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**A Virtual Reality Experience for
Cultural Heritage**

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A mio zio Diego

“Your heart is free. Have the courage to follow it.”

Malcolm Wallace - Braveheart

Summary

Today, the urban expansion, pollution, abandonment, conflict, atmospheric agents, looting and even tourism threatens the cultural heritage of the past at an ever-increasing rate. For this reason the virtual heritage can be a powerful support to cultural heritage for education, entertainment, restoration, promotion and preservation for future generations. This has become possible thanks to the new methods of automatic digital 3D models reconstruction, based on solid geometric mathematical laws, which make it possible to create increasingly realistic models in ever shorter times. Furthermore, thanks also to the new virtual reality technologies that are available today to a cheaper cost, is possible to produce Virtual Reality experience for a large audience, than the past years. In this thesis, we have designed, developed and validated a Virtual Reality application as a promoter of cultural heritage, allowing the visualization of complex 3D models obtained from architectural/archaeological surveys, using standalone visors. In particular, will be described our adopted solutions and modifications, such as our extended point cloud models importer, our adaptive rendering techniques solutions, and our memory management system, that have allowed us to obtain the application as has been designed. The thesis is aimed target both people with non-specific backgrounds in the field of study, and to specialized people of architectural/archaeological surveys (such as architects or civil/ambient engineering students). For this reason, the application aims at supporting the courses of “Tecniche Innovative del Rilevamento” and “Advance Survey and Representation Techniques” courses at Dipartimento di Architettura, Ingegneri adelle Costruzioni e Ambiente of Politecnico di Milano.

Sommario

Oggi, l'espansione urbana, l'inquinamento, l'abbandono, i conflitti, gli agenti atmosferici, il saccheggio e persino il turismo minacciano il patrimonio culturale del passato a un ritmo sempre crescente. Per questo motivo il patrimonio virtuale può rappresentare un valido supporto per il patrimonio culturale ai fini educativi, d'intrattenimento, di restauro, di promozione e di coservazioni per le generazioni future. Ciò è reso possibile grazie ai nuovi metodi di ricostruzione automatica di modelli digitali 3D, basati su solide leggi matematiche e geometriche, che permettono di realizzare modelli sempre più realistici in tempi sempre più brevi. Inoltre, grazie alle nuove tecnologie di realtà virtuali disponibili oggi a costi inferiori, è possibile produrre esperienze di Virtual Reality per un vasto pubblico, rispetto agli anni passati. In questa tesi, abbiamo progettato, sviluppato e validato un'esperienza in Virtual Reality come promotrice del patrimonio culturale, permettendo di visualizzare, mediante visori standalone, i complessi modelli 3D ottenuti da rilevamenti architettonici/archeologici. In particolare, verranno descritte le nostre soluzioni e modifiche adottate, come la nostra estensione dell'importatore di modelli point cloud, le nostre soluzioni adattabili di tecniche di rendering e il nostro sistema di gestione della memoria, che ci hanno permesso di ottenere l'applicazione così come era stata concepita. La tesi è rivolta sia a persone con conoscenze non specifiche in materia di studio, sia a persone specializzate in rilevamenti architettonici/archeologici (come studenti di architettura o di ingegneria civile/ambientale). Per questo motivo, l'applicazione mira a supportare i corsi di "Tecniche Innovative del Rilevamento" e "Advance Survey and Representation Techniques" del Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente del Politecnico di Milano.

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Chapter 1

Introduction

“Learn about the past to better understand the present and predict the future” [32].

This statement is used to justify our interest in ancient societies, but what happens to it if the cultural heritage of the past is lost. That is why it is so important to approach a cultural heritage study from a multidisciplinary point of view, providing several inputs which complement each other to preserve for the future. A rapid pace of development of digital photography, 3D models, and mobile technology has made it possible to begin to capture, preserving, and present cultural heritage sites and artifacts in virtual and immersive contexts. Photogrammetry is a valid example of automatic acquisition of cultural heritage models, as well as it is a flexible measurement tool in many different applications. In particular, in 3D reconstruction photogrammetry is now widely used to reconstruct from small objects of the past to big archaeological sites, even with the use of a common smartphone camera. Seeing in the coming years a continuous expansion, with a forecast by experts of a significant growth rate on the market in all the main areas of 15% per year [24]. The realistic model that are generated by a survey, sometimes are not easy to understand and interpret. In this case the potentialities of VR applied to cultural heritage, to the factors like interactivity, visualization and realism can make a big difference helping users to deeper understand some additional aspects that normally not are perceive from a common 3D desktop application.

1.1 Our Objective

The objective of this thesis was to design, development, and validation of an application in Virtual Reality about cultural heritage and how is possible to exhibit 3D models of archaeology and architecture surveys. Our application targets both to person of these sectors, like university researchers, professors or students, and common people without some particular background acknowledgment about surveys and 3D models. In particular this application could be used like support to the courses of “Tecniche Innovative del Rilevamento” and “Advance Survey and Representation Techniques” of Dipartimento di Architettura, Ingegneria delle Costruzioni

e Ambiente at Politecnico di Milano, to explain to the students how these models appear and what information can be extrapolated for different scopes (like restorations organization, conservation, and exhibitions). The platforms selected for this application are the standalone virtual reality visors. These devices don't need to be plugged to a computer, but belong to a limited computational and rendering power. For this reason, we have adopted several customized solutions to obtain the application, such as our extension on the 3D cloud point modeling importer, our adaptations of two rendering techniques and our manual memory resource management system. The resulted application shows up like a virtual museum where users can select, visit, observe and interact with different famous cultural heritage pieces. Among the available cultural heritage, stand out monuments like the face of Notre Dame de Paris, the hall of the Natural History Museum of London, an archer of the Chinese Terracotta Army, etc.

1.2 Thesis Outline

The thesis is organized as follows:

- **Chapter 2 - *Photogrammetry*** where we describe the photogrammetry and its evolution during the years. Next, we explain one of the main processes used to 3D objects reconstruction, and which applications photogrammetry has nowadays. Finally, we compare 3D reconstructions photogrammetry and Laser Scanner (another automatic 3D reconstruction process), and present one of the main formats used by architects and archaeologists during surveys.
- **Chapter 3 - *Virtual reality and cultural heritage*** we describe what virtual reality is, introduce a little of its history and provide an overview of the main technologies used today. Subsequently, we present how cultural heritage is supported by virtual heritage, introducing in what kind of applications we can find it, and which were the relationships between the virtual heritage and virtual reality, during the years.
- **Chapter 4 - *Objectives and requirements*** we illustrate the different objects and requirements that have conditioned the implementation of the application.
- **Chapter 5 - *Technical Challenges and Solutions*** we introduce the technologies used for the implementation of the application, such as the selected visor and its characteristics. Next, we describe the limitations encountered during the implementation and what techniques were adopted to resolve them, in our application. In particular, we discuss our extensions and adaptations on the importer of 3D models, on two rendering techniques used and our manual memory resource management system, which have proven to be valid solutions for the project.

- **Chapter 6 - *Our Application*** we describe, with the support of several screenshots, the various scenarios where users can find themselves during the experience, and illustrate the functionalities provided by the application.
- **Chapter 7 - *Experimental Results*** we provide the results of the prototype of the application during the tests and its evaluation by the students of the Video Game Design and Programming course of the Politecnico di Milano.
- **Chapter 8 - *Conclusion*** draws some conclusions about our work and delineates future implementations.

Chapter 2

Photogrammetry

In this chapter we first explain what photogrammetry is and what evolution this science has had throughout history. Secondly, one of the used photogrammetry process to reconstruction the 3D coordinates of an object, nowadays. Third, what are the scientific applications in which we can use photogrammetry, with a more in-depth explanation of 3D reconstruction presenting a comparison between photogrammetry and another reconstruction technique used. Finally we end with an example of a digital 3D model produced during an archaeological or architectural survey.

2.1 What is photogrammetry?

Photogrammetry can be defined as the “science of measuring in photos” [23]. We use this science to determine distances, velocity, areas, colors and coordinates of objects in photos, in order to create maps, 3D models, or simply get reliable geometric data. From a single image, we can get all two-dimensional coordinates of an object with a high accuracy, but is also possible to get third-dimensional coordinate from an image with the use of Single-view geometry process [42]. This process can often produce solutions contain a significant error.

To get 3D coordinates with few errors, we can use a Multi-view geometry process. That uses (i) two or more images, (ii) stereoscopic viewing principle and (iii) least square error to decrease the rebuilding error. Stereoscopic viewing principle is at the base of our vision system, where our brain at all times gets two slightly different images resulting from the different positions of the left and right eye and reconstruct a 3D object. This principle is used in photogrammetry to get three-dimensional coordinates of an object from multiple 2D images.

The least squared error is used to iteratively reduce the error on the chain of the different observations used during the reconstruction process.

Photogrammetry is applied to several scientific fields. It is used in meteorology to get speed and position data on clouds and winds, in accident recording to get distances and positions of cars crashes, in medicine to acquire body measurements, in mapping to recreate scale reliable map and 3D modeling to get complete digital models. Photogrammetry exploits different scientific methods and technologies from

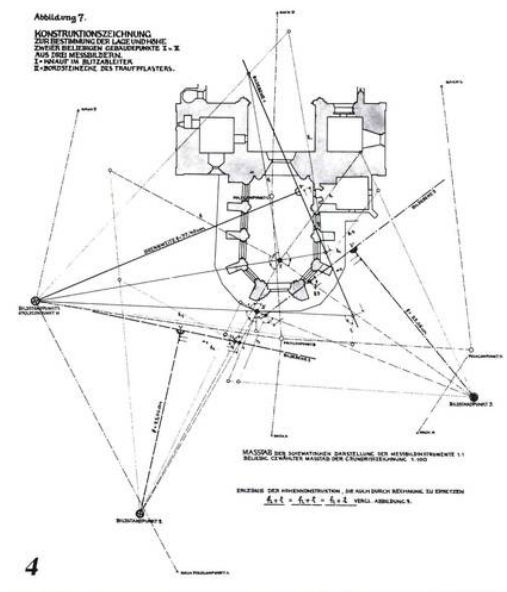


Figure 2.1: Meydenbauer's architectonic surveys.

many disciplines including optics, computer vision and single/multi-views geometry.

