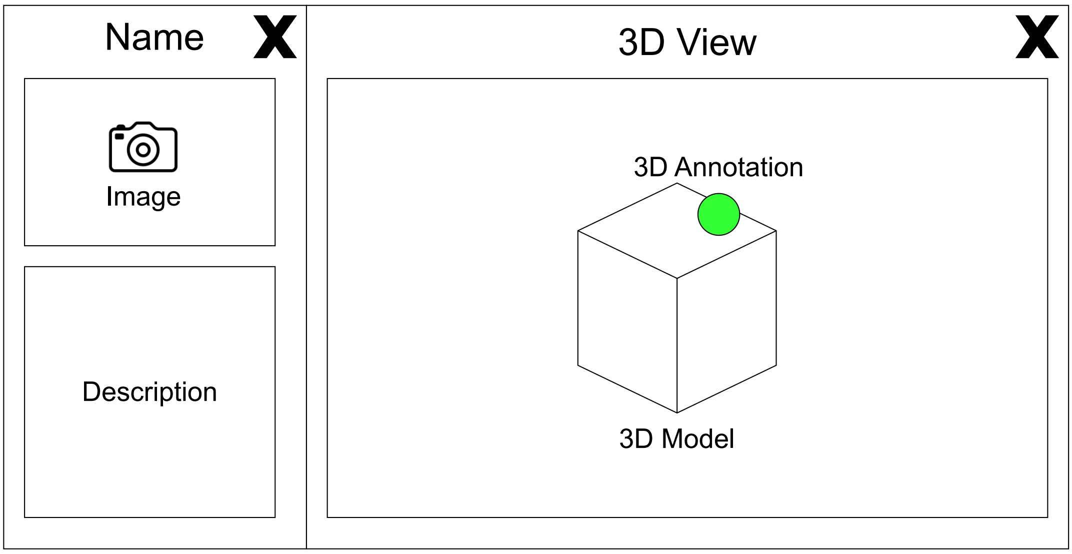

Figure 3.6: Drawing of the Design for the Interactive Visualization Tool

The idea for this feature came first from the viewpoint of a visitor and their curiosity to look through an object as a whole and not only from one set angle, everything else came afterwards in order to enrich this feature and making it more than just a simple visualization window.

360° Images Normally, 2D images are used as textures for plane shaped 3D objects, when inserted into a Virtual Environment. However, in the case of 360° Images, spheres are the most appropriate shape to use as a base to texture, but instead of applying the texture on the outside of the object, a 360° Image should be applied as a texture on the inside of the sphere. This allows for the full 360° Image to be visible from inside the sphere by simply rotating a camera at it's center. Nonetheless, this is not enough to make 360° Images truly usable inside a 3D Environment. A method for connecting the 360° Images between each other and the outside environment is needed. For this we considered the use of teleportation arrows, as already seen being used in other Virtual Tours that use 360° Images. These arrows should be created and moved automatically when two 360° Images move close to each other, Figure 3.7 shows a simple drawing of this interaction.

These arrows would transport a user from one 360° Image to the center of another image. This feature comes from the fact that a Virtual Tour would require the use of many 360° Images and having to place and link every arrow to connect the various images together would be extremely time consuming.

Lastly, this idea came from the necessity to make use of the various 360° scans that were being done at the time, which could have automatically been turned into 3D models, but since that would require extra costs with no quality guaranties we decided to try and make use of the acquired 360° Images.

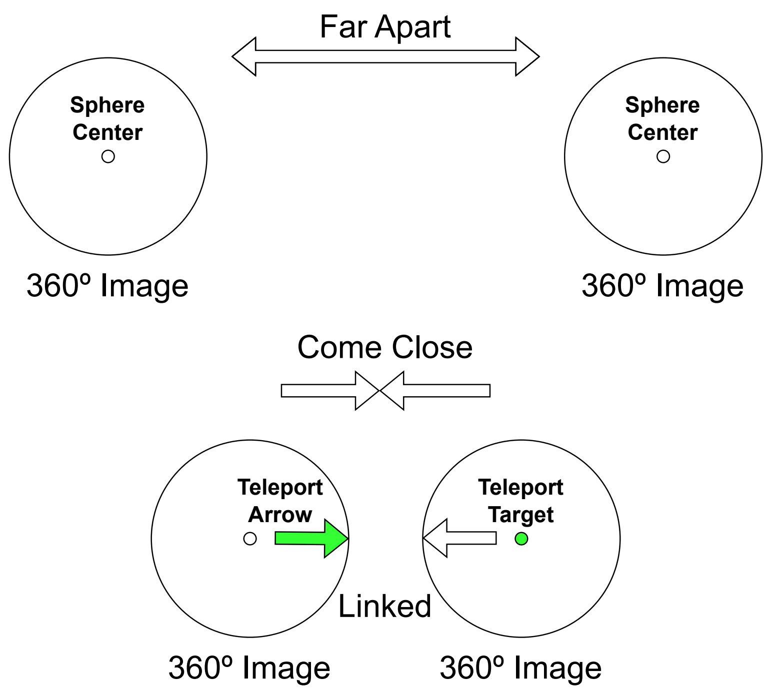

Figure 3.7: Simple Drawing of the Automatic Creation of Teleportation Arrows inside 360° Image Spheres

4

System Development and Description

The development of the proposed features and additional improvements done throughout the development phase will be discussed in this chapter. We will start by giving a quick overview of the website and application, followed by an explanation of the development of the new features and additional improvements.

4.1 Platform Overview and Architecture

The application's architecture was designed early on, the proposed design can be seen in Figure 4.1. The application was developed with Unity in the WebGL format, allowing it to be ran inside a website, which has already been developed. A database was also paired with the application in order to save the content that gets uploaded to it, such as 3D models, images, sound and video files. With the addition of annotations this database will have to be updated to allow the addition of annotations to a 3D model's data. The two user types Editor, a user that creates/edits Virtual Tour, and Visitor, a user that explores a Virtual Tour, should be easily understood. Lastly, all of the Features previously talked about in this section are present in a separate diagram that describes the interface, seen in Figure 4.2. The Basic Interactions feature refers to the rotation, zoom and moving interactions already described for the Interactive Visualization Tool.

The application was developed using Unity in the WebGL format with an already developed accompanying website and database. The database and application were the systems that were mainly focused on to add the proposed features.

Similarly to a user, we will begin by looking at the landing page of the website, visible in Figure 4.3. Through this page we can go to the Editor's side of the application or the Visitor's, the user can also log into their account or register a new one, which can be done in any other page too.

After selecting either interface, the user is met by the same page regardless of their choice. This page is visible in Figured 4.4, where we can also see the Visitor Interface while exploring a Virtual Tour, the user is pointing towards the 3D model of a human heart and is able to read the model's description on the right side of the page next to

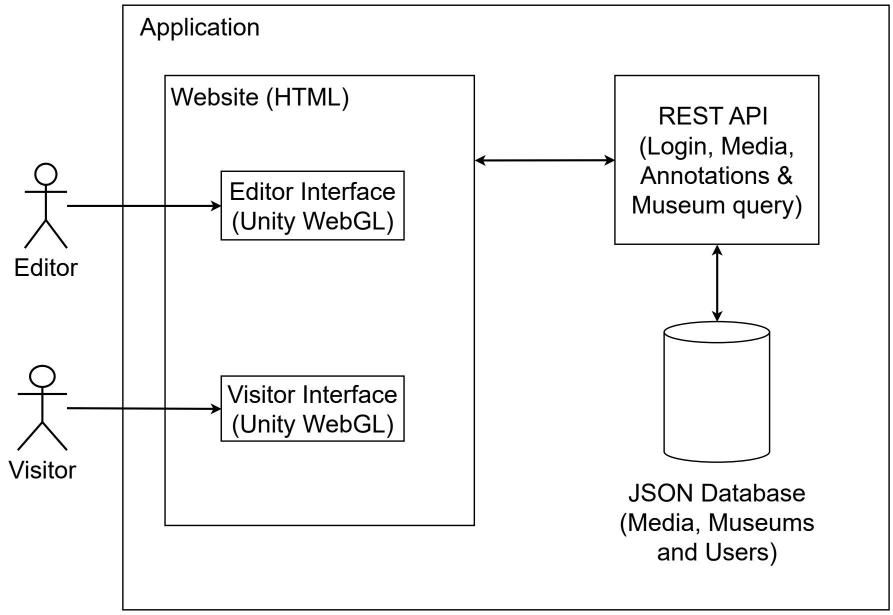

Figure 4.1: Diagram of the Proposed Architecture

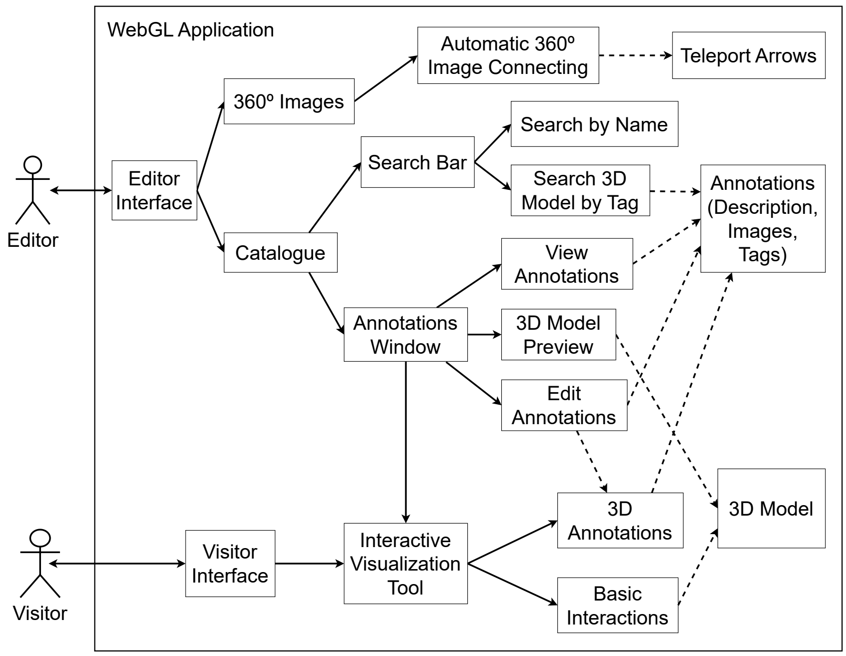

Figure 4.2: Interface Diagram

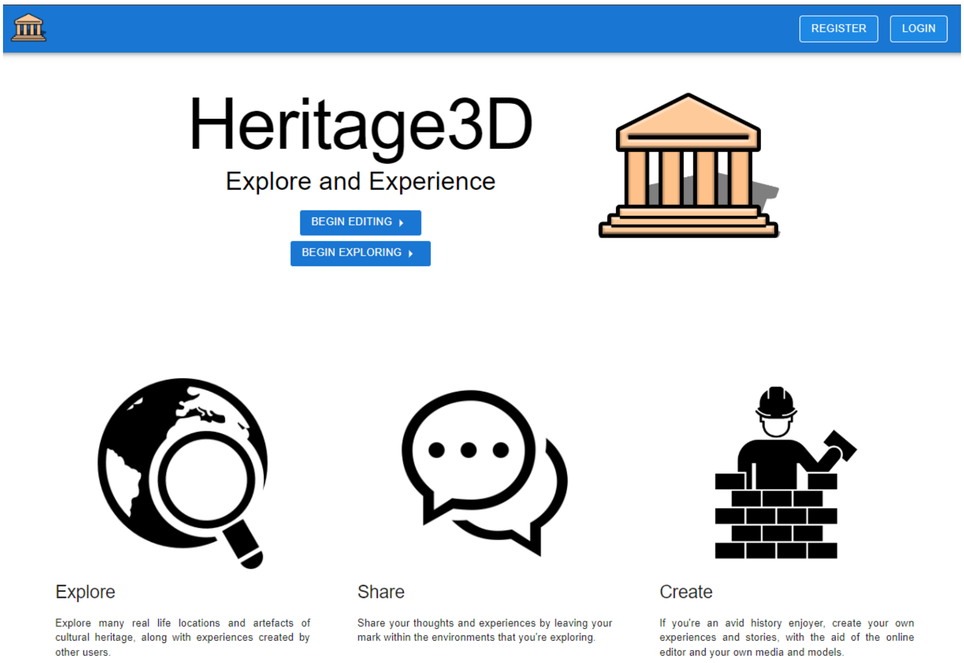

Figure 4.3: Landing page

the application's window and can interact with the 3D model further, with the proposed Interactive Visualization Tool, by left clicking the model with their mouse. The user in Figured 4.4 is also inside a 360° Image, where they cannot move and can only rotate their camera and teleport from one 360° Image to another by clicking the green arrows inside the image. Outside of a 360° Image the user can move by using the arrow keys or the WASD keys. We can also see three buttons with their corresponding keybinds above them in the Visitor Interface, the button on the far left with the letter C above it allows a user to open a catalogue where they can upload their own content to use in specified spaces, the middle button allows the user to leave the normal walking mode and instead fly through the virtual tour and get to view it the same way an editor can. Lastly, the button on the right allows the user to unlock and lock back their mouse in case the user prefers to actively rotate their camera by dragging the screen, instead of passively doing so by just moving their mouse, which is the default setting.

Lastly we will look at the Editor Interface, which can be see in Figure 4.5, where we can see two menus on the left, with various buttons below them, and another menu on the right. Menu A serves as the item list, containing all items added to a Virtual Tour and highlighting in blue the current selected item, also seen with a green sphere in the scene. Menu B is the Tool menu which contains some supporting features in this application. Menu C has the Edit features for the currently selected item.

The previously referred buttons, which can be better seen in Figure 4.6, from left to right are used to access the Media Catalogue, Sky Menu, Guide Menu, Museum List and the last button lets the user lock their mouse to the center of the screen.

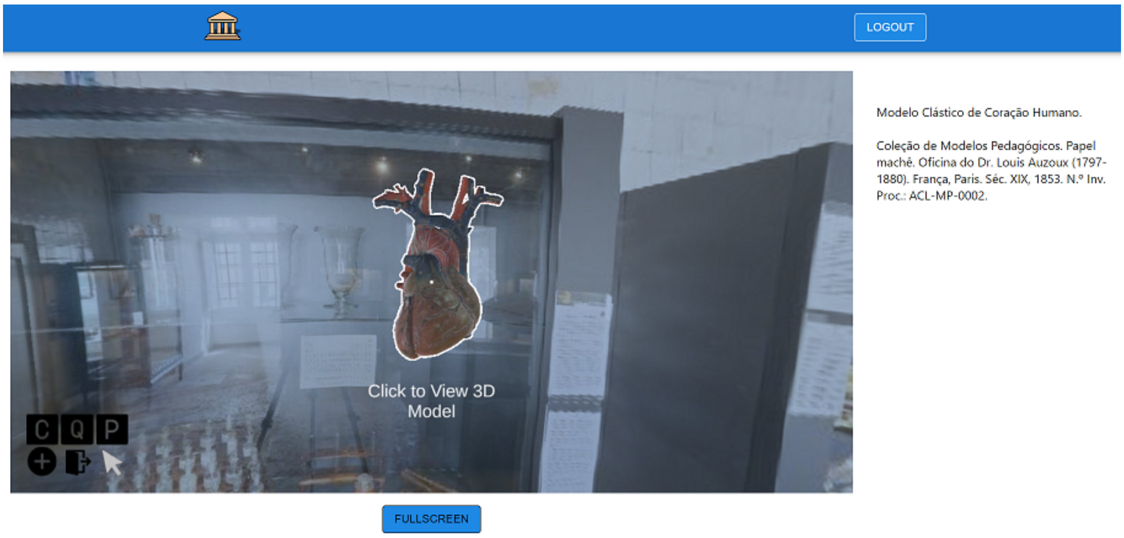

Figure 4.4: Website page with the Visitor Interface.

Figure 4.5: Editor Interface with side menus open. **(A)** – Scene item listing, containing all items added to the scene and in blue highlighting the current selected item, also seen with a green sphere in the scene. **(B)** – Tool menu which contains some supporting features. **(C)** – Edit features for the current selected item

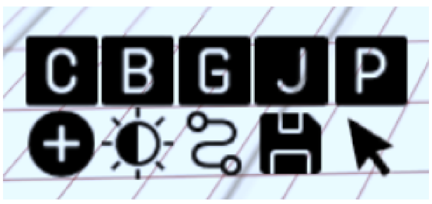

Figure 4.6: Buttons from the Editor Interface. **C** – Media Catalogue, **B** – Sky Menu, **G** – Guide Menu, **J** – Museum List, **P** – Lock Mouse Button

4.2 3D Models

This section will cover all the developed features related to 3D models. The classification and interaction with 3D models will be the core themes in this section, as we will cover the development of the annotations and the Interactive Visualization Tool.

4.2.1 Annotations

As described in Section 3.5, a 3D model can have various kinds of annotations linked to it, those being, a description, tags, images and 3D Annotations. No more kinds of annotations were added as no need had been found during development and because the *Academia das Ciências de Lisboa* had only asked to add certain preselected names and descriptions to the models of their items, this made it so any additional annotations had to be useful or needed in some sort of way. Tags were added for their value as classification tools, enhancing the ability to document, catalogue and search for 3D models. 3D Annotations, annotations that are linked to a point within a 3D model, were added as a way to allow users to interact with a 3D model and it's annotations at the same time, while Images were added as another form of documentation.

Every annotation is linked to their respective 3D model inside the database and is also loaded together with the 3D model whenever a signed up user opens up their catalogue.

Annotations can be accessed from the annotations window, which can be seen in Figure 4.7, and is accessed through the catalogue by clicking on the cog wheel inside the 3D model's card. By looking at the annotations window we can see that we have immediate access to edit the model's name, description and tags. Changes done to these three annotations need to be saved by clicking the Save button. The Image buttons allows us to access another window with all the images linked to that model and the 3D button leads us into the Interactive Visualization Tool's window, where the user can interact with the model and add 3D Annotations, which will be further explored in the next subsection.

4.2.2 Interactive Visualization Tool

This tool was created to broaden the extent a user can interact and view a 3D model. One of the reasons we had for building it as an unique window was to make it be more easily imported from the editor interface, after being developed, into the visitor interface.

This Interactive Visualization Window can be seen in Figure 4.8, where we can see a zoomed in 3D model of the human body with a 3D annotation, represented by a red sphere, stuck to it's chest. From here the user can move the model around with the arrow or WASD keys, zoom in and out of the model with the mouse wheel, rotate the model by dragging it, hide the annotation by clicking the G key and open the annotation by clicking on it. If this window was open in the Editor Interface it would also be able to add new 3D annotations, a function that will be explained further in the next subsection.

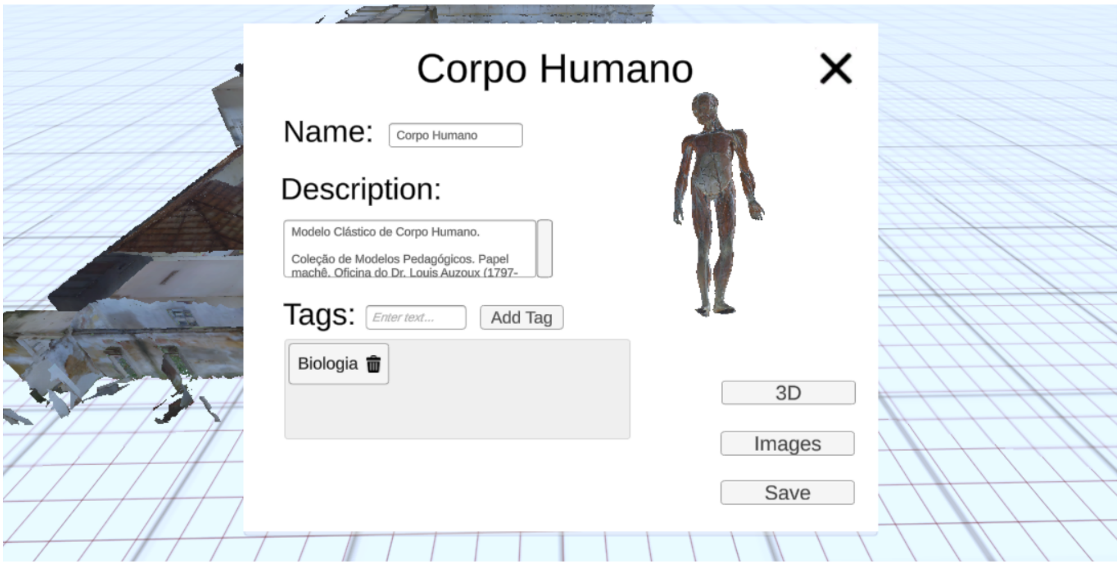

Figure 4.7: Annotation Window

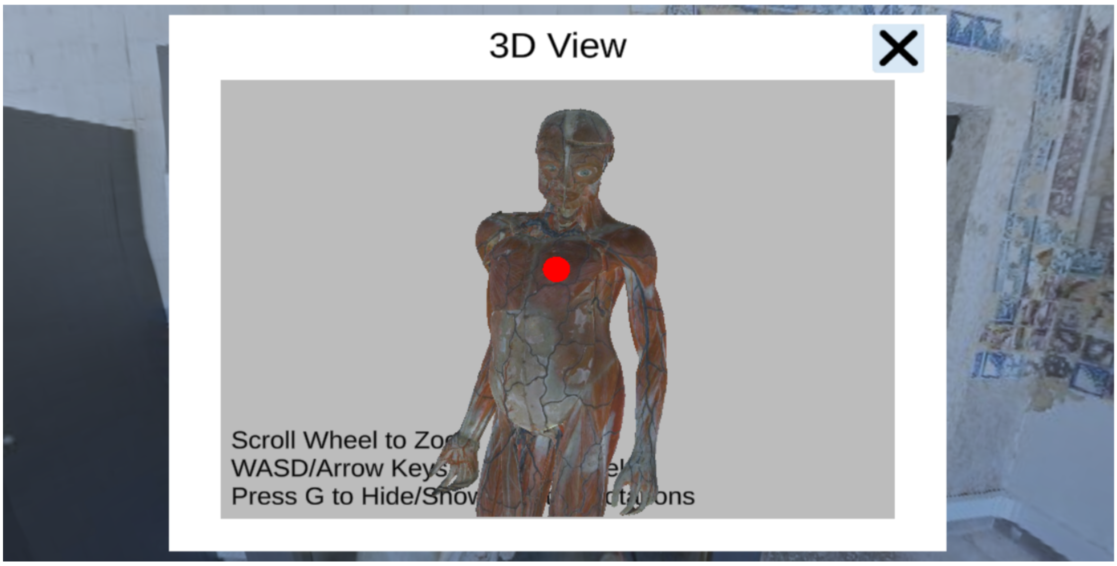

Figure 4.8: Interactive Visualization Tool inside the Visitor Interface

Ultimately, the Interactive Visualization Window gives the user a lot more options to be able to view and interact with a 3D model, creating a more interesting experience that should help with a museum's goal to teach their visitors and document their 3D models.

4.2.3 3D Annotations

A 3D Annotation is an annotation that is directly set to a point of a 3D model. These annotations have a tittle, description and an image, which is not required to create a new 3D annotations. They are represented by a red sphere that turns green when hovered on or when selected. A selected 3D Annotation opens up a new window to the left of the base Interactive Visualization Window, showing the information it has saved, an example of this can be seen in Figure 4.9.

Inside the editor interface the Interactive Visualization Window also has the ability to add new 3D Annotations by clicking the F key and then choosing the locating where they would like to put the annotation by left clicking it with their mouse and then filling in the information they wish to add.

3D Annotations are very versatile and could be used to help tell the story of the original object or create a new narrative, as we did in the figure used illustrate this feature by using the 3D Annotation to point out the position of the heart in the human body, using it in a similar way to a basic biology class.