2.2 History of photogrammetry

We can divide photogrammetry in four main development cycles¹:

- Plane table Photogrammetry (from about 1850 to 1890) when was coined the term “Photogrammetry” and the first studies were done.
- Analog Photogrammetry (from around 1890 to 1960) in which optical or mechanical instruments were invented used to reconstruct geometry from photographs.
- Analytical Photogrammetry (from about 1960 to present) in which the use of computer systems applied to photogrammetry was partially started.
- Digital Photogrammetry (which has just started) that applied a fully digital pipeline.

Plane table Photogrammetry

Photogrammetry was invented around the 19th century by the French Aimé Laussedat and the German Albrecht Meydenbauer. Although, Laussedat did not coin the term “photogrammetry”, he is considered to be the father of it¹, since he was the first person to use terrestrial photographs for topographic map compilation.

¹https://ibis.geog.ubc.ca/courses/geob373/lectures/Handouts/History_of_Photogrammetry.pdf

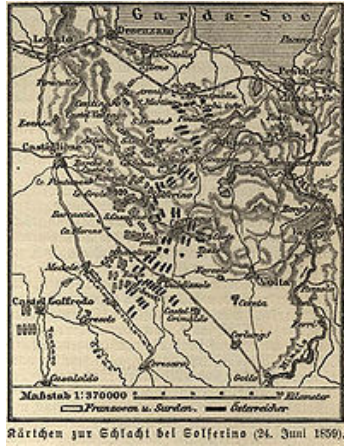


Figure 2.2: Battlefield map of Solferino reconstructed from aerial photographs by Nadar.

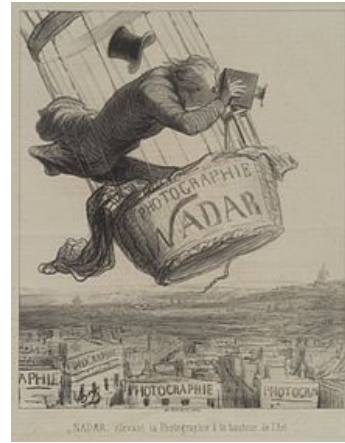


Figure 2.3: Nadar obtaining photography from a balloon.

In 1849, he presented his process, called Iconometry, like “the art of recovering the real dimensions of objects on images in which those dimensions are altered by perspective” [6]. In 1858, Laussedat searched to apply his process to a series of aerial photographs taken from kites, without success. The term “photogrammetry” was coined successively, in 1893, by Dr. Meydenbauer, who was the first person to use images to get measurements and information for architectonic purposes. He exploited this science to recreate monument plans and monument foundations (Fig. 2.1), with an accuracy of about 0.2 mm on his reconstructions. Such a high accuracy was achieved, thanks to the large image format size (40 cm x 40 cm) and the ratio between the photo scale and the map scale. In 1859, Gaspard Felix Tournachon (a.k.a Nadar) succeeded where Laussedat failed. Emperor Napoleon ordered to Nadar obtain aerial photographs in preparation for the Battle of Solferino. Nadar applied aerial photogrammetry mapping to reconstruct the battlefield (Fig. 2.2). Nadar succeeded in his job thanks to the use of a balloon (Fig. 2.3) and his previous aerial photographic experiences. Later, in 1893, Cornele B. Adams formulated his “Method of Photogrammetry” based on two aerial photos of the same area taken with a camera from two different positions to rebuild the terrain information. With his formulation Adams gave an incipit to the triangulation process. Triangulation is the method of determine and calculate 3-dimensional object coordinates by photogrammetric means, by using photographs exposed from different positions, covering the same object. The mathematical formulation of this process, nevertheless in this period, was far away respect how is known today.

Analog Photogrammetry

Two advances and new inventions brought photogrammetry in its second phase (Analog Photogrammetry). The first was the development of the airplane by the Wright brothers in 1903, which given a better camera platform for photogrammetry

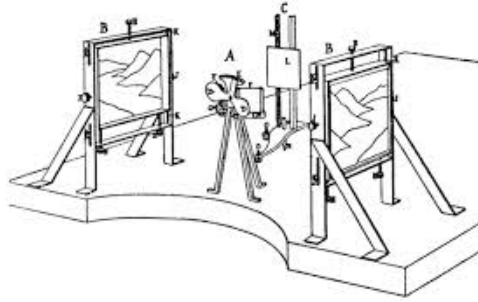


Figure 2.4: *Deville's Stereo Planigraph prototype.*

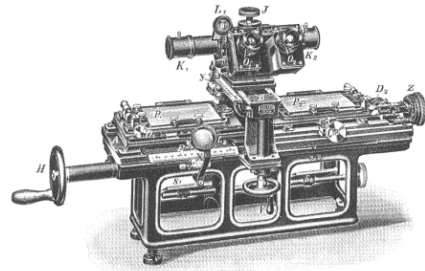


Figure 2.5: *Stereo Comparator, an instrument that allows measurement simultaneously on two photographs.*

mapping, than the terrestrial cameras or air balloons. The second was the stereoscopic principles that became widely used. The first aerial photomapping from an airplane, that acquired great success, was done by Captain Cesare Tardivo for a 1:4000 map of Bengasi in Libya, and it was presented in a paper at the International Society of Photogrammetry meeting in Vienna, in 1913. Instead, in support to stereoscopic principles, the first instrument was the Stereo Planigraph (Fig. 2.4), a stereoscopic-plotting instrument that taken advantage of stereo overlapping photos to achieve objects coordinates. This instrument was invented by Eduard Deville, in 1896, but due to its complexity, it is remembered only for Deville's surveys on the Canadian Rocky Mountains. In 1899, Sebastian Finsterwalder published his most famous papers: "Photogrammetry in the Italian High Alps", "Periodic variations of glaciers. Vime Report". These papers are important for the photogrammetry community, because they on the base of modern 3D coordinates reconstructions used by photogrammetry software to retrieve digital models, today. His studies have shown the conditions that must be met for the rays to intersect to correctly construct a three-dimensional point coordinates. Finsterwalder applied his methods of geodetic survey on mountains and glaciers with the use of phototheodolite, a precision optical photo instrument for measuring angles between designated visible points in the horizontal and vertical planes. In 1901, Dr. Carl Pulfrich designed the first stereocomparator (Fig. 2.5), an instrument used to perform topographic measurements through the accurate comparison of stereoscopic photographs taken with an instrument that was located at a distance very large from the target, making it useful in astronomical investigations. He presented his results at the 73rd Conference of Natural and Medical Sciences. In 1908, Eduard von Orel developed the first stereoautograph, a optomechanical measurement instruments for the evaluation of terrestrial photos for mapping purposes. This instrument was useful for mountainous areas, where it was difficult to use an airplane for mapping. Another great contributions on mountains mapping was done by Professor Reinhard Hugerhoff, when, in 1921, invented the first analog stereoplotter, a complex mechanical plotter that incorporated two photogoniometers to determine precise altitudes for mapping purposes. In this period, thanks to the improvements done on aircrafts, differ-



Figure 2.6: The Explorer.

ent photogrammetry aviation corporations were born. For example, ABC Airbone Corporation founded by Talbert Abrams (a.k.a Ted), who developed a dedicated airplane for map surveys called The Explorer (Fig. 2.6). This plane had a large glass "nose", twin tail booms, a pusher engine, and a tricycle landing gear"². The Explorer ensured a wide view that allowed to take aerial photographs more easily. In this period many other instruments and cameras for all photogrammetry aspects and cases were invented.

Analytical Photogrammetry

The invention of computers made significant advances to photogrammetry developments from around 1950. Computers are considered on the main advance that has brought photogrammetry in its third period called Analytical Photogrammetry. In this period the main challenges of photogrammetry was to find solutions for:

- **camera calibration:** a way to estimate camera parameters, like focal length of lens and the distortion parameters³.
- **space resection:** the process in which the position and orientation of photographs is determined based on photogrammetric measurements of the images [36].
- **interior camera orientation:** defines the internal geometry of a camera or sensor as it existed at the time of data capture [38].
- **exterior camera orientation:** is the position and orientation of the camera when the image was taken.

In 1950, Everett Merritt published the first works on analytic photogrammetry and coined this term. He worked for the Naval Photographic Interpretation of U.S.