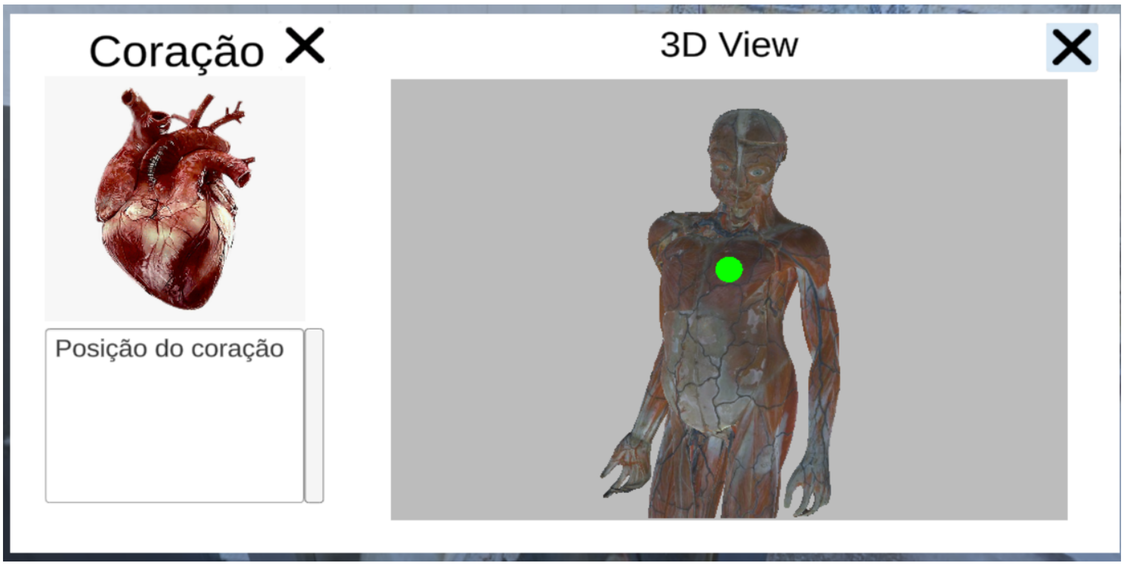

Figure 4.9: Interactive Visualization Tool inside the Visitor Interface with a 3D Annotations open

4.3 Search Bar

The search bar is one of the simplest features, as it is a very common and well known component in most modern applications. Nevertheless, our Search bar can be seen in Figure 4.10 on the top right corner of the catalogue, above the item cards. The search bar is composed of a text box and a button with the word search written on it, allowing a user to search for any item by name while in their respective tab, meaning you can only search for an image if you are also inside the image tab and so on. However, inside the 3D model tab a user can also search for a model based on it's tags, and the search bar can receive more than one tag by simply leaving a blank space between each tag. When searching with more than one tag the system will only show the 3D models that have all the tags that are being searched for.

The search bar might be a simple feature, but it's necessity becomes more keenly felt the bigger a user's library of items is. It is a necessary component in order to properly catalogue a wide library of any sort, helping the user look up specific items after they have long been stored, and this implementation of a search bar achieves that purpose.

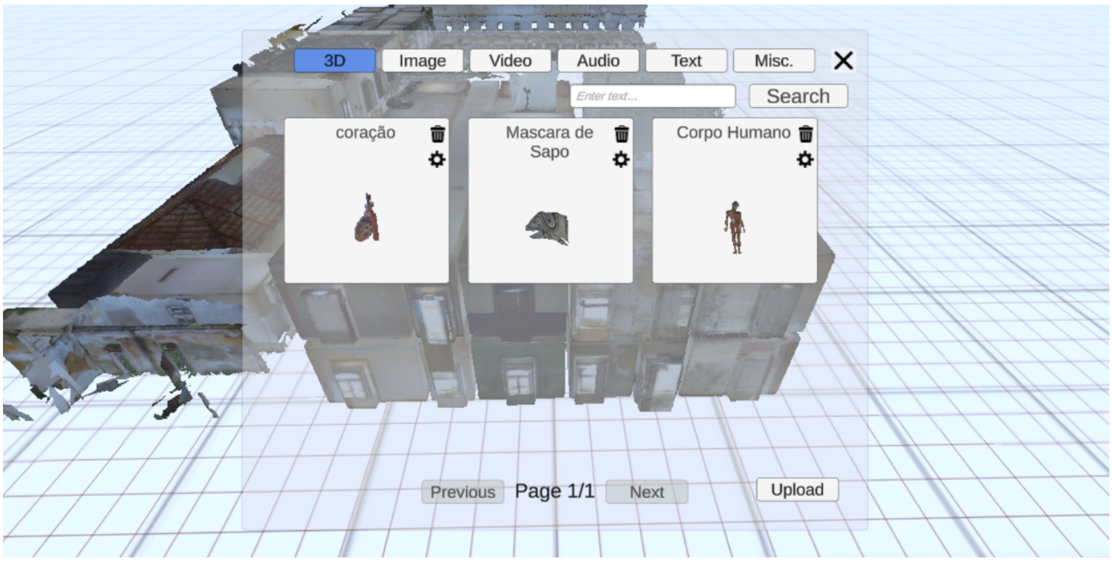

Figure 4.10: Inside Catalogue 3D Model Tab

4.4 360° Images

This section will cover the implementation of 360° Images and the automatic image linking function that supports the creation of Virtual Tours around 360° Images.

4.4.1 Implementation

To differentiate 360° Images from regular images inside the catalogue, the item card of every 360° Image has "360" written on the top left corner of the card, which can be seen in Figure 4.11.

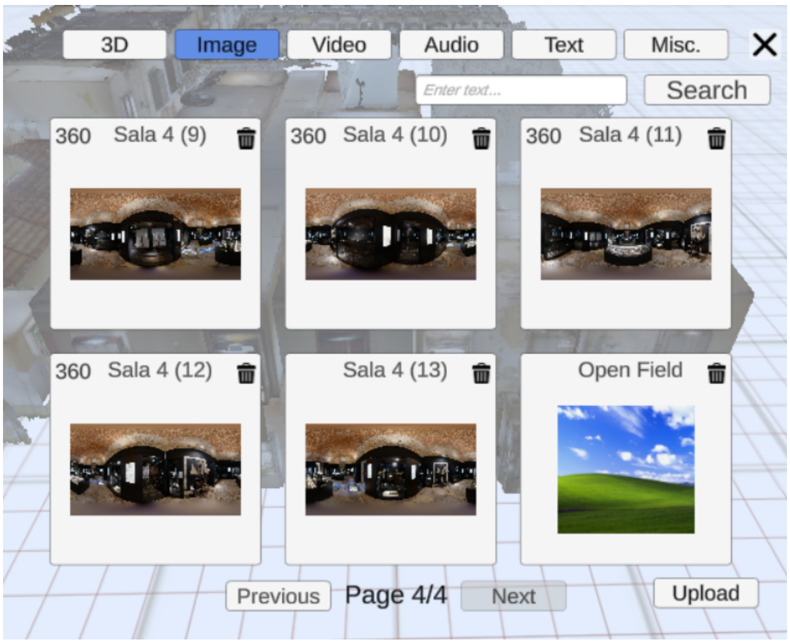

Figure 4.11: Catalogue Image Tab

To be able to use a 360° Image inside a Virtual Environment, they are used as the texture for the default sphere model in Unity, but the texture's normals are inverted so that the 360° Image can be viewed from inside the sphere.

While inside the sphere users are unable to move, this is because outside of the center of the sphere, the two dimensional nature of the 360° Image quickly becomes apparent, breaking any immersion that could have been had. However a Virtual Tour cannot be made up of only one 360° Image, requiring us to think of method that allows traversal between spheres and between a sphere and the environment outside of it. To do this we made use of the teleportation portals that were already present in the application, to help connect the outside environment to a 360° Image Sphere, and added teleportation arrows to connect spheres between each other. These connectors have been made with the limitations of 360° Images in mind so they can be directly set to the center of a 360° Image Sphere, without any extra work from the user other than adding the image and portal/arrow to the Virtual Environment.

Nevertheless, this solution was still a little bit too cumbersome for the average user, as it would require the user to create and correctly place at least two teleport arrows every time they want to add a new 360° Image to their Virtual Tour. Leading us to search for a solution to this problem, which we will be explaining in the next subsection.

4.4.2 Automatic Linking

The solution we found to simplify the creation process for 360° Image based Virtual Tours was to make it so when two images came close enough to each other they would automatically create a teleportation arrow that points towards the center of the other image. A visual example of this feature can be seen in Figure 4.13, where two 360° images have come close to each other and we can notice two green arrows have appeared, each pointing to the image they connect to.

Naturally, if two connected 360° Images are moved away from each other their connection will be broken and the arrows linking them will be destroyed, as seen in Figure 4.12 but they can still reappear if the images come close enough to each other again.

When either of the connected 360° Images is moved the teleportation arrows related to them are moved in order to continue correctly pointing to the center of the image they link to.

However there might still be cases where the user wants two 360° Images to be close to each other but not be connected. The solution in this situation is to use the item list menu, discussed in Section 4.1 and visible in Figure 4.13, to delete the arrows that are connecting the two images. Automatic arrows are named with the convention of first is the name of the sphere they are inside, then a textual arrow icon (->), followed by the name of the sphere they teleport to, an example for this would be "Image 1 -> Image 2", allowing them to be easily identified inside the item list menu.

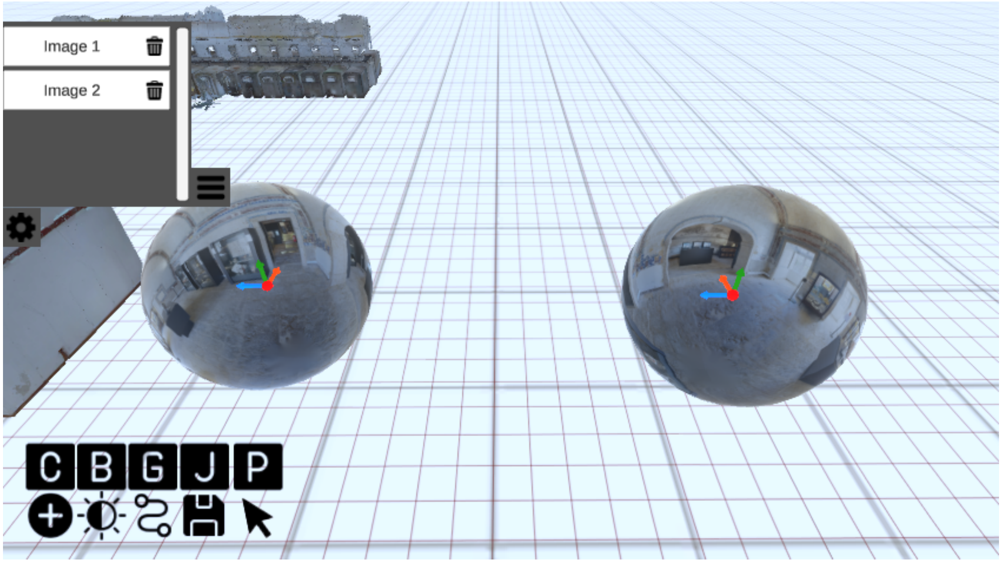

Figure 4.12: Two unlinked 360° Images Inside the Virtual Environment

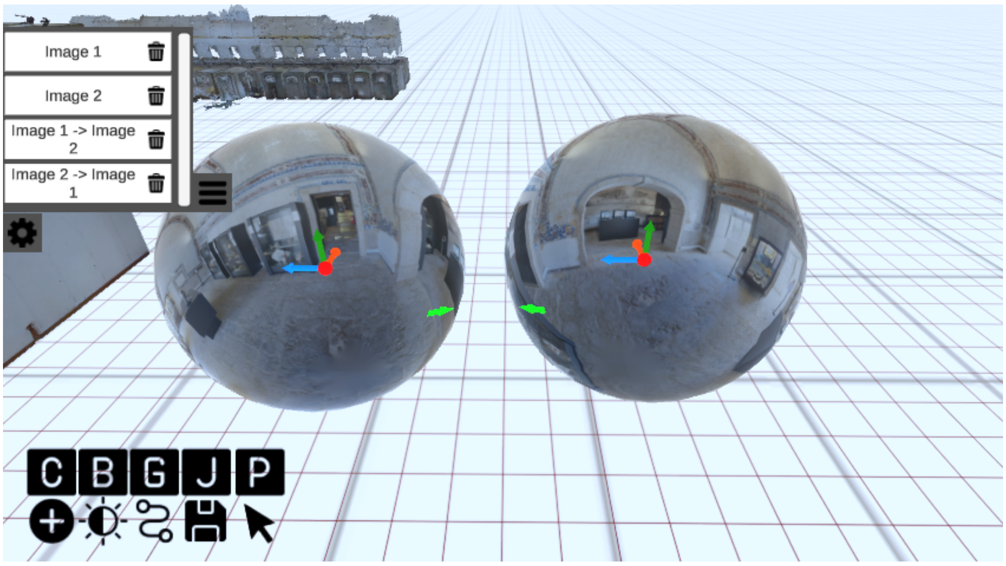

Figure 4.13: Two linked 360° Images Inside the Virtual Environment

4.5 Memory Optimization

Halfway through development, while adding new items to the application, an unexpected error occurred that stopped the application from running. Upon further inspection, we found that the error was caused by the application using almost all the RAM in the computer that it ran in, causing it to no longer have any more RAM available and the application to error.