²https://www.b-29s-over-korea.com/ted_abrams/ted_abrams01.html

³<https://www.mathworks.com/help/vision/ug/camera-calibration.html>

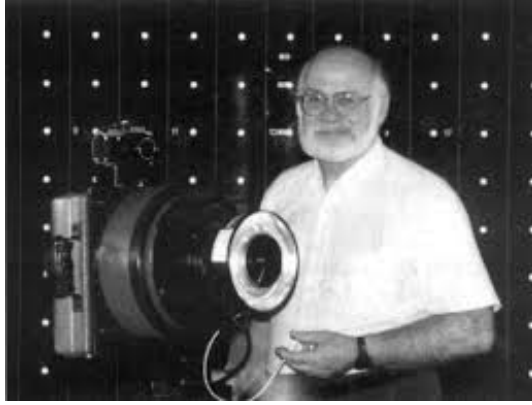


Figure 2.7: Duane Brown with his camera used during moon surveys in Apollo mission.

and developed a series of analytical solutions for the problems above. In 1953, Dr. Hellmut Schmid published the first rigorously correct least square solution¹ for multi-station analog photogrammetry. Schmid's principles are considered the basic of multi-camera systems used in modern software for 3D reconstruction. In 1957, Uno Vilho Helava developed the first analytical plotter able to achieve measurements with all kind of photographs (aerial or terrestrial) and all kind of photo orientations (oblique, horizontal or vertical). He used servo controls with the support of a computer, instead of the optical or mechanical controls of previous instruments, not only to drive the instrument for the map reconstruction, but also to digitally transform coordinates between the images and the generated maps. Duane Brown (Fig. 2.7) gave great contribution in this period. Brown started his studies, in 1955, inside the RCA Missile Test Project for a U.S. Air Force program, where he developed new approaches to camera calibration and some mathematical formulation to perfect Schmid's least square solution. In 1961, Brown left the air force's project to change his photogrammetry application goal and, in 1963, he founded his corporation called Duane Brown and Associates (ADB). Brown started to apply his work on NASA's space missions, with the use of the radio telescope at Greenbank [17] [12]. His most famous contribution was on the Apollo program for the moon surface mapping.

Digital Photogrammetry

After the Apollo project, Brown changed, another time, his photogrammetry target and started to work on a new project to develop a software tool that did not require explicit technicians to perform the measurements. Therefore, Brown tried to create a software that, other than be simple to use, had to be optimized to work on the normal personal computers of that time, compared to the main-frame used for research until then. This software was released in 1982, and it was called STARS. With the introduction of these software concepts, and the birth of digital cameras the Digital Photogrammetry, was born. A great contribution at the start of this period, was also given by Gilbert Louis Hobrough. In 1967, Hobrough invented the Gestalt Photo Mapper [30] (Fig. 2.8), an automated digital orthophotographic system that



Figure 2.8: Gestalt Photo Mapper.

used the correlation of stereo images for digitizing terrain models. This system was composed by a printer located in a dark room, a photo scanner, a computer and an input output console for the operator. Today photogrammetry is used to build realistic 3D models. This is possible because most of the complex and delicate operations, that before were done analogically are now integrated into photogrammetry software completely in a digital way. Some examples of the most famous softwares are Agisoft Metashape⁴, Agisoft PhotoScan⁴, AutoDesk ReCap⁵ and COLMAP⁶.

2.3 3D reconstruction with multiple images with Two/Multi-views geometry

Multi-view geometry is the process that is able to reconstruct in a reliable way 3D object coordinates from different perspective 2D images [33].

This requires acquiring multiple images from different viewpoints and working with points that appear in more images. This process is also called **Stereophotogrammetry** and it is based on:

- **collinearity constraint:** "a 3D world point, its image in the camera, and the camera's projection center must all lie on a straight line" [34].
- **coplanarity constraint:** "the viewing rays through corresponding image points must be coplanar, because they intersect in the 3D point" [34].

It follows that, even if only the relative orientation between the two cameras is known, we can reconstruct a straight-line-preserving model of the 3D world by intersecting rays corresponding through the same 3D point. Additionally, if the cameras are calibrated, we can also reconstruct an angle-preserving model of the world in the same way. Looking the image 2.9 we can see how reconstruct the 3D coordinates of the point \mathbf{x}_0 using two images. We considering known: (i) vectors

⁴<https://www.agisoft.com/>

⁵<https://www.autodesk.com/>

⁶<https://colmap.github.io/>

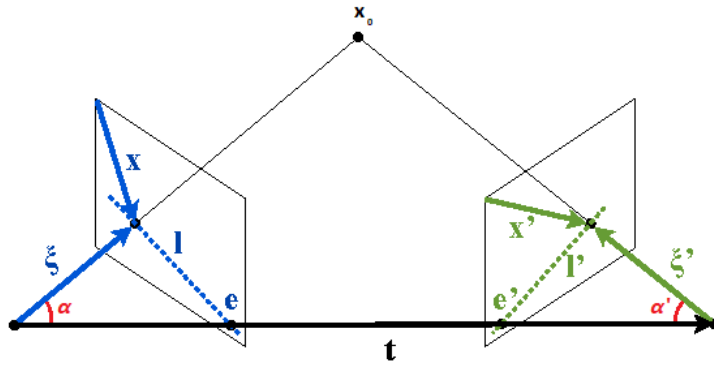


Figure 2.9: Example of Stereophotogrammetry reconstruction of a point \mathbf{x}_0 .

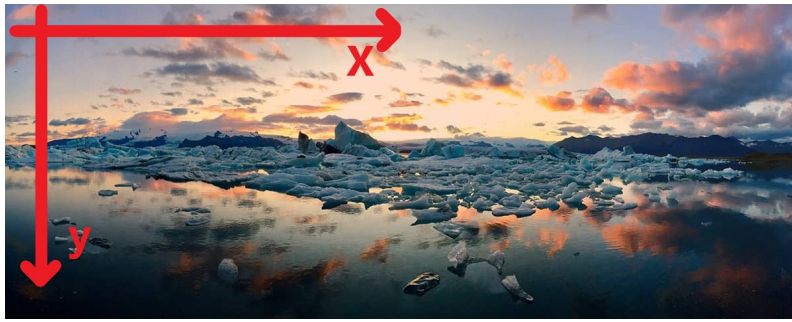


Figure 2.10: Image coordinates.

\mathbf{x} and \mathbf{x}' as the distances between the projection of the searched 3D point and the origin of the corresponding 2D coordinate system of image of the two cameras oriented like in the image 2.10; (ii) the cameras external orientations defined to be two matrices normally represented by P , each composed by cameras' position (in this case indicated by the points with ξ , ξ' distances from the two images) and orientation (in this case indicated by angles α , α'). We can find a unique solution for two cameras, stacking for each image an equation where we multiply the points projection distances \mathbf{x} and \mathbf{x}' with the matrix P and P' and for both equation the unknown 3D coordinates of the point \mathbf{x}_0 .

In case of more than two images, we can chain two-views relative orientations together, working step-by-step with only two images at time. Obviously such iterative procedure will lead to error buildup on the reconstruction. In most applications, the image network (where with image network we consider groups of more than two cameras) can be polished with a global least-squares optimization. The optimization proceeds in the usual way with a classic least square solution $\mathbf{y} = J\mathbf{x}$, where in this case: (i) \mathbf{y} are the observations of the calculated 3D object's position at each step by a pair of pictures; (ii) \mathbf{x} is the unknown position linearized at the approximate previous solution; (iii) J is the coefficient matrix (also called design matrix). With the least squares optimization we find a final solution, updating at each step the

approximate solution with the new iteration, up to convergence. In this case we can obtain great three-dimensional representation with a number of cameras $>10^4$.

2.4 Photogrammetry Applications

Photogrammetry is nowadays applied to a wide variety of areas. This is possible thanks to (i) wide availability of digital camera; (ii) the possibility to save a huge number of digital images on computers; (iii) the increasing quality of images that has give the possibility of extracting many different and complex information from them.

2.4.1 Mapping

Photogrammetry mapping, or a.k.a Photomapping, is the process of making a map from a photomosaic. A photomosaic is a unique picture composed by a huge number of “tile” pictures placed in a specific way to compose a single target photo. This application field of photogrammetry remained until the 21th century the main use of photogrammetry. Today, it is widely used by Google for Google Earth and Google Maps services with the use of satellites.

2.4.2 3D modeling

The rise of **Virtual Reality** and **3D applications** has caused an increasing demand for realistic 3D models. Although photogrammetry is not the only possible survey solution to achieve realistic 3D models (see section 2.5), it is the most common solution used today. Photogrammetry models have had their greater succed expecially in cultural heritage applications for restoration planning, materials conservation, and to quickly produce plans of large and complex archaeology sites (Fig. 2.11). They are also well used in video games and cinematic world to recreate environments, characters, and common object of all days. An example is given by “Star Wars Battlefront”⁷ games where photogrammetry was used to recreate a large number of environments known by all enthusiasts, like the Forest Moon of Endor (Fig. 2.12) or Echo Base (the rebellion base of Hoth).

⁷<https://www.ea.com/it-it/games/star-wars/star-wars-battlefront>

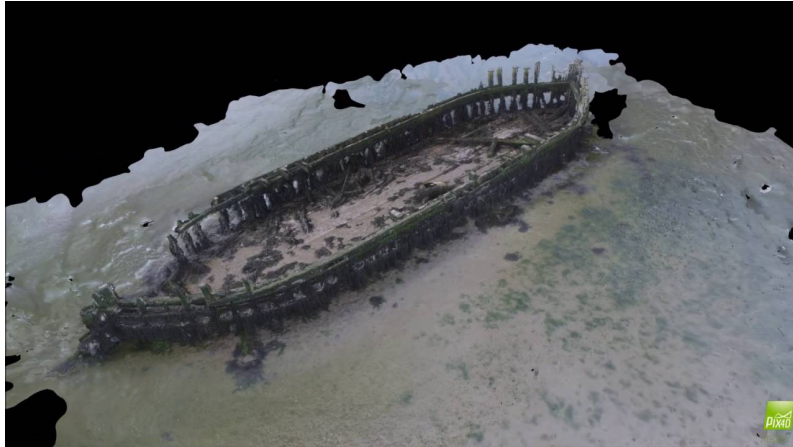


Figure 2.11: Underwater archaeological site.



Figure 2.12: Star Wars Battlefront Forest Moon of Endor.

2.4.3 Medical 3D Navigation

In this case the main medical purposes of photogrammetry are body measurements and assisted surgery, with applications that can be used for educational purposes for medicine interns or as a guide for precise manipulation of the surgeon during surgical operations.

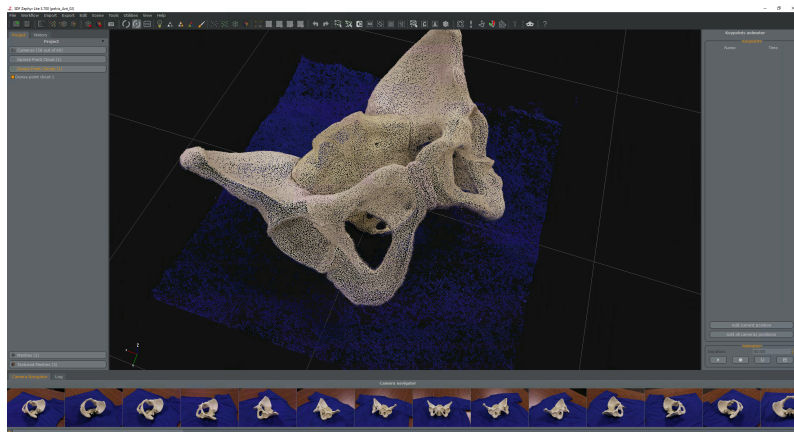


Figure 2.13: An example of photogrammetry medical application.

2.4.4 Measurements acquisition

In this case, photogrammetry can even from a single image extrapolate different data, like velocity, distances, sizes and directions. This application of photogrammetry is largely used today in meteorology to study the winds and clouds directions or for monitoring purposes of rivers, where we are able to prediction water levels and streams and avoid landslides or flooding. Finally, we can use photogrammetry measurements acquisition to extract car speeds and directions in police departments to resolve some accidents or criminal cases (Fig. 2.14).



Figure 2.14: Photogrammetry reconstruction of an accident scene.

2.5 Photogrammetry VS Laser Scanning

As we explained in the previous section, one of today's main purposes of photogrammetry is that to create realistic 3D models directly on work sites. However, exist different solutions to achieve this goal. In this paragraph we expose the main differences, pros and cons between the two major solutions used nowadays, **photogrammetry systems (POS)** and **laser scanning systems (LSS)**. Laser scanning is a technique, that exploits the flying time of a laser ray after an object collision to reconstruct its coordinates [4].

The major different aspects are:

- **Available sensors:** POS can exploit a lot of possible usable sensors, depending on the application requirements, target geometry, dimensions, power consumption and radiometric spectral. On other hands, LSS offer much less variability and flexibility. However, this is not a disadvantage for LSS because its sensors are able to get a faster and more precise depth-measurements, without using specific and complex software algorithms.
- **Platforms:** POS have been placed on almost all possible platforms from small balloons to geostationary satellites, while LSS have several limitations. This is not due of space constraints, but for a working distance limitation of the laser ray that LSS can employ. Today, we can find commercial LSS with flying

height up to 6000m. However, it remain a smaller distance than the POS applications can work with, that are used for space missions or on satellites.

- **Acquisition time and covered area:** POS is able to cover a larger areas in less time, thanks to the variable camera lens angle that can reach maximum effective field of view (FOV) of 75° . LSS system, instead, today typically have a $20\text{-}40^\circ$ scan angle, so with greater scanning time, on the same area, respect POS.
- **Weather and light dependencies:** weather and light conditions influence very much POS system that, in different cases, can produce completely different models. Since POS work on captured pictures, external conditions, for example light exposure, can make objects' colors result darker in some points w.r.t. others points. This problem does not exist with LSS since this solution does not depend on presence of colors for accurate measurements.
- **Object reflection:** the lasers used in LSS are monochromatic lights with a very narrow spectral width. The POS, on the other hand, normally has complete coverage over the entire visible spectrum $390\text{-}750\text{nm}$. With LSS, objects that have narrow spectral characteristics in the laser wavelength region will show a higher response than the POS. On the other hand, an object that completely absorbs this spectrum range will reflect weakly, with the system not being able to record the reflected wave. In opposite way, with POS all objects are "visible" thanks to the broader available spectrum, but POS may have saturation problems that generate overexposure lights. Today the problem of overexposure is easily removed and corrected by different computer graphics algorithms.
- **Automatization:** under ideal conditions, LSS can provide fully automatically raw x, y, z data for every 3D point of the environments, instead photogrammetry process, especially when involving 3D reconstruction, need more manual intervention for sensors orientation and cameras calibration. For this reason, LSS are much more automatized systems w.r.t. POS.

2.6 PLY, a photogrammetry model

PLY is a 3D model format known as Polygon File Format or Stanford Triangle Format and was principally designed to store three-dimensional data from 3D scanners and photogrammetry. It was invented by Stanford University in 1994 and was inspired by the already existing OBJ file. It may be organized in two possible different formats:

- Binary format: less human readable, but often use in 3D model software or game engines (like Unity).
- ASCII format: more human readable, but with more memory consumption.

In both cases, there is a common structure with:

- An header, defining how the model is organized with the total number of vertices, faces, and whether or not the colors are stored on vertices. If the colors are not setted the models will apply completely grey or white depending on the viewer.
- A list of vertices, organized one per line in float format.
- A list of faces, organized one per line in integer format.

In our project we used this 3D format to display what is produced by architects and archaeologists during their surveys. Our data, contained all the color information in each vertex, thus creating a realistic reproduction that, with an adequate number of points, does not look like a point cloud, but a solid model.

2.7 Summary

In this chapter, we have defined photogrammetry with a brief description of the main features, fields of application and the processes of this science. Then, we have introduced the history of photogrammetry, reporting all the main phases that have characterized it until our days. Later, we have deepened one of the main acquiring mathematical process used to obtain three-dimensional coordinates from the 2D images, the Multi-view geometry. Finally, we have introduced the different application fields where photogrammetry is used today, with a major focusing on the 3D models rebuild, also describing the main differences that we can find between this kind of photogrammetry application and laser scanning, concluding then with one of the digital format used in archaeology and architectural surveys (PLY).

Chapter 3

Virtual Reality and Cultural Heritage

In this chapter, we present the definition of Virtual Reality, its history, and the underlying technologies. Next, we explain the concept of Virtual Heritage, when and why we have had this evolution from cultural heritage, with an overview of different virtual heritage applications and a deeper presentation on the VR applications that over the years have been presented.

3.1 Virtual Reality

We define Virtual Reality (VR) as a three-dimensional, interactive, computer generated environment where the user is completely immersed [18]. Ideally, the virtual world should be able to trick users in believing they are living a real experience. To create such an experience, we must keep track of the user's movements (such as head movements) and bring in them accordingly into the virtual environment in real time, generating a virtual space that can be passive or active towards the



Figure 3.1: Phantasmagorical show.

user. VR applications involve audio video feedback, however in the recent years VR also involve other senses like haptic, smell, and force perception with the support of external systems. These elements, are the key to create a good level of immersion inside a virtual world. Today the most common VR systems are the Head-Mounted Displays (HMD), devices consisting of two screens mounted in a device similar to the eye glasses and fixed in relation to the position of the eye of the wearer and which show the virtual world through the orientation of the user's head (and position in some cases) obtained from one or more localization systems [37]. The explosion of HMDs is mainly due to their low price, the small size and the high quality technology that these devices have achieved. Currently famous devices on the market are the Oculus Quest¹ and Oculus Go² for the standalone devices, Samsung Odyssey+³, HTC Vive⁴ and Oculus Rift⁵ for cable devices. Projective-based systems are virtual reality systems composed by several projection-screen based on stereoscopic view and different cameras to track the users' motions inside the virtual world [10]. These systems have seen a greater use in the past, but due to their dimensions (around a room) and necessary equipment (several projectors and cameras) did not reach a wide market. The most famous projective-based systems, are ImmersadeskTM, CAVE[®] [40] and its child systems like ReaCTorTM.

3.1.1 History of Virtual Reality

The first experiments to recreate an unreal environment, like in VR, were born much earlier than the birth of modern digital computers. In the 18th century experiments with panoramic painting and theatre performances were able to involved the user in sensation similar to modern VR illusion.

Examples of these applications were 360-degree paintings and Phantasmagoria (Fig. 3.1) [5], theatrical performances that used smoke and mirrors along with magic lanterns (a kind of early image projector), invisible screens and sound effects to create the illusion to perceive figures and elements that were not really present. In 1838, Charles Wheatstone proved that the human brain perceives only 2D images from each eye and is able to merge these information in a single 3D representation, giving us the sense of depth. Based on this idea, Wheatstone invented the first stereoscope (Fig. 3.2). This device used a pair of mirrors at 45 degree angles that, was able to give the perception of a single three-dimensional image, using two images. This is the basic principle that is still used in modern VR sys-



Figure 3.2: Wheatstone's Stereoscope.

¹<https://www.oculus.com/quest/>

²<https://www.oculus.com/go/>

³https://www.samsung.com/hk_en/hmd/hmd-plus-xe800zba-hc1/

⁴<https://www.vive.com/>

⁵<https://www.oculus.com/rift-s/>



Figure 3.3: Link Trainee.

tems. Research for war purpose has contributed a lot to the VR evolution. In 1929, Edward Link created Link Trainee (Fig. 3.3), a flight simulator able to reproduce flight movements, turbulence and disturbance. This project was funded by the US aviation and used during World War II to train pilots in safe environments before traineeship on field. During the years VR has inspired also the world of writing and cinema, with which has created a close bond.