To more accurately diagnose this error, unity's memory profiler[1] was used. This tool lets us take snapshots while the application is running to analyze how the memory is being allocated with an in-depth list of the assets loaded by the application including how

[1]Unity Memory Profiler, https://docs.unity3d.com/Packages/com.unity.memoryprofiler@1.1/manual/index.html, last access 08/2024

much memory they are taking up. It also allows us to compare these results with other snapshots by showing the difference in memory used by each asset and asset type.

Through this analysis we found that the problem was caused by the unexpected massive size of the textures that were being used, with the main culprit being the 360° Images being uploaded, as each image had the dimensions of 8192x4096 pixels and an allocated size of 224 MB, leading to a dozen 360° Images plus three 3D models exceeding the maximum memory available in a computer with 16 GB of RAM, limiting the size of the Virtual Tours that could be constructed.

Since the usage of 360° Images is important in order to answer one of the research questions, this issued had to be solved. Two solutions were considered, the first was to edit the images manually to reduce their size, while the other one was to have the application reduce the size of the images automatically on upload. With the end user in mind, we found that the automatic solution would be better, as it would take the work off the end user's hands, which we do not expect to be very proficient in editing images.

The developed solution resizes any image with height or width above 1024 pixels to a format where the smallest sides are equal to 1024 while the widest ones are equal to 1024 times the ratio between the original height and width. The new resized image is also the one that is sent to the database on upload, as this also helps to massively reduce the time it takes to load in the images inside the catalogue and when starting up a Virtual Tour.

However the image quality does worsen a little bit after resizing, which can be seen in Figures 4.14 and 4.15, where they shows the same view from inside a 360° Image Sphere with an image that was not resized first and one that was resized after. The resized image is noticeably pixelated in comparison with the original, but this does not affect the legibility of the image. As previously stated the original image has an allocated size of 224 MB, but after being resized it goes down to 21.3 MB, an over ten times reduction and the actual dimensions of the image were only reduced by four times the original image, from 8192x4096 to 2048x1024 pixels. This saves us a lot of memory space and tremendously reduces load times.

This resizing is also done to the images used to texture the 3D models. There is no noticeable drop in quality in this case, but the image size is still significantly reduced. The texture of the 3D model of the human body, which is the largest texture in the models used for this thesis, went from a size of 128 MB to 10.7 MB after resizing. Another example comes from the 3D model of the human heart, which went from 32 MB also to 10.7 MB.

4.6 Editing Virtual Tours

As previously mentioned in Chapter 3, the application used as the base for the development of the proposed features did not allow a user to edit a Virtual Tour after it had been saved.

Figure 4.14: Not Resized Image View inside 360° Image Sphere

Figure 4.15: Resized Image View inside 360° Image Sphere, with a zoomed in view of the top right corner of the image, showing the pixelation from resizing the image

A Virtual Tour refers to the personalized setup of various 3D models and 360° Images inside a Virtual Environment, containing such details as the position, rotation, size and other functionalities of the items used. Once the Virtual Tour is completed in the Editor Interface, it is saved to the database, making it accessible through the Visitor Interface.

During the development of the application there were many times when Virtual Tours had to built in order to showcase the new additional features and how they would look while being explored by a visitor. In these situations whenever a new Virtual Tour was needed, they always ended up having to be created from scratch more than once, as any minor error or forgotten detail could not be fixed once the tour had been saved and the editor page closed. This created a sense of urgency that made adding the ability edit already saved Virtual Tours one of the top priorities once the main features had been complete.

To fix this problem a new menu was created, it lists all the virtual tours that have been saved, which can be seen in Figure 4.16. We call it the Museum List to make it easier to understand it's purpose to the average user. with this menu we can load in an already saved Virtual Tour, delete it or save a new one. When loading a Virtual Tour all the assets that are currently present in the scene are removed and then the selected Virtual Tour is recreated.

To save a new Virtual Tour a user only needs to click the "Add Museum" button and then insert the name they desire to give to their creation. To edit an already saved Virtual Tour a user should load in the desired museum, edit it, then delete the older save and create a new one based on the new edit. Only logged in users have access to this feature, the Museum List will not load the saved museums otherwise.

Once finished this feature helped a lot in wasting less time building Virtual Tours and instead put that effort towards other parts of this thesis, such as preparing for both of the user studies that were ran. The evaluation process for the application will be covered in the next chapter.

Figure 4.16: Museums List Menu

5 Evaluation

To test the application two user studies were conducted, this chapter will cover said studies, the results that were gathered, how the results helped us answer the proposed research questions and the enhancements that were made in response to the studies. Firstly, it will be explained how the tests were carried out and what data was collected from them in Section 5.1. Afterwards, the questionnaire that was given to the participants will be covered, explaining the reasoning behind it's use in Section 5.2. The following two sections (5.3 and 5.5) will cover each one of the studies that was conducted separately, explaining the tasks and questions given to each participant and the results that were gathered. Between the sections about each study, in Section 5.4, we will also cover the improvements that were made after the first user study, explaining the rationale behind their implementation. Following the coverage of both studies, a combined analysis of the results from both user studies will be done in Section 5.6, where the final conclusions about the application and the gathered results will be taken. Lastly, Section 5.7 will close this chapter by answering some of the proposed research questions.

5.1 Evaluation Protocol

The testing was divided into two different user studies, with different goals. Those goals being:

- **First Time User Usage** - The first study's goal was to test how a first time user would react to both the editor side of the application and the visitor side while interacting with the new functions that were added.
- **Confirm Previous Results and Answer Research Questions** - the following study's goals were to confirm the results from the first study and to answer some of the proposed research questions, specifically the second and the third questions.

Each testing session included two people, one person performing the tasks as a user, and another overseeing the session. All of the tasks were performed on the same computer, as to reduce the risk of having hardware performance related changes. The same computer was also used in both user studies. The participants were initially informed about the application and it's relation to this thesis, they were also asked for their consent to collect the required anonymous data.

Google Forms[1] was used to help collect the necessary data and guide the session by having all the tasks described and ordered. For tasks that could require a tester to look back at the task's description, a paper with the task's description written on it was also provided.

Testers were asked to do the tasks related to both the visitor and editor interface. However in the first study the order by which they did each block of tasks was shuffled in order to have one half of the participants start with the editor interface while the other with the visitor interface. In the second study a rigid order was established where every tester started with the tasks related to the visitor interface.

The protocol used was the same for the visitor and editor interface. Firstly, the participants were given a quick explanation about interface and it's the controls. Then they were made to complete the tasks that were given out. Some of the tasks were timed in regards to their completion time. Several observations were also taken during testing. After completing all the tasks related to on interface the testers were given a small questionnaire relating to the interface and tasks they had just done.

Lastly, once testing was complete one final questionnaire was given. After finishing this last questionnaire the session was over.

5.2 Questionnaires

Questionnaires were given upon completion of all the tasks surrounding each interface and once testing was complete. Totaling to 3 questionnaires. All questionnaires contain questions which are answered with a Likert-scale, from 1 to 5, in which 1 signifies "Strongly Disagree" and 5 "Strongly Agree".

The first two questionnaires contain questions about the tester's experience with the interface they have just used. These questionnaires vary slightly within each study, so their contents will be covered in the Sections that relate to each respective study. While the last questionnaire starts with 10 standard SUS questions [9], in order to quantify the usability of the application, followed by some questions that separate the participants demographically (by age, gender and education level) and by their experience with similar applications.

The 10 SUS questions used were:

1) I think that I would like to use this system frequently.

2) I found the system unnecessarily complex.

3) I thought the system was easy to use.

[1]Google Forms, https://www.google.com/forms/about/, last access 09/2024

4) I think that I would need the support of a technical person to be able to use this system.

5) I found the various functions in this system were well integrated.

6) I thought there was too much inconsistency in this system.

7) I would imagine that most people would learn to use this system very quickly.

8) I found the system very cumbersome to use.

9) I felt very confident using the system.

10) I needed to learn a lot of things before I could get going with this system.

5.3 1st User Study

The first study's goal was to test how a first time user would react to both the editor side of the application and the visitor side. To make sure the application is not too complicated or hard to understand for a first time user and that it has all the features most users would need.

Since we wanted to test both the visitor and editor interfaces in the same session, half of the participants started their session with the tasks related to the editor interface while the other half started with the visitor interface. This was done in order to control for the possibility that a participant's knowledge of one of the interfaces would effect their results in the tasks for the following interface.

Tasks in this study were made to slowly introduce the participants to the application while having them interact with it, each tasks will be further explained during this section. Participants were also given aid when required, any question about how to operate the application were given an answer during testing, but when they did so we noted down how many times help had been given for each task.

5.3.1 Editor Interface

First we will cover the tasks related to the editor interface and the questions made after finishing all the tasks related to this interface.

Task E0 – Basic Introduction

This is not a task, it is a simple introduction about the editor interface, explaining the basic controls of the application and how to access the item catalogue. This introduction only gives the basic knowledge necessary for the participants to be able to focus on the tasks that will be given afterwards.

Task E1 – Add two 360° Images

The participant was asked add two 360° Images and line them up. This task will introduce the participant to the 360° Images editor function, while at the same time we will try to see if they can notice/understand the connection being created between the two when they come close to each other.

Task E2 – Add 3D Model

This task had the participant upload a new 3D model to the application, add it's respective annotations and then place the model inside one of the 360° Images placed in the previous task. We sought to test the user interface for the upload of 3D models and the addition of annotations to them while also introducing the placement and movement of 3D models in the virtual space. The completion time for this task was timed.

In this task we noted that participants would like to have a way to preview where the 3D annotation they were about to create was going to be placed.

Task E3 – Create a Virtual Tour

Lastly, with the knowledge gained from the previous tasks, the participant is now ready to try to create a Virtual Tour.This will test the creation tools for a Virtual Tour made up of 360° Images and 3D models. The completion time for this task was also timed.

In this task we noted that for most participants the mobility spheres, that allow an object to be selected and moved, for the teleportation arrows that connect two 360° Spheres were in the way and made it harder for participants to select and move the 360° Spheres they meant to move. we also noted that these same mobility spheres were difficult to use because the arrow that allow mobility through their respective axis were too small for most participants to notice from afar.

Questionnaire

In this questionnaire we had two questions inquiring about the user experience of the tools used during the tasks.

E_Q1 - I found the Annotations Interface easy to use

E_Q2 - I found the creation tools for Virtual Tours very cumbersome to use

5.3.2 Visitor Interface

Task V0 – Basic Introduction

A simple introduction to the visitor interface of the application, explaining the basic camera controls required to start doing the tasks.