In 1957, Morton Heling built a prototype of his project, a cabin called Sensorama (Fig. 3.4) [16]. It had a stereoscopic color display, stereo sound, a vibrating seat, a fan system that was used to create wind effect and a smell system generated by different chemical reactions. This cabin was a little immersive cinema with different short films. Heling carried on his work and in 1960 created the Telesphere Mask [16], a first prototype of Head-Mounted Display (HMD), described as a telescopic television apparatus for individual use. The Telesphere Mask was in every way a 3D video headset, like our modern devices, except that instead of connecting to a smartphone or PC, Heilig used miniaturised TV tubes. In 1968, at Harvard University, Ivan Sutherland presented Sword of Damocles (Fig. 3.5) [41] the first Augmented and Virtual Reality HMD able to track head movements and make virtual objects appear in the real world. This system exploited a ceiling mounted tracking system to display simple virtual wireframe graphics objects.

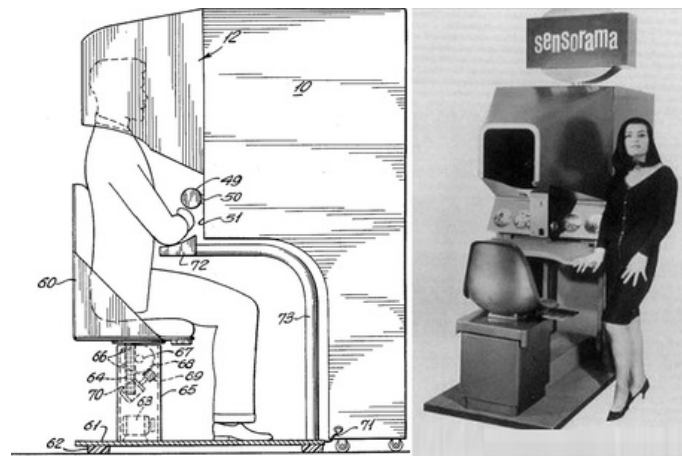


Figure 3.4: Sensorama.



Figure 3.5: *Sword of Damocles.*

In the mid-1970, Myro Krueger invented a new device that, without using goggles, was able to bring the user in a virtual environment. This system was called Videoplace [19] and was a complete artificial reality laboratory that, thanks to use of different projectors, video cameras and special purpose hardware, was able to recreate each user in the interactive/virtual world. In 1989, Jaron Lanier coined the term Virtual Reality [20]. His company, Visual Programming Lab (VPL) was the first commercial company that started selling of VR glasses and gloves to the customer market, in 1984. VPL's Dataglove was an interactive glove able to track hands' movements and orientation, reproducing them in the virtual world. With this device Jaron Lanier began collaborating with other companies like NASA⁶ and Nintendo⁷. Such collaboration brought to produce Virtual Interface Environment Workstation (VIEW) (Fig. 3.6) [14] and Nintendo Power Glove⁸. From 1989, VR began to have a certain importance in the Video Games world and different famous companies, like Sega⁹ and Nintendo began campaigns of products. However, both project did not succeed. Nintendo soon after the launch of the Nintendo Virtual Boy, withdrew the product from the market for its little success. While the SEGA' product never arrived on the market, thus remaining a prototype.



Figure 3.6: *Virtual Interface Environment Workstation.*

In 21th century, thanks to the dimension reduction of chips and technology evolution, VR devices have rapidly growing. A successful example is represented by Palmer Luckey's project. In 2010, he designed and prototyped his first device, Oculus Rift. With this project, he raised a \$2.4 million crowdfunding and opened his company, Oculus. The company was bought for \$2 billion by Facebook, in 2014, and is

⁶<https://www.nasa.gov/>

⁷<https://www.nintendo.com/>

⁸https://it.wikipedia.org/wiki/Power_Glove

⁹<https://www.sega.com/>

one of the main VR realities that on the market. Many companies have produced their HMDs (like Oculus¹⁰ or Vive¹¹) or mobile phone devices (like Google Cardboard¹²). These devices, thanks to several different sensors, cameras and displays, provide an immediate immersion for the users in virtual environment. Current research is pursuing the introduction of additional elements on HMDs to increase the senses' involvement, like smell producing systems and new tracking motion systems. For example, a Kickstarter^{®13} in April 2019 has started selling a mask called Feelreal Mask (Fig. 3.7) (from the company name Feelreal¹⁴) that can be applied on different commercial HMDs. This mask is able to reproduce smells, wind effect, heat sensation, and water mist, thanks to a set of different components like a micro-heater for the heat sensation, a micro-cooler system that reproduces the wind with different fans and so on. Nowadays, on the market, the main competitors are Oculus, with its Oculus Quest, Oculus Go and Oculus Rift, Windows with its wired Windows Mixed Reality¹⁵ and PlayStation¹⁶ with its pure VR entertainment system, PlayStation VR. VR is continually evolving and expanding, sometimes pushed by the futuristic and imaginary concept of VR in films, like happen in The Matrix^{®17} (1999 by Lana Wachowski and Andy Wachowski) or Ready Player One^{®18} (2018 by Steven Spielberg).



Figure 3.7: Feelreal Mask.

3.1.2 Head-Mounted Devices (HMD)

Head-Mounted Displays represent the most common VR systems today. They rely on the same principle of the stereoscope, showing two slightly different two-

¹⁰<https://www.oculus.com/>

¹¹<https://www.vive.com>

¹²<https://vr.google.com/cardboard/>

¹³<https://www.kickstarter.com/>

¹⁴<https://feelreal.com/>

¹⁵<https://www.microsoft.com/en-us/windows/windows-mixed-reality>

¹⁶<https://www.playstation.com>

¹⁷<https://www.warnerbros.it/scheda-film/genere-fantascienza/matrix/>

¹⁸<https://readyplayeronemovie.com/>

dimensional images to give the user a sense of depth [28]. These devices are generally equipped with different tracking systems, which are used to estimate the user's head position and orientation within the virtual world. We can divide HMD in two different categories:

- **Wireless HMDs** represented usually by smartphones or standalone devices. Normally this kind of HMDs result more portable and comfortable in the motions, due to absence of cables; However they are limited on the 3D rendering, low computational power, battery life, etc. They are several wireless devices like Google Cardboard, where with a smartphone, and a “container” composed by two lenses, used to create stereoscopic vision, is possible to obtain a simple HMD device. There are other dedicated devices like Oculus Go (Fig. 3.8) and Oculus Quest, that have an hardware similar to a smartphone, but own several optimization, like dedicated tracking systems, dedicated controllers and a more quality screen.



Figure 3.8: Oculus Go.

- **Wired HMDs** are not subject to power limitations, since they are connected with a cable to a computer. Thus, their computational power is limited by the type of the computer and not to the visor model. These devices less portable and have some limitation for the movements. Wired HMDs differ for the degree of freedom (DoF) and for the different tracking. Examples of this types of HMDs are, the Asus VR device with 6 DoF and without scale-room motions possibility or HTC Vive (Fig. 3.9) where, with additional external sensors placed inside the room, give the possibility to move inside the VR world like the real world.



Figure 3.9: HTC Vive.

These devices normally are composed of two different parts:

- **Output devices:** systems responsible for the representation of the virtual world. Today the main sense that is involved in output VR system is the sight, for this reason HMDs normally are equipped with two small LCD or OLED stereoscope screens, that appear similar to a pair of big glasses and where is presented to the user the virtual environment. In order to create a good and realistic experience, the image on the screen must be updated in real time respect user's head motion. For this reason HMDs own a set of different tracking system that are responsible for determining the user's position and orientation. We can divide the head tracking systems depending on the DoF available, normally we can find 3 DoF where only the rotation on the xy axes is tracked and 6 DoF where additionally also depth movements are tracked.
- **Input devices:** systems used to interact with VR environment. Initially computer mouse and keyboards or video game joysticks were used to interact in virtual worlds, these solutions were cheaper and represented the most common technology. Unfortunately these devices did not create real interactive sense inside the virtual world and additionally required a good controller knowledge since the user has to use them without seeing it. Today, input devices are much simpler, and consist of joysticks, normally one per user's hand, composed by buttons, touchpads, thumbsticks and triggers (that the user learn to use very fast) with 3 or 6 Degrees of Freedom (DoF). However the last devices let users interact in virtual environments with gestures [27], thanks to hand tracking system (composed of different grayscale cameras) how is announced for example by Oculus at Oculus Connect 6¹⁹ conference.

3.2 When cultural heritage became virtual heritage

With the broad term “heritage” we refer to the study of human activity not only through the recovery of remains, as is the case with archeology, but also through

¹⁹<https://www.oculusconnect.com/>



Figure 3.10: First virtual heritage tour of a 3D reconstruction of Dudley Castle in England.

traditions, art, cultural evidences, narrative, etc. [31]. In 1991, the ICHIM Conference on Hypermedia and Interactivity in Museums²⁰ was the first scientific event to highlight the importance of introducing new technologies in cultural heritage. In this conference was discussed the utility and the potential benefits for cultural heritage and museums that this emerging computer system technologies, like Virtual Reality, Web Technologies and Augmented Reality, would provide. Introduction of these information and communication technologies (ICT) in cultural heritage helped coin the term **Virtual Heritage**. Virtual heritage or cultural heritage and technology is the body of work dealing with ICT and their application to cultural heritage. The first use of the term virtual heritage was in a museum exhibition in 1994, where a virtual tour of a 3D reconstruction of Dudley Castle in England of 1550 was produced (Fig. 3.10). Thanks to this new cultural heritage application, there was a shift in the concept towards considering that the context of a cultural artefact was more important than the item itself. The concept of virtual heritage have hit all aspects of the cultural heritage world. In the research these new techniques have helped achieve information that was previously more complicated or even impossible to find. Museums have made the content and context of their collections more accessible and attractive to the wide public, thus have enriching the museum experience [39]. The first idea of virtual museum was introduced by André Malraux in 1947, a lot of years before the introduction of ICT. He put forward the concept of an imaginary museum, a museum without walls, location or spatial boundaries, with its content and information surrounding the objects, might be made accessible across the planet [25].