Task V1 – Traverse through a Virtual Tour

The participant was asked to traverse through a Virtual Tour, created with 360° Images taken from a room in the *Academia das Ciências de Lisboa*, and attempt to draw the room while pointing out the positions of each 360° Image.

The goal of this task is to test the user experience for a visitor exploring a Virtual Tour made with 360° images and to be able to tell how immersed he is by asking them to draw what they see.

We noted through this task that some participants did not like that the mouse was locked to the screen and would prefer the mouse to be unlocked and camera rotation to be an active action where the user drags the screen to rotate the camera.

Task V2 – Interact with 3D Models

The participant was asked to interact with the 3D models already present in the Virtual Tour and read their 3D Annotations. This task seeks to test user experience for the Interactive Visualization Tool in the visitor interface, which allows a visitor to interact with a the 3D models present in a Virtual Tour.

We noted in this task that some participants would like to have a more visual method of identifying if an object or annotation is able to be interacted with, such as through outlining the 3D models inside a Virtual Tour so they do not blend too much with the environment, and by changing the color of a 3D Annotation when hovered over.

Questionnaire

Similarly to the previous questionnaire, this one also has two questions inquiring about the user experience of the new features that were added and tested during the tasks.

V_Q1 - I did not like the Navigation Method

V_Q2 - I found interacting with models easy to use

5.3.3 Results and Analysis

Some of the results gathered will be shown in this subsection, with the addition of a quick analysis of their possible meaning. Further conclusions will be taken in the following subsection and the results from both studies will be discussed together in Section 5.6.

Population Characterization The 1st User Study was performed by 10 participants from the Computer Science Department, those being made up of 2 female, 7 male and 1 marked as other, ranging ages 19 to 33, with an average age of 23.4. This data can also be found in Table 5.1 and Figure 5.1. Another metric that was measured was the experience of the participants with similar applications (3D editing software), most had some experience with at least 1 other application, but 40% of the people tested had no experience with similar applications by their own admission. This data can be seen in Table 5.2.

Table 5.1: Gender Distribution in the 1st Study

Gender	Users(#)
Male	7
Female	2
Other	1

Table 5.2: User's Level of Experience with Similar Applications in the 1st Study

Experience	Users(#)
None	4
Some	5
A lot	1

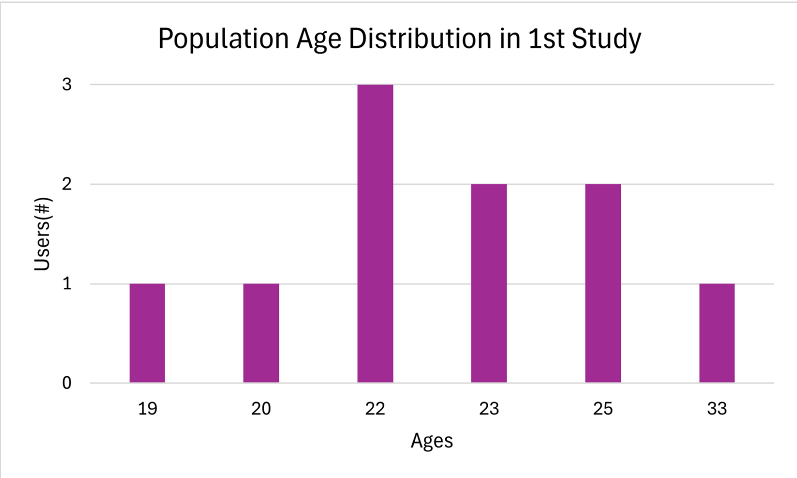

Figure 5.1: Population's Age Histogram in 1st Study

Questionaire Answers Outside of the SUS Questionnaire, there were two other questionnaires given out to the participants after they finished all the tasks for each interface. A Likert-scale from 1 to 5 was used, in which 1 signifies "Strongly Disagree" and 5 "Strongly Agree". The results for each question were processed into median, 1st and 3rd quartile, they can be seen in Table 5.3. From these results we can see that most participants found the application somewhat easy to use. The biggest outlier is the 3rd quartile of the question **V_Q1**, where some participants show displeasure with the navigation method in the Visitor Interface.

Table 5.3: Median, 1st and 3rd Quartile of the answers received from the 1st User Study Task Questionnaires

Questions	Median	Q1	Q3
E_Q1 - I found the Annotations Interface easy to use	4	3.25	4
E_Q2 - I found the creation tools for Virtual Tours very cumbersome to use	2	2	3.75
V_Q1 - I did not like the Navigation Method	2	1.25	4
V_Q2 - I found it easy to interacting with the 3D models	5	4	5

Task Completion Time The time taken to complete the second and third tasks for the editor interface was taken, these results can be seen in Table 5.4. The second task (E2) had a mean completion time of 300.2 seconds with a standard deviation of 76.8 seconds. Similarly the third task (E3) had a mean completion time of 286 seconds with a standard deviation of 58.7 seconds. By looking at the results we saw that some experienced participants took longer when interacting with a new interface, which was seen in the completion time for Task E2 where some experienced participants took much longer to complete when compared to all inexperienced participants, but once they had some experience with the system they became faster than the participants with less experience, seen in their completion time for Task E3.

Table 5.4: 1st Study Completion Time for task E2 and E3 in seconds and average number of times help was asked

Completion Time	$\bar{x} \pm \sigma$ (s)	Average num. Help
E2	300.20 ± 76.84	1
E3	286.00 ± 58.70	0.8

Interface Task Order As previously mentioned the order by which each participant interacted with the editor and visitor interfaces was altered, making it so half of the participants started their sessions with tasks related to the visitor interface while the other half started with tasks related to the editor interface. Through the task completion time and number of times help was given to participants during the third task of the editor interface, which can be seen in Table 5.5, we found that participants that started with the visitor interface were 76 seconds faster at completing the task and only asked for help an average of 0.4 times while participants that started with the editor interface asked for help at least 1 time on average. A t-test was also performed to verify if the difference in participants was significant. Using a probability of 95%, a two-sample t-test showed that there was significant difference in the completion time between participants that started with the editor interface ($\bar{x} = 324 \pm 53.67s$) and participants that started with the visitor interface ($\bar{x} = 248 \pm 35.53s$), $t(8) = 2.64$, $p = 0.03 < 0.05$. Figure 5.2 shows a visual representation of the comparison between completion time for the task E3 based on which interface the participant interacted with first. It is worth noting that there is no inner line inside the Editor box because the median time is equal to the first quartile in that sample. On the other hand, no significant increase in performance was found in the use of the visitor interface when the participant had previously used the editor interface.

Table 5.5: 1st Study Completion Time for task E3 in seconds and average number of times help was asked based on first interface used

Completion Time	$\bar{x} \pm \sigma$ (s)	Average num. Help
Editor Interface	324.00 ± 53.67	1
Visitor Interface	248.00 ± 35.53	0.4

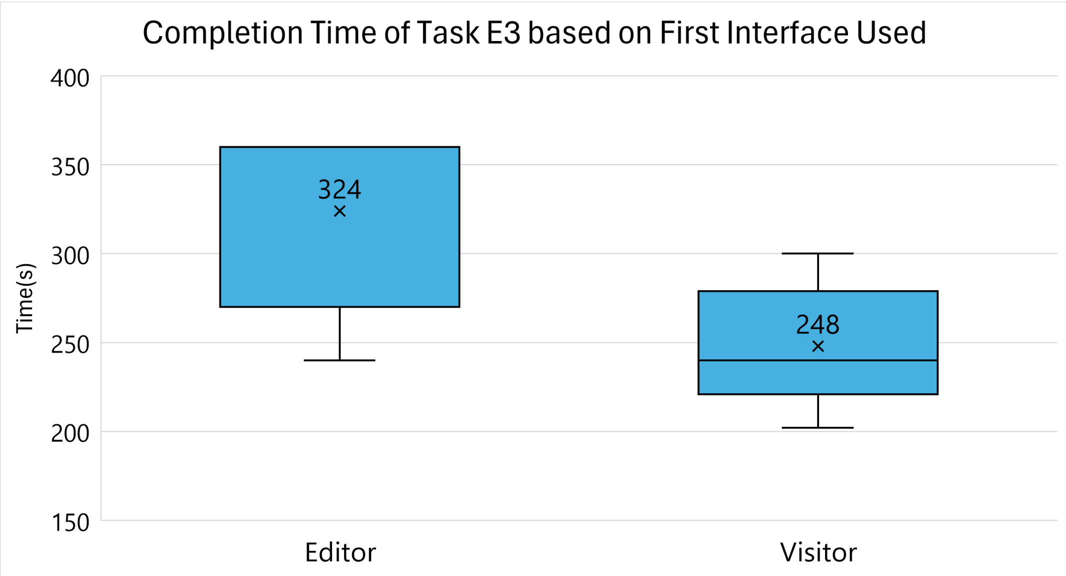

Figure 5.2: Box plot containing a comparison of the Completion Time for Task E3 in the 1st Study based on First Interface Used, in seconds. The visible values over the cross inside the box represent the mean time, while the top of the box contains the 1st quartile, the line inside the box represents the median time and the bottom of the box is the 3rd quartile. Lastly, the edge of the lines that come out of the box represent the maximum and minimum times recorded.

Virtual Tour Mapping As previously mentioned, the first task for the visitor interface required the participants to draw the room the virtual tour was attempting to simulate with the use of 360° Images. Out of the 10 participants 6 successfully drew the room they had just visited perfectly, while the other 4 participants could not fully replicate the room. However the failed attempts were only off by one or two mistakes, showing there was still a good understanding of the room being simulated.

SUS Questionnaire After processing the results gathered from the SUS questionnaire that was given out, the individual scores ranged from 55 to 100 and the average of all the SUS Scores was 78, which is higher than 68, meaning it's an above average score [36] and that this application has a decent level of usability and user experience. It is also worth noting that only only 3 participants scored the application below 68. The unprocessed responses to the SUS questions can be seen in Table 5.11.

5.3.4 Discussion

Throughout this user study, we noticed that, even for Computer Science students the developed application seems to have a steep learning curve on a first time usage, this specifically refers to the Editor interface as it is the most complex of the two, while the Visitor interface is much more well received for the fact that it is very simples and made with the use of the average user in mind.

Table 5.6: Median, 1st and 3rd Quartile of the answers received from the 1st User Study SUS Questionnaire

Questions	Median	Q1	Q3
1) I think that I would like to use this system frequently.	4	3	4
2) I found the system unnecessarily complex.	2	1.25	2
3) I thought the system was easy to use.	4	2.5	4.75
4) I think that I would need the support of a technical person to be able to use this system.	2	1	2.75
5) I found the various functions in this system were well integrated.	4.5	4	5
6) I thought there was too much inconsistency in this system.	1	1	1
7) I would imagine that most people would learn to use this system very quickly.	4	3.25	4.75
8) I found the system very cumbersome to use.	1.5	1	2
9) I felt very confident using the system.	4	3.25	4.75
10) I needed to learn a lot of things before I could get going with this system.	1	1	2

One of the methods we have seen that can help with the learning process is the usage of the Visitor interface to introduce a user to the system, as previously seen in the results gathered and can be seen in Figure 5.2.

The Annotations Interface did better than expected in this study, as almost all participants were able to use it without asking for help. While talking about the user experience in the editor interface, we also saw that most users used the zoom function as their way to move around the Virtual Environment, when the intended way was to use the arrow keys, which we found to be unexpected, but not problematic, since the zoom function could in fact be also used as a mobility method, we just had not thought of it as such.

We also did not expect the need for an active drag option for the visitor interface, but some tech savvy participants mentioned they would prefer it's addition because it felt more natural to them.

The Virtual Tour Mapping helped us confirm that our implementation of 360° Images within a 3D Environment can be used to simulate room size spaces, as most participants had a perfect grasp of the room and it's layout, and the ones that did not were very close to a complete understanding of the room. However most users did not take this task very seriously, rushing through their drawings of the room, which negatively affected some of the results. This lead us to remove the Virtual Tour Mapping from the next study, as it took a lot of time and we felt that adding new questions to the task questionnaires would give us more accurate results. Nonetheless, we have yet to compare the user experience between Virtual Tours based around 360° Images and 3D models, which will be done in the following study.

By using the Average SUS score from this user study, we can reason that the new features we added to the application are in an acceptable state from the point of view of a Computer Science student. Nevertheless, there were still some usability and interface issues that the participants pointed out. Those issues were fixed before we conducted the second user study and will be covered in the next Section.

5.4 Usability Enhancements

From the 1st User Study we received quite a few comments from the participants tested on ways we could improve or fix the developed application. Most of the comments were about simple fixes such as lowering the sensitivity on the rotation of the camera and the rotation of a 3D Model while inside the Interactive Visualization Tool. The changes made from the remaining comments will be discussed further, as we think there is an interest in talking about them and the reason why they were made. We will begin by covering the changes made in the Visitor Interface.

3D Model Outline While exploring a Virtual Tour through the Visitor Interface, one participant commented that the 3D models were blending with the 360° Images, making it hard for them to identify when they were looking at a 3D model. So they proposed the addition of an outline for the 3D models. This suggestion was implemented to help users identify 3D models but also so users can more easily understand that they can interact with the 3D models. An example of this feature in action can be seen in Figure 5.3

Active Drag to Rotate the Camera In the Visitor Interface the mouse used to be locked in the center of the screen, allowing users to rotate the camera by simply moving their mouse. However some participants did not like the mouse being locked and said they would prefer to drag the screen to rotate the camera as it is done in the Editor Interface. Since most participants still seemed to prefer the mouse being locked, a new button and key binding were created that allowed users to choose if they wanted the mouse locked

Figure 5.3: 3D Model Outline Showcase inside a Virtual Tour

or unlocked, but the mouse is still locked by default when entering a new Virtual Tour. This button can be seen in Figure 5.3, below the P icon, shown as a white mouse cursor, indicating that the mouse is locked right now and that this function is also bound by the P key, the button turn black if the mouse is unlocked. An aspect that made it more complicated to fully implement this feature was that we had to change how the 3D model interaction text message worked, as it had been programmed to appear when the object was at the center of the screen, and we had to change it to be based on the position of the mouse.

3D Annotations Interaction Indication Some participants mentioned not being able to tell if 3D Annotations could be interacted with. 3D Annotations are represented by red spheres on a 3D model. One participant offered the suggestion of changing the size of the those red spheres depending on how far they were from the mouse pointer, making them grow the closer they got from the mouse pointer. However this solution was not used as it could lead to more confusion than not and it might clutter a 3D model when it has more than two or three 3D Annotations close to each other. The solution that was used instead was to add a change in color to the sphere when hovered over, from red to green, while green is also the color used when a 3D Annotations is selected and it's details are being shown. This solution was chosen for it's simplicity and wide use in many other kinds of applications, making it easier for most users with any kind of technological experience to understand they can interact with the 3D Annotations.

3D Annotation Creation Preview To create a 3D Annotation a user needs to click the F key and then left click with their mouse on the location they wish to create the 3D Annotation. Once understood this is a very simple order of actions, however it proved a little hard to understand for the first time to some participants, especially the last action where they need to click in the position they desire. To help ease this confusion a preview was added after pressing the F key that shows where the red sphere that represents the 3D Annotation will be dropped if the user decides to left click at that moment. This preview also only shows up on valid position, meaning it will not appear unless the user has the mouse cursor on the 3D model.

Decluttering Usage of 360° **Images** While creating a Virtual Tour in the Editor Interface, a few participants showed confusion when trying to move 360° Image Spheres when those where close to overlapping. The Reason for this confusion came from the high number of mobility spheres on screen, a recreation can be seen in Figure 5.4 where we can see that there is a large number of mobility spheres (red spheres) some even overlapping from the addition of only three 360° Images, making it very hard to discern which sphere will make an image move. These mobility spheres were left above the teleportation arrows in case the user wanted to tweak it's position a little bit because the automatic positioning was not to their liking, but the confusion this choice created was greater than the freedom it was supposed to give, as most participants simply accepted the position that was automatically set. That being the case, we decided to remove those mobility spheres from the automatically created teleport arrows in order to visually simplify the manipulation of 360° Images.

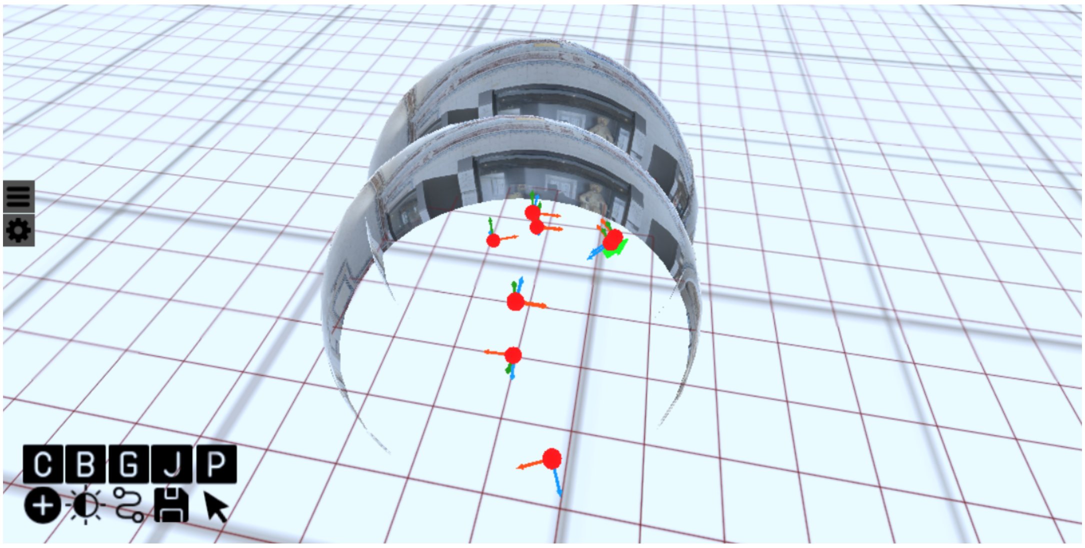

Figure 5.4: Example of the cluttering issue with 360° Images

5.5 2nd User Study

This study's goals are to confirm the results from the first user study and to help answer some of the research questions that were proposed in the first chapter, specifically the second and third questions.

We used what was learned from the first study to streamline the structure of the second study. The reason for this was so we could reduce the amount of time it takes to complete the study, making it to be more appealing to attract more testers, and to add some more questions to help us answer the proposed research questions.

One of the ways this study was simplified was by making the order by which every user interacts with each one of the application's interfaces the same. We learned from the first user study that by starting out with the visitor interface the users would have a better performance in the following tasks in the editor interface. With this in mind we decided to make every user start with the visitor interface in this next study, not just to shorten the time each user takes to complete the tasks in the editor interface, but also to give a more practical introduction to the application by showing them an example of what a Virtual Tour is. Likewise, we will also start by covering the tasks related to the visitor interface in this section.

The second study is still very similar to the first, but most tasks were slightly altered and new questions were added to the questionnaires related to both interfaces. The second study went from taking 45-60 minutes to only lasting 30 minutes at most, with most users needing only around 20 minutes.

5.5.1 Visitor Interface

Most tasks here were slightly changed to have the 3D model of the *Forte da Trafaria* that was added to the Virtual Tour in mind.

Task V0 – Basic Introduction

A simple introduction to the visitor interface of the application, explaining how the basic camera and movement controls work, so the participant can start doing the tasks immediately.

Task V1 – Traverse through a Virtual Tour

The user was asked to traverse through a Virtual Tour composed of 360° Images, taken from a room in the *Academia das Ciências de Lisboa*, and a 3D model of the *Forte da Trafaria*.

The goal of this task is to compare the user experience for a visitor exploring a Virtual Tour made with 360° images and exploring a 3D model of a building.

Task V2 – Interact with 3D Models

The user was asked to interact with the 3D models already present in the Virtual Tour and read their 3D Annotations. This task sought to test user experience for the visitor interface and to compare the experiences of viewing objects inside the virtual environment versus interacting with them through the Interactive Visualization Tool.

Questionaire

Three new questions were added to this questionnaire from the 1st study. These additions were made to help answer how the participants felt about the two types of environments, 360° Image versus 3D, and the two methods for observing 3D models, inside the Virtual Environment versus the Interactive Visualization Tool.

Question 3 is asking the participants preferred method to observe the 3D models, either inside the Interactive Visualization Tool, where they can interact with and rotate the models as they please to get a full view of them, or inside the Virtual Environment where the models are static and some aspects of the model are invisible or just very hard to see.

Question 4 and 5 are more self explanatory, as they are trying to grasp which kind of environment the participants liked more, 3D or 360° Image based, and how immersed they felt in each environment by comparison.

V_Q1 - I did not like the Navigation Method

V_Q2 - I found interacting with models easy to use

V_Q3 - I liked to observe the 3D Models in the Interactive Visualization Tool more than inside the Virtual Environment

V_Q4 - I liked to navigate inside the 3D building more than inside the 360° Images

V_Q5 - I felt less immersed inside the 3D building than the 360° Images

5.5.2 Editor Interface

Task E0 – Basic Introduction

This introduction was improved upon from the one used in the previous study based on the aspects where users asked for help that we deemed should be contained in this introduction, such as the controls to move the camera up and down in the 3D space and how to lock the mouse.

Task E1 – Add two 360° Images

The user was asked add two 360° Images and line them up. This task introduces the user to the 360° Images editor function. However we no longer checked if the user can notice the connection being created between the two images, as all users in the previous study understood the connection, especially after exploring a Virtual Tour first.

Task E2 – Add 3D Model

This task was changed to no longer have the participants upload a new 3D model to the application, they simply had to add it's respective 3D annotations and then place the model inside one of the 360° Images previously placed. We sought to test the user interface for the addition of 3D annotations while also introducing the placement and movement of 3D models in the virtual space. The completion time for this task was no longer timed.

Task E3 – Create a Virtual Tour

Lastly, this task was not changed, but it's description was altered to be more concrete, where we previously openly asked a user to build a Virtual Tour, now we specifically told them the minimum requirements for a complete Virtual Tour, which were also the ones used in the first study. A Virtual Tour requires at least 4 360° Images and 2 3D models, where 1 of the models must be inside a 360° Image and the other one inside the 3D model of the *Forte da Trafaria*. This was the only task where the completion time was timed in this study.

Questionnaire

Only one new question was added to this questionnaire. This question was added to make sure we get the participants opinions about the usage of 360° Image while creating a Virtual Tour, as the 3D model of the *Forte da Trafaria* was also present inside the Virtual Environment of the editor interface during this study, leading users to consider placing objects inside it while answering question **E_Q2**.

E_Q1 - I found the Annotations Interface easy to use

E_Q2 - I found the creation tools for Virtual Tours very cumbersome to use

E_Q3 - I found 360° Images very cumbersome to use

5.5.3 Results and Analysis

Some of the results gathered will be shown in this subsection, with the addition of a quick analysis of their possible meaning. Further conclusions will be taken in the following subsection and the results from both studies will be discussed together in Section 5.6.

Population Characterization The 2nd User Study was performed by 22 users, those being made up of 8 female and 14 male participants, ranging ages 14 to 45, with an average age of 24.1. This data can also be found in Table 5.7 and Figure 5.5. A request was also made to have some members of the Department of Conservation and Restoration participate in the study, we were able to gather 6 participants from this request. This was done in order to get a population that is closer to the end user this application is made for, people that deal with Cultural Heritage. Another metric that was measured was the experience of the users with similar applications (3D editing software), most had some experience with at least 1 other application and only 27.3% of the people tested had no experience with similar applications by their own admission. This data can be seen in Table 5.8.