The definition that today is given to the term virtual museum is: a collection of digitally recorded images, sound files, text documents, models and other data of historical, scientific, or cultural interest that are accessed through electronic media²¹. The main types of ICT tools used to create virtual heritage models are:

- **3D creation software:** we can use this type of software, in the first phase of reconstruction, to transform three-dimensional objects into 3D digital models

²⁰<http://www.archimuse.com/conferences/ichim.html>

²¹<https://www.britannica.com/>

from laser scanners, sound waves scanners or photogrammetry systems.

- **3D modelling software:** we can use this type of software, in a second phase, to adapt the previously generated model, so as to correct it from possible software errors.

The technologies used to represent virtual assets, have several key features in common [10]:

- Multiplicity of contexts with a continuity.
- Good instructional design.
- Pro-active learning contexts.
- Good balance between learning and leisure.
- No text-heavy pages to interfere with the learning experience.

These technologies used in virtual heritage are:

- **Web technologies:** the increased efficiency of Internet connection makes it possible to transmit large media files. The most popular technology for the WWW visualization includes Web3D²² which offers tools and an open standard for real-time 3D communication.
- **Virtual reality:** this technology (see 3.1), is represented by common visualization displays like HMDs and 3D polarizing stereoscopic glasses. An example is ReaCTorTM, a VR environments that use CAVE[®] [15].
- **Augmented reality:** with AR systems, the users can enjoy an enhanced experience by visualizing, interacting and navigating additional cultural heritage virtual content. Virtual artifacts, that are positioned by application developers using software methods (i.e. computer vision techniques) or specialized tracking devices (for example InertiaCube4²³), are visualized by users with the use of smartphones or other devices.
- **Mixed reality:** a combination of VR, AR and real environment.
- **Serious games** [3]: the popularity of video games, especially among young people, makes them an ideal medium for educational purposes. The term “serious game” describes a relatively new concept: computer games that are not limited providing entertainment, but allow for collaborative use of 3D spaces learning and educational purposes. Examples of successful serious games included are Revolution (Francis 2006) and the Virtual Egyptian Temple (Jacobson and Holden 2005) (Fig. 3.11), or other games halfway between serious games and entertainment games are Civilization^{®24} and Total War^{®25} series .

²²<https://www.web3d.org/>

²³<https://www.intersense.com/inertiacube4>

²⁴<https://civilization.com/>

²⁵<https://www.totalwar.com/>



Figure 3.11: The Virtual Egyptian Temple (2005).

Virtual heritage today lives a thriving period thanks to a continued evolution of these technologies. We can affirm, indeed, that virtual heritage applications have made great strides in the last few years but still needs the help and assistance of the media and technology communities to be better presented to the public.

3.2.1 Purpose of virtual heritage

Virtual heritage can be a powerful solution for different purposes like education, entertainment, preservation, restoration and promotion. We can divide these different purposes in three main domains [1]: (i) 3D documentation, (ii) 3D representation, and (iii) 3D dissemination. The first one mainly focuses on preservation and restoration purposes. Today, the urban expansion, pollution, abandonment, conflict, atmospheric agents, looting, and even tourism threatens the cultural heritage of the past at an ever-increasing rate. Most of cultural heritage is made of wood, paper or other materials that can degrade itself, risking being lost at any moment. Examples are what happened in June 2014 and February 2015 when the Islamic State of Iraq and the Levant destroyed at least 28 historians religious buildings, or what happened to Notre Dame de Paris on April 15, 2019, when a fire in the structure broke out under the roof eliminating a secular structure. These examples demonstrate how much is important to create digitized representations of cultural assets in order to preserve them for posterity. Modern techniques of 3D reconstruction, (see 2.5 and 3.2.2) have facilitated the conservative aspect of virtual heritage. These 3D virtual models have given the possibility to test different restoration approaches through software simulation or physically restoration techniques on 3D printing model, before start working on the real cultural heritage.

3D representation and 3D dissemination, are strictly connected and we can see the second as an extension of the first one. In this case, education, entertainment and promotion are the main pillars that represent these two virtual heritage aspects. Additionally, virtual heritage is a powerful representation solution for all of those monuments that are not reachable by all people, like The Mazotos Shipwreck [22] (a commercial ship dated to the late classical period located in the sea area of

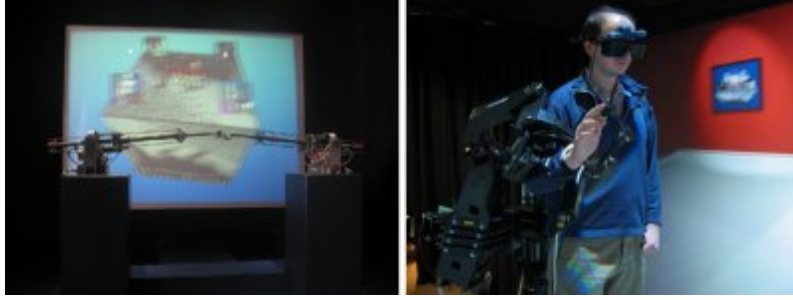


Figure 3.12: PERCRO.

Mazotos), or The Freiria Complex (a complete destroyed Rome villa) [32]. Thanks to emerging second-generation technologies, it was possible to pass from the small circle of users (like researchers and museums), to a large number of users. Past limitations were due not only by the devices cost, but also by their dimension. An example is PERCRO (Fig. 3.12) at the Museum of Pure Form in Italy [9] where the system occupied an entire room.

Today a virtual heritage application can educate people with a funny experience or take it to places not normally reachable. Modern portable cheap technologies are now within everyone's reach. This makes it possible to create applications for a large audience.

3.2.2 VR in cultural heritage

Differences with all other computer systems

Many researchers have investigated the potentialities of VR applied to cultural heritage, to the factors like interactivity, visualization and realism [29]. These virtual heritage systems are contributed the most in museum exhibitions, both as virtual reconstruction of existing museum or archaeological sites, or as ex-novo creation of a virtual environments, not corresponding to existing structures. In both cases the VR applications, where were proposed, have always been appreciated by visitors. Additionally, since the images displayed within the applications, are not predetermined or pre-registered, but generated in real time, the public is able to interact with the programs and define their own behavior and thus obtaining a greater experience. Finally, the human curiosity of new, especially inside the young people, has further contributed to attract a good number of users. Some expressive data are given, for example, by the two VR systems installed at the Foundation's Cultural Center by The Foundation of the Hellenic World. In this case, before the opening to the public the applications (when were available only by schools, universities and research centers) registered a turnout approximately five hundred daily people. After opening to the public in 1999, in two years the registered turnout was about one hundred thousand people [15].

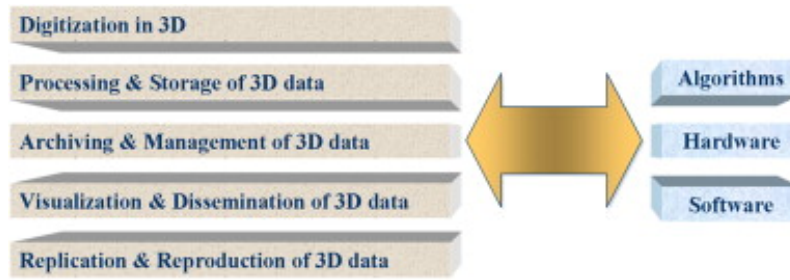


Figure 3.13: The five main processes of cultural heritage recording.

Recover cultural heritage model for VR application

A virtual model is a valid and fundamental cognitive tool through a user can interact with in a virtual environment. This technology can be applied to the world of cultural heritage as a promoter of it. In this case is possible to talk about the recording of cultural heritage how a multidimensional process that addresses not only the problem of three-dimensional digitization of objects and monuments, but involves all the aspects of this new digital content management, representation and reproduction [29]. We can define five different aspects of digitalization of a cultural heritage (Fig. 3.13), with their own algorithms, hardware devices and more sophisticated software. In this section we will focus on the first two points, while a valid representation of the fourth point is represented by our application that will be described at chapter 6.

A digital format is potentially more reliable, allows the collection of more precise data and to produce different hypotheses without bearing the costs of a physical reconstruction model [32]. Through these models it is possible to segment statues, buildings and other arts of cultural heritage in order to further study the artistic techniques used or test different restoration methods before applying them to the physical asset. Additionally the mere fact that they are digital items makes them a viable basis for remote work systems, which can be accessed anywhere.