Table 5.7: Gender Distribution in 2nd Study

Gender	Users(#)
Male	14
Female	9
Other	0

Table 5.8: User's Level of Experience with Similar Applications in 2nd Study

Experience	Users(#)
None	6
Some	15
A lot	1

Questionaire Answers Outside of the SUS Questionnaire, there were two other questionnaires given out to the participants after they finished all the tasks for each interface. A Likert-scale from 1 to 5 was used, in which 1 signifies "Strongly Disagree" and 5 "Strongly Agree", the results for each question were processed into median, 1st and 3rd quartile, they can be seen in Table 5.9. From these results we can see that most users found the application easy to use. We can also tell that they preferred navigating inside the 3D building over navigating inside the 360° Images almost unanimously, while they slightly tipped more in favour of the Interactive Visualization Tool over the classic method of observing a static 3D model inside a Virtual Environment. No significant outlier was found this time.

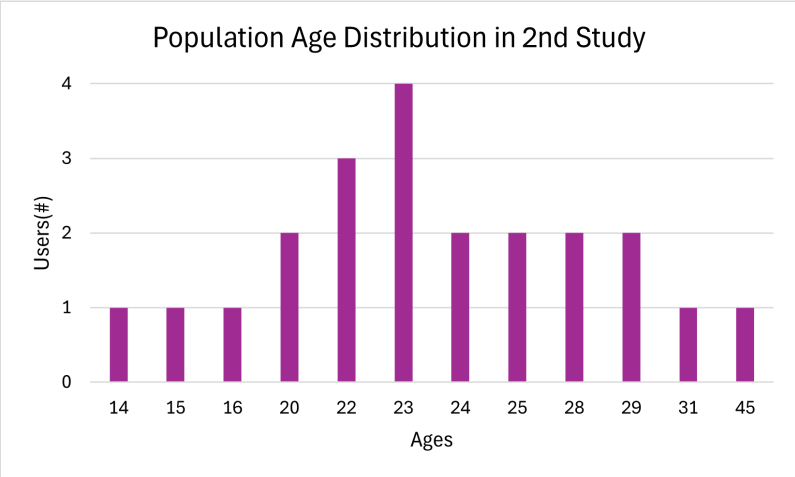

Figure 5.5: Population's Age Histogram in 2nd Study

Table 5.9: Median, 1st and 3rd Quartile of the answers received from the 2nd User Study Task Questionnaires

Questions	Median	Q1	Q3
E_Q1 - I found the Annotations Interface easy to use	4	3	5
E_Q2 - I found the creation tools for Virtual Tours very cumbersome to use	2	2	3,75
E_Q3 - I found 360° Images very cumbersome to use	2	1.25	3
V_Q1 - I did not like the Navigation Method	2	1	2,75
V_Q2 - I found interacting with models easy to use	5	5	5
V_Q3 - I liked to observe the 3D Models in the Interactive Visualization Tool more than inside the Virtual Environment	3.5	3	4
V_Q4 - I liked to navigate inside the 3D building more than inside the 360° Images	5	4	5
V_Q5 - I felt less immersed inside the 3D building than the 360° Images	2	1	3.75

Task Completion Time Only the third tasks for the editor interface (E3) had it's time completion taken, results can be seen in Table 5.10. This task had a mean completion time of 154.1 seconds with a standard deviation of 70.6 seconds, a significant reduction when compared to the first study, to be exact, there was a 131.9 second reduction in the mean completion time, but an 11.9 second increase in the standard deviation when compared to the first study. This data was also analyzed by separating it into two groups based

Table 5.10: 2nd Study Completion Time for task E3 in seconds and average number of times help was asked, divided by departments and total completion time

Completion Time	$\bar{x} \pm \sigma$ (s)	Average num. Help
Dep. of Conservation and Restoration	200.00 ± 90.55	2.3
Dep. of Computer Science	136.94 ± 55.58	0.5
Total	154.14 ± 70.60	1

on if the participant was part of the Department of Conservation and Restoration (DCR) or the Department of Computer Science (DI). Through the task completion time and number of times help was given to participants during task E3 we found that members of the DCR were 63 seconds slower at completing the task and asked for help 2.3 times on average while members of the DI only asked for help 0.5 times on average. A t-test was also performed to verify if the difference in participants was significant. Using a probability of 95%, a two-sample t-test showed that there was significant difference in the completion time between members of the DCR ($\bar{x} = 200 \pm 90.55s$) and members of the DI ($\bar{x} = 136.94 \pm 55.58s$), $t(20) = -1.99$, $p = 0.03 < 0.05$. Figure 5.6 shows a visual representation of the comparison between completion time for the 3rd Task based on these two groups.

SUS Questionnaire After processing the results gathered from the SUS questionnaire that was given out, the individual scores ranged from 40 to 92.5 and the average of all the

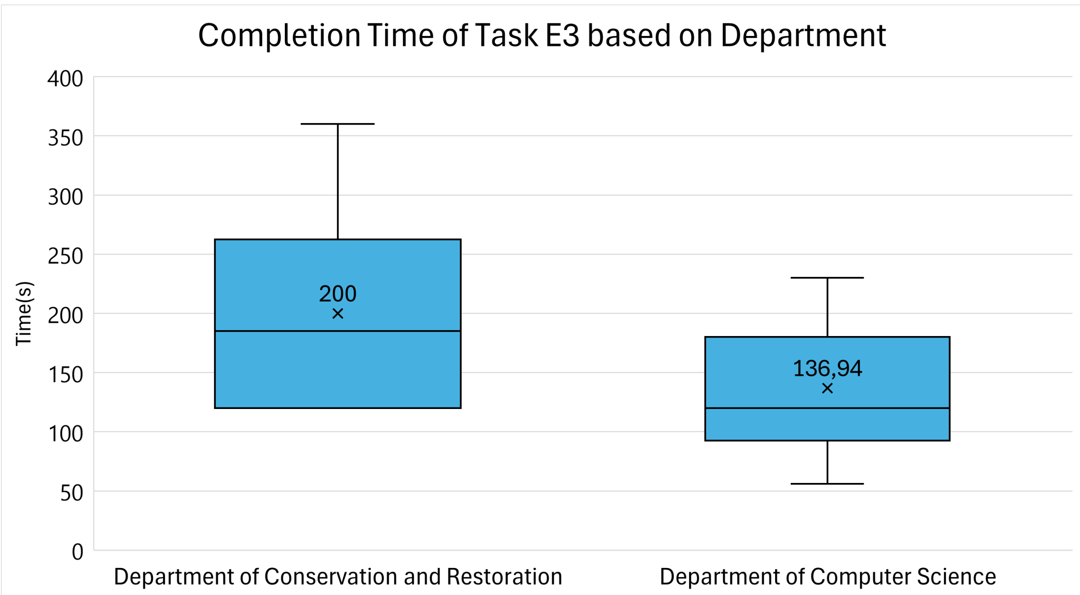

Figure 5.6: Box plot containing a comparison of the Completion Time for Task E3 in the 2nd Study based on Department, in seconds. The visible values over the cross inside the box represent the mean time, while the top of the box contains the 1st quartile, the line inside the box represents the median time and the bottom of the box is the 3rd quartile. Lastly, the edge of the lines that come out of the box represent the maximum and minimum times recorded.

SUS Scores was 71.6, which is higher than 68, meaning it's an above average score [36] and that this application is still at decent level of usability and user experience, even though the score went down by 6.4 points compared to the first study. This time 9 participants scored the application below 68, with only two of those being below 68 by 0.5 points. The unprocessed responses to the SUS questions can be seen in Table 5.11.

Table 5.11: Median, 1st and 3rd Quartile of the answers received from the 2nd User Study SUS Questionnaire

Questions	Median	Q1	Q3
1) I think that I would like to use this system frequently.	3	3	4
2) I found the system unnecessarily complex.	2	1.25	2.75
3) I thought the system was easy to use.	4	3	4
4) I think that I would need the support of a technical person to be able to use this system.	2	1.25	3
5) I found the various functions in this system were well integrated.	4	4	5
6) I thought there was too much inconsistency in this system.	2	1.25	2
7) I would imagine that most people would learn to use this system very quickly.	4	3	5
8) I found the system very cumbersome to use.	1.5	1	2
9) I felt very confident using the system.	3.5	3	4
10) I needed to learn a lot of things before I could get going with this system.	1.5	1	2

5.5.4 Discussion

Through this followup study the steep learning curve for a first time user that was previously discussed was confirmed again. This confirmation was especially true for the members of the Department of Conservation and Restoration (DCR), who are less tech savvy in comparison to the other participants tested, most DCR members even asked for or proposed the creation of a manual on how to use the application.

With the Average SUS Score from this user study, we can maintain that the application is in an acceptable state from the point of view of a wider population, even though the SUS Score went down in comparison to the 1st Study.

However the results that were gathered from the other two questionnaires have either stayed the same or improved, even after more than doubling the population size from one study to the next.

Ultimately, this study helped confirm that the application has a good level of usability and user experience within a larger population. A final analysis of all the results gathered from both studies will be done in the next section. While the final conclusions about the evaluation of the application will be taken in Section 5.7.

5.6 Data Comparisons

Through the conducted studies, we were able to confirm that the application and features developed were done well, leaving the application with a good level of usability and user experience.

The SUS Scores of both studies were above 68, meaning the application is in a positive state. However the SUS Score from the second study was lower than the one from the first study by 6.4 points.

Nevertheless all other metrics either remained the same or improved during the second study. One of those being the results from the other questionnaires that were given out, whose comparison can be seen in Table 5.12, the median results remained the same for the repeat questions, but the quartiles tell us another story, the biggest example being the third quartile for question **V_Q1**, it went from a 4 in the first study to a 2.75 in the second, meaning the upper half of the dataset, which should correspond to the most negative responses, responded positively to the question about their opinion on the Navigation method, suggesting there was an improvement in the users experience with the Visitor Interface. This also happened in most other repeat question on a smaller scale.

Another significant improvement was seen in the completion time for the third task of the editor interface (E3), that can be seen in Table 5.13 where there was a 131.90 second reduction in the mean completion time, visually represented in Figure 5.7. This indicates that the improvements that were done in between both studies helped improve the first time experience and usability of the application, making it so most users are able to complete the same task faster and with less effort.

Overall, a significant improvements were seen throughout the studies that were conducted, with both studies confirming the application has a good usability and user experience. The results from the studies also helped in answering some of the research

Table 5.12: Questionnaires Comparison, Scores from 2nd Study minus Scores from 1st Study

Questions	Median	Q1	Q3
E_Q1 - I found the Annotations Interface easy to use	0	-0.25	1
E_Q2 - I found the creation tools for Virtual Tours very cumbersome to use	0	0	0
V_Q1 - I did not like the Navigation Method	0	-0.25	-1.25
V_Q2 - I found it easy to interacting with the 3D models	0	-1	0

Table 5.13: Both Studies Completion Time for task E3 in seconds and average of times help was asked, plus comparison of the results from the 2nd Study minus 1st Study

Completion Time	$\bar{x} \pm \sigma$ (s)	Average num. Help
1st Study	286.00 ± 58.70	0.8
2nd Study	154.14 ± 70.60	1
Difference	-131.86 ± 11.91	0.2

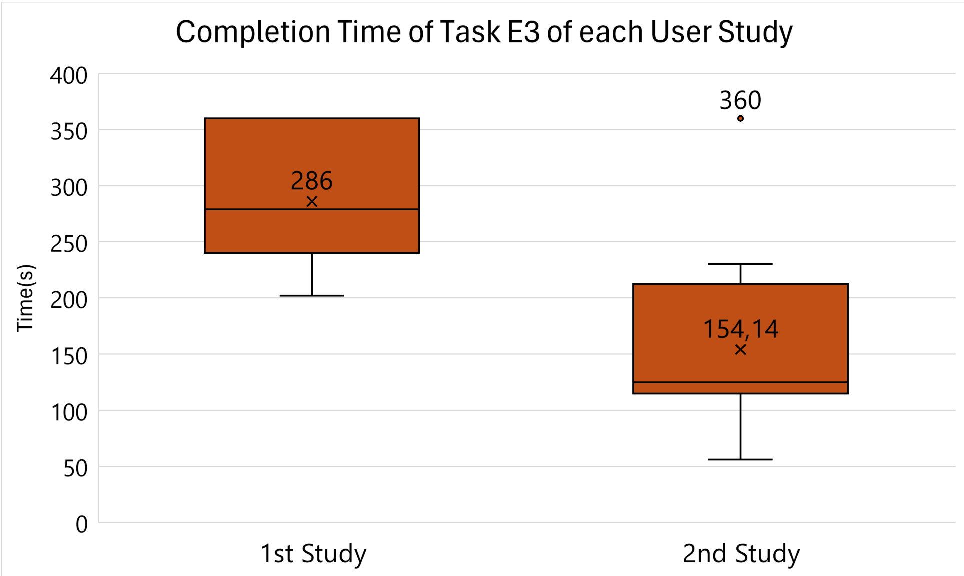

Figure 5.7: Completion Time of Task E3 of each User Study, in seconds Box plot containing a comparison of the Completion Time for Task E3 in each User Study, in seconds. The visible values above the cross inside the box represent the mean time, while the top of the box contains the 1st quartile, the line inside he box represents the median time and the bottom of the box is the 3rd quartile. The edge of the lines that come out of the box represent the maximum and minimum times recorded. Lastly, the visible value outside the box represents an outlier.

questions we had proposed. The next section will explain how said results helped to answer the research questions and what answers were reached.

5.7 Final Discussion

As concluded in the previous section the application and features developed are in a good state of usability and user experience. Improvements were also seen in the results from one study to the next.

Nevertheless, the second study also had the goal to help us answer some of the research questions that were proposed in the first chapter.

The first research question asks if an Interactive Visualization Tool creates a better viewing experience than simply observing a 3D model inside a Virtual Environment. By looking at the results for question **V_Q3** on Table 5.9, where we asked the participants of the second user study this exact question, the median result was 3.5 while the 1st quartile was 3 and the 3rd quartile was a 4, meaning the participants slightly preferred the Interactive Visualization Tool over the classic observation method. We can observe that the most negative answers showed indifference to either method.

With these results we can answer the first research question by saying that an Interactive Visualization Tool is in fact better than simply viewing an object inside a Virtual Environment. It is also worth noting that these results came from participants using our implementation of an Interactive Visualization Tool, so the results could have been even better with a more developed implementation.

The second research question asks if 360° Images can be used as a substitute for 3D Models of room spaces in a Virtual Environment.

To answer this research question we first need to add the results from the Virtual Tour Mapping done in the first study, where we found that users can still get a good grasp of a room's architecture, with most being able to get a perfect grasp of the room being simulated. This gives allows us to say that 360° Images can be used as Virtual Environments, but how do they compare to 3D models?

In the results for questions **V_Q4** and **V_Q5** on Table 5.9, we can see that the participants almost unanimously agreed they preferred navigating inside the 3D building more than inside the 360° Images. Yet when asked to compare the level of immersion they felt from each navigated space the results were not so unanimous. The median for question **V_Q5** was 2, while the 1st quartile was 1 and the 3rd quartile was 3.75, this means most users felt more immersed inside the 3D building than inside the 360° Images but they were not completely certain about this affirmation with some even slightly leaning towards feeling more immersed inside the 360° Images.

These results also lets us positively answer the second research question. 360° Images can be used to substitute 3D models of room spaces. However users do prefer the 3D models to simulate real environments, but as initially stated the usage of 360° Images over 3D models comes from a lack of resources rather than by choice, still our studies showed that the users do not have any serious aversion to the use of 360° Images and they can still get a perfect grasp of the room space from them.

This concludes the evaluation of the developed application, the results gathered were ultimately positive and helped us not just answer most of our research questions but also assess the state of the application and the new features that were added.

6 Conclusion

In conclusion, we were able to successfully implement all the proposed features and address the research questions we had set. In addition to the proposed features we were also able to add an editing function to the application, allowing a user to alter already saved Virtual Tours, and optimized the memory usage of the application in order to make it able to fit more items and to reduce load time for 2D images. The user studies that were conducted also confirmed the successful implementation of the various features that were added and the satisfactory state of usability and user experience of the developed application.

For the first two research questions, the user studies were able to answer them and were further discussed in the previous chapter's Section 5.7. In short, for the first research question we were able to conclude that an Interactive Visualization Tool is in fact better than simply viewing an object inside a Virtual Environment, as users can appreciate the increased flexibility such a tool brings and the new ways they can interact with a 3D model.

On the other hand, for the second research question we confirmed that 360° Images can be used to substitute 3D models of room spaces. However participants did prefer the usage of 3D models to simulate real environments, so 3D models should be used if possible to provide the best experience, while 360° Images can be used as a cheaper alternative.

The user studies were not able to answer the third research question, which pertains to answering what information should be stored as a 3D model's annotations, but as referenced in Section 3.4, while collecting data from the museums we were able to see that they currently only use an artifact's name and description as annotations. However, the work done in this thesis also made us determine that tags are key in order to effectively catalogue a 3D model, and with the addition of an Interactive Visualization Tool, 3D Annotations should also be considered by museums, as they add a new way to document, interact and tell a 3D model's story.

These factors lead us to answer the third research question by saying that a 3D model's annotations should at least comprise the object's name, description, tags and 3D annotations to correctly catalogue and document a 3D model.

This research should have helped make a case for museums to turn their Virtual Tours 3D. For one it would help museums to differentiate themselves by scanning the assets they already have in their possession and putting the 3D models in full display, allowing visitors to freely observe and interact with them, defining the museum by it's collection and not the building itself which usually becomes the focus of Virtual Tours base on 360° Images. While the 3D models can also be used as a method of documentation, which can be complemented with annotations to give a complete view of the original object and it's history even after the object erodes away, something 2D images have a much harder time providing.

6.1 Future Work

There are a few paths we think the development of this application can take, the best one would be the adoption of the application by a real museum, adapting the application to the specific needs that will arise during the adoption process.

However before being adopted by a museums, a revamping of the User Interface (UI) could also be considered, as the UI is very simplistic and as the focus of this thesis was in the new features the UI style was kept the same. A study on what kind of UI would best fit an application such as this one, especially from both the point of view of the user that will edit the Virtual Tours and the user that visits said tours could be interesting, as most museums tend to use very antiquated designs for their websites and media.

Lastly, for an option that is outside the current development paradigm of this application, a study could be done into innovative ways of building Virtual Tours, as most tours and this application base themselves around what is already being done in the real world, where there is an attempt to try and copy the organization of a display from real life to it's Virtual Tour counterpart, when Virtual Environments have a much greater degree of freedom than the physical world we live under. This research could also help find new ways to showcase the 3D models of scanned objects, as certain kinds of furniture do not translate well to a Virtual Environment, opening up space for the creation of new kinds of furniture for Virtual Environments since concepts such as gravity are not of concern.

These feel like a good set of options that cover each possible kind of development, from looking inside the box, to changing the box and ending by thinking outside the box.

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USER STUDY 1

Editor Section

Task 0 – Basic Presentation

Este é o interface de edição de Visitas Virtuais desta aplicação. Para mover a camara usam-se as teclas WASD e para rodar a camera usa-se o rato enquanto se prime o botão direito do rato ou pode se prender o rato clickando no botão com forma de cursor de rato (para desprender o rato tem de se clickar duas vezes no botão Esc). Para abrir o catalogo de objectos presentes no sistema basta clickar na tecla C ou no botão por baixo da letra C no interface.

Task 1 – Add two $360°$ Spheres

Primeiro vais tentar adicionar duas imagens 360º no mundo e alinhar as esferas uma ao lado da outra.

Task 2 – Add 3D Model

O Staff de um museum precisa de adicionar um novo modelo 3D de uma mascara de sapo ao sistema.

Também setá preciso adicionar as anotações correspondentes:

- Nome, "Máscara de Sapo"
- Descrição, "Máscara Jurupixuna(Sapo)"
- Tags, "Máscara" e "Brasil"
- Anotações 3D
  - Por baixo da boca do modelo com uma imagem de pessoas mascaradas, com o nome "Representação Artistica" e descrição "Desenho de pessoas a vestir mascaras jurupixunas"

– No pé esquerdo, com o nome "Pé Esquerdo" e descrição "Este pé está danificado"

Agora vais tentar executar a tarefa descrita na história. Adicionando um modelo 3D de máscara de sapo, as suas anotações e depois colocar o modelo dentro de uma das esferas 360º adicionadas na tarefa anterior.

Task 3 – Create a Virtual Tour

Agora vais tentar criar uma Virtual Tour com todos os objetos que estão presentes no catálogo, menos a máscara de sapo.

Visitor Section

Task 0 – Basic Presentation

Este é o interface para Visitantes desta aplicação. De momento basta saber que se move o rato para rodar a camera.

Task 1 – Traverse through a Virtual Tour

Agora vais explorar a Virtual Tour da Sala 5 da Academia das Ciências de Lisboa, visitando todas as esferas 360° e acabando na esfera onde começaste a visita. Depois irás tentar desenhar o espaço que a visita está a simular, apontando também as posições simuladas.

Task 2 – Interact with 3D Models

Agora vais ler a descrição da anotação 3D que está na artéria aorta(vermelha) e experimentar interagir com o modelo 3D do coração e do corpo humano.

User Study 2

Visitor Section

Task 0 – Basic Presentation

Este é o interface para Visitantes desta aplicação. De momento basta saber que dentro de uma imagem 3D apenas é preciso usar o rato para rodar a camara e interagir com objetos dentro do modelo. E fora de uma imagem 360º usa-se as teclas WASD para mover e o rato para rodar a camara.

Task 1 – Traverse through a Virtual Tour

Agora vais explorar uma Virtual Tour. É esperado que tente explorar a visita o máximo possível.

Task 2 – Interact with 3D Models

Agora vais procurar o modelo 3D do coração e ler a descrição da anotação 3D que está na artéria aorta(vermelha) do modelo 3D.

Editor Section

Task 0 – Basic Presentation

Este é o interface de edição de Visitas Virtuais desta aplicação. Para mover a camara usam-se as teclas WASD, Espaço para subir, Shift para descer e para rodar a camera usa-se o rato enquanto se prime o botão direito do rato ou pode se prender o rato clickando na tecla P ou no botão com forma de cursor de rato (para desprender o rato tem de se clickar na Tecla P). Para abrir o catalogo de objectos presentes no sistema basta clickar na tecla C ou no botão por baixo da letra C no Interface.

Task 1 – Add two 360° Spheres

Primeiro vais tentar adicionar duas imagens 360º no mundo e alinhar as esferas em linha.

Task 2 – Add 3D Model

Agora vais tentar adicionar duas anotação 3D no modelo do sapo e depois irás colocar o modelo dentro de uma das esferas 360º adicionadas na tarefa anterior.

1. A primeira anotação 3D será colocada em cima da cabeça da Mascara de Sapo, tem como titulo “Representação Artistica”, descrição “Desenho de pessoas a vestir mascaras Jurupixuna” e uma imagem.
2. A segunda anotação 3D será colocada no pé esquedo do modelo 3D e tem o titulo “Pé esquerdo”, descrição “Este pé está danificado” e não tem imagem.

Task 3 – Create a Virtual Tour

Agora vais tentar criar uma Virtual Tour com os objetos que estão presentes no catálogo (usa pelo menos 4 esferas 3D, 2 modelos 3D e coloca pelo menos 1 modelo 3D dentro do edifício 3D visível no mundo).

I

Questionnaire Consent

In order to take this test, you must be aware of what data will be collected and how it will be processed and, if you agree, you consent to this testing session.

Data Concerns

All data collected will be used only in the context of this thesis. It will be anonymized before processing. Collected information during the session consists of my visual observations, our verbal communication and the answers to the questionnaire below.

Anytime during the session, you can ask questions regarding our session.

By choosing "I consent" below, you agree to voluntarily participate in this academic study, agree to the collection and processing of your data and that you are informed about the health risks of participating.