In past this models were manually created by a human programmer and required long developing time, resulting very expensive. In order to overcome this problem, different techniques and instruments to create virtual model through observation of real object were created [26]. These new automatic virtual reconstruction methods are based on 3D laser scanning, 3D sound waves scanning (for underwater surveys) and new photogrammetry techniques in order to acquire the object faithfully. All of these techniques are reverse engineering processes, which ensures a photorealistic reconstruction of every detail, shape and decorations of an object [7]. Thanks to these techniques is now possible to achieve more realistic models where before was not possible, with very reduced times and cost. Examples are underwater work done on The Mazotos Shipwreck (Fig. 3.14) in 2017 by Cyprus University of Technology [22] or on The Mercurio Shipwreck in 2019 by Università Ca' Foscari of Venice [35]. Where the two obtained models were recovered and inserted in two VR experiences and subsequently proposed to the public and experts, making them visitable. Additionally, with these kind of surveys we can scan cultural heritage in differnte

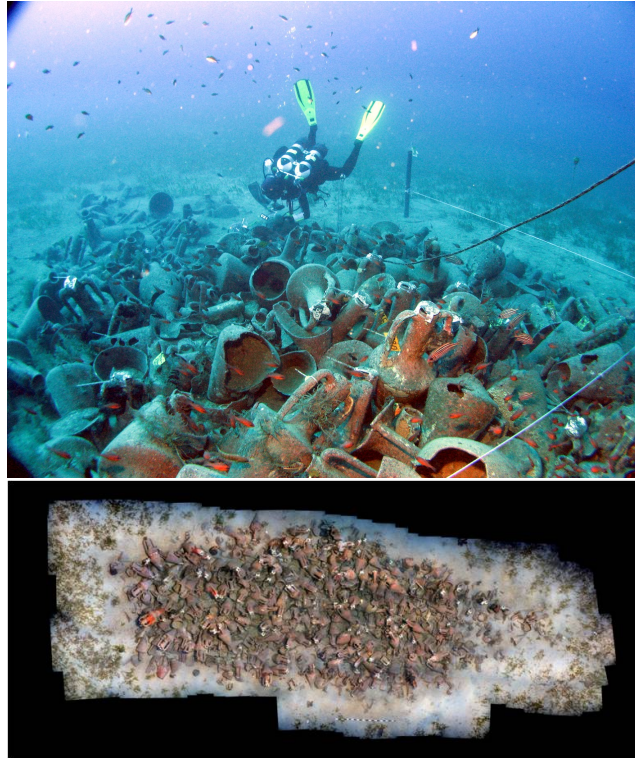


Figure 3.14: Above an image taken during underwater survey of "The Mazotos Shipwreck", and below the resulting model.

ways, for example with ultraviolet light in order to achieve new information that previously could not be known. An example was The Digital Michelangelo Project realized by the Stanford University, in 2000 [21].

The use of VR applications of cultural heritage of past years compared to the present day

How we have hint in the previous paragraphs, VR applications in the past few years were used mainly for exhibition experience in museums, thus leading to a certain trend. We already know that exists different ways to propose a virtual reality experience, with the use of HMDs or immersive virtual reality environments. As for HMDs in the past, these systems have become synonymous of heavy helmets, multiple cables and high end computing gear that did not facilitate its use with the broad public. This aspect played in favor to the VR projection-based systems, like ImmersadeskTM [11] (Fig. 3.15) or CAVE[®]-like systems. These systems, after different tests and studies [9] [31] [15], have brought to the public pro and cons described below in more detail.

In favor of the project-based VR systems were:

- offers a better possibility to have a greater perception of the cultural heritage exhibits with a nearer vision, thing that normally is not possible in a museum.
- the fact that systems can allow visitors to travel through space and time without stepping out of the museum building.

- works is always “in progress” and can easily change during time.
- allows visitors to experience a virtual world without being isolated from the other members of the group. This aspect is particularly important for both educators and students where education is a social experience.

The cons, instead, which were recorded are:

- users had a short trial time in a crowded place.
- sometimes complex devices needed user training.
- limited interactivity with less engagement.
- special staff and special space for VR infrastructure.
- the costs of VR infrastructure were high and not for all museums, let alone a private individual audience.

Today things have changed in favor of HMD technologies. Now we have increasingly light and small HMDs with the possibility to be wireless and with their graphic capabilities to implements realistic virtual environments. These aspects have determined the access to virtual reality to a wider number of users, creating opportunities and solutions for the dissemination and promotion of virtual heritage, thus leading to being able to enjoy VR applications at much lower costs [13]. Furthermore, the evolution of game engines like Unity²⁶ or Unreal Engine²⁷ helped the developers for production several application, allowing a larger diffusion. With these changes much of the past cons, that we have exposed for the previous VR systems, have been exceeded, but new ones were born:

- hardware limitation that in case of standalone HMDs or smartphone are very critical.
- limited interaction for user, in that we have seen a standardization of input devices. Although some virtual reality companies have promised the introduction of more natural interaction systems in the future.
- for a long time of use, if the HMDs are not well designed, the user can feel fatigue sensation on the head.
- the devices standardization procedure led to have less user adaptive systems.

Of course, the application design has not changed weight in the development, even today this aspect is at the base of success or not of a VR application.

²⁶<https://unity.com/>

²⁷<https://www.unrealengine.com/>



Figure 3.15: Immersadesk™

3.3 Summary

In this chapter we have introduced earlier the history evolution of Virtual Reality during the years to then explain in detail what is a Head Mounted Display and its main characteristics of today's devices. Second, we have described how was coined the term of virtual heritage and how this new patrimony can help its predecessor (the cultural heritage). Third and last thing, we have explained the differences, pros and cons that a VR virtual heritage application has, compared to other applications and what the future of these VR applications will be.

Chapter 4

Objective and Requirements

Our objective was to design, implement and validate a virtual reality application that allow people to navigate and manipulate different cultural heritage pieces (such as monuments, buildings, statues, columns, etc.) and to have a more in-depth understanding on how these cultural heritages are acquired and digitized through architecture surveys. For this reason, the application was meant to provide support for lectures of “Tecniche Innovative del Rilevamento” and “Advance Survey and Representation Techniques” courses of Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente at Politecnico di Milano. We organized a meeting with two professors from the department, to fully understand the techniques used to obtain 3D models of monuments from photogrammetry surveys and discuss the fundamental requirements. After the meeting we outlined several prerequisites for our application. First, the possibility to import the complex models that are generated by architects during surveys (a PLY point cloud model containing vertex-only coordinates and vertex-colors) and the generated solid model, obtained from the point cloud model. Secondly, the application had to give the possibility to navigate the buildings through different points of view and interact with smaller heritages with rotations, motions or zoom to have a better prospective to observe in more details survey’s failures or particular results of a technique used by the artist during production. Third, the application had to give a familiar and comfortable place to create an immersive experience, like for example a gallery or a museum, where the user can select which and what kind of cultural heritage arts visit. Giving the user the opportunity to observe places and cultural heritage that are normally difficult or impossible to visit. Fourth, the application had to be designed for standalone HMDs (like Oculus Quest), these visors come with low memory, low computational power and several rendering limitations, but with the possibility to be used almost anywhere with no need for a computer. Fifth, the application had to have the possibility to add new cultural heritages in an easy and fast way without updating the application.

Chapter 5

Technical Challenges and Solutions

In this chapter we explain the different challenges that we have found during the implementation of the application and what were the different solutions that we adopted to solve them. Especially, will be described our extended PCX importer, our adaptive of Occlusion Culling and Fixed Foveated Rendering versions, and our manual system of memory management with AssertBundles, that we produced to gave us the chance to obtain the designed application.

5.1 Technologies

In this section, we describe the HMD adopted with its main characteristics.

5.1.1 Oculus Quest

We adopted the new standalone HMD of Oculus, Oculus Quest (Fig. 5.1). Oculus Quest is a wireless Virtual Reality (VR) Head-Mounted Display (HMD) that can be used almost anywhere with no need a computer, but it present several limitations. Examples of them are the power and rendering limitations that have conditioned the implementation of the application. Oculus Quest has two controllers, five built-in front-facing cameras and a gyroscope like tracking system, and two OLED displays (each 1440x1600) with 72Hz refresh rate, a horizontal field of view of up to 100 degrees, and a pixel density to 558ppi. Thanks to its sensors the device is able to map the surrounding environment and the users' positions in a safe guard zone where them users can move freely. If users leave the safe area, the device shows the perimeter limits within the virtual world and activates the cameras to show the external environment to the users. The controllers' position are determined with 6 degrees of freedom (DoF) without the need of additional lights on the them and external supports. Additionally, Oculus Quest in the future will be able to have hands tracking by Oculus default system without the support of controllers, thus increasing the level of virtual experience for the user. The devices has 4Gb of RAM and 64Gb or 128Gb of storage. The headset weighs approximately 570g and has

a headband designed to place its weight on all skull parts of the user to have a completely comfort in movement.



Figure 5.1: Oculus Quest

5.2 Challenges and limitations

The main challenge was to produce a fluid cultural heritage application with a standalone HMD. During implementation some limitations and challenges have conditioned the architecture and the application' implementation. One of the main critical problems was a RAM memory limitation. The device declared memory RAM is around 4GB, but the producer normally limits the applications' RAM to 2.2GB to safeguard the functioning of the device. However, this bound was very far from the needed memory to load the architecture models to be shown, where a single model could exceed 1Gb of memory. Additionally, we found another problem due to the photogrammetry models with a high poly and high vertices count. This other limitation was due to the device's rendering power, that created a color distortion of pixels, and a low frame rate, bringing the CPU and GPU of the device to throttling. A throttling problem born when the CPU's (the same thing worth with the GPU) temperature reach critical values and the system must reduce the working frequency and limited the computation. All of these limitations were linked not only by the used of a standalone device, but could be generated also by an unoptimized coding way. For this reason, all written code has tried to be optimized at its best.

5.3 Solutions

In this section, we discuss the architecture that we have given to our application and the solutions we adopted to deal the limitations and challenges. In particular, we describe in detail our extended PCX importer, our adaptive Occlusion Culling and Fixed Forward Rendering systems and our memory management system through AssetBundles.

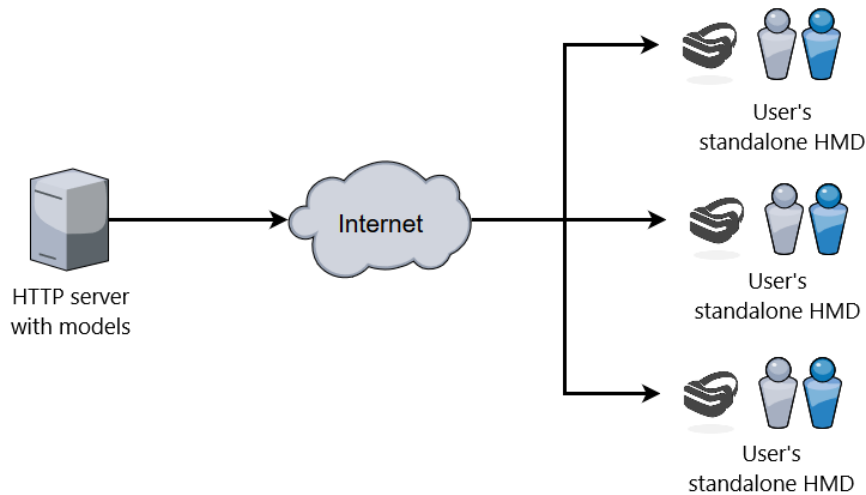


Figure 5.2: Application Architecture.

5.3.1 Application's Architecture

As is possible to see from Fig. 5.2 the application's architecture is a classical client-server solution. The server is used to download in real time the models. This server can be represented by:

- A private server with a known IP address.
- A public cloud storage (like for example Google Drive¹ or OneDrive²). In this instance the service must give the possibility to have a direct download link.

In both previous solutions the download models, in addition to having a specific format (see 5.3.8), must be organized with a standard order. The organization is due to the possibility from users to change, at run time, which server to use to download the models. These models, if compressed, have a size of about hundreds of Mb, so they need a fast Internet connection with low latency and high responsiveness to be downloaded in reasonably short time. For this reason, our application is part of a collaboration with Vodafone Italia aimed at showing the benefits of 5G. Thanks to its efficiency, it was possible to send data with a very low latency and very high speed. The decision of having an external server where download in real time the different models, has given us the possibility to bring this application on standalone devices with lower RAM memory.

5.3.2 PCX Importer

Unity does not import into the engine PLY models, but give several ways to implements own libraries or packages to bring the models into the engine. We have resolved this format problem, to import and visualize architects' models (see section 2.6), with the use of a version of PCX³ importer modify by us, to perform vari-

¹<https://www.google.com/drive/>

²<https://onedrive.live.com>

³<https://github.com/keijiro/PCx>

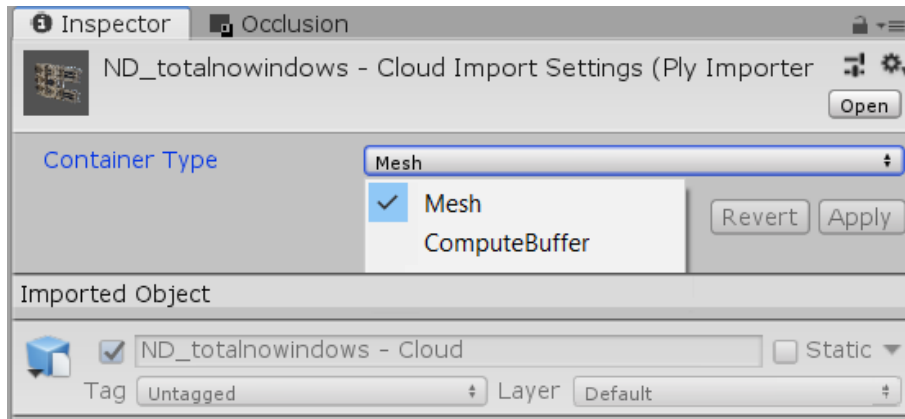


Figure 5.3: The two possible formats usable with PCX importer.

ous operations on the models and improve the rendering performance. PCX is an importer birth on Oct, 2017, and developed by Keijiro Takahashi a Unity’s evangelist. It is free and can be downloaded directly from Takahashi’s GitHub page⁴. PCX works with the 32-bit vertex index format introduced in Unity 2017.3, so it is not compatible with previous versions of Unity. It gives the possibility to store the model in two different ways (Fig. 5.3):

- **Mesh**: a computer graphics collection of vertices, edges and faces.
- **ComputeBuffer**: where the points are stored in a ScriptableObject⁵ (a data container that you can use to save large amounts of data, independent of class instances), which uses a buffer to store point data.

PCX is not a official Unity’s importer and it is still on beta version. For this reason from the two possible PLY formats previously seen (see section 2.6) is possible to importer only the binary format.

5.3.3 Our Extended PCX Importer

In our application we changed the PCX importer, giving us the possibility to create several submeshes, in order to have the possibility to render only the pieces of monument observed by users. With our extended PCX, we implemented three different phases:

- a reordering phase, where the vertices of the complete mesh are reordered, so that the different pieces can be arranged to be adjacent with a specific sequence. In this phase the vertex colors (stored in a separated array respect to the position array) must follow the vertex positions, in order to preserve them.
- a cutting phase, where are generated all the different submeshes, in the same way happen in standard PCX converter for a unique mesh. After several

⁴<https://github.com/keijiro>

⁵<https://docs.unity3d.com/Manual/class-ScriptableObject.html>

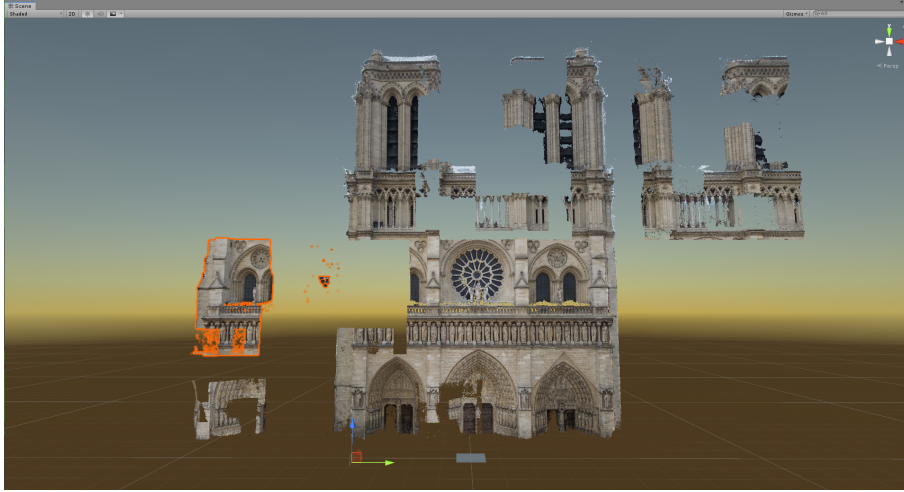


Figure 5.4: Example of a cut mesh with *The Face of Notre Dame*.

performance tests, we founded the right block size to cut the original meshes, with a size of about 5000 vertices per submesh (Fig. 5.4).

- a composing phase, where each portion created is linked to be a child object of a unique empty object.

5.3.4 Occlusion Culling

The view region or Frustum of a virtual camera, is composed by a solid shape with two parallel planes call Near Clipping Plane and Far Clipping Plane that represent the upper and lower base and 4 other plane that linked the two principal bases. This solid shape normally represent the field of view (**FOV**) and it is set by the width of the near plane and the distance between the two principal planes. This rendering solution is called view frustum or viewing frustum and is the region of space in the virtual world that appear on the screen. All objects that are inside the frustum are rendered (Fig. 5.5) with a specific order, before the far away objects and after the near objects. This solution avoid possible unrendering objects, but affect more on the rendering performance. Usually this rendering solution does not create complications, due also to the high GPU power that we have today, but can create a bottleneck for all devices with a limited computational power (like in our case). To avoid this problem, another rendering solution called Occlusion Culling⁶ with some tricks

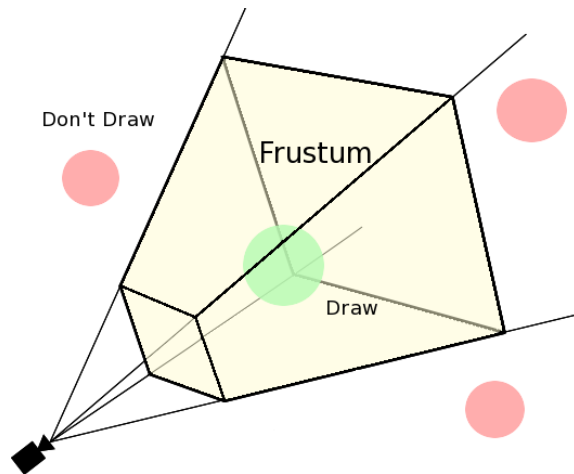


Figure 5.5: View Frustum.

⁶<https://docs.unity3d.com/Manual/OcclusionCulling.html>

and changes made by us, was used for the application implementation. Occlusion Culling is a feature that disables rendering of objects when they are not currently seen by the camera, because they are obscured (occluded) by other objects. With this solution Unity will ensure only visible objects get sent to be rendered. This reduces the number of draw calls and increases the performance. To achieve this, all objects, that in game do not change its position and form, must set like Static Object⁷. Where in Unity a static object is an object where some information can be pre-computed in the editor. Some examples are rendering information, light effects and physical reactions.

5.3.5 Our Adaptive Occlusion Culling

We have adopted Occlusion Culling solution in our application, to partially avoid the rendering power limitation and increase the frame rate (fps). However, due to our type of point cloud models, we could not directly use it as explained above, but we made some changes. Indeed, on the first tests we have not obtained good result. This because Unity Occlusion Culling is not able to manage the meshes having for each triangle all three identical vertices, how was in our case. So, to successfully use these rendering techniques we thought of putting each sub-piece of a monument in an invisible cube. This solution, with this additional parent with a solid mesh for each piece of monument, have resolved the previous problem. Indeed, every time a cube containing a piece of the monument is not observed by the user, it is not rendered, and with it the point cloud of the monument contained (Fig. 5.7). In this way we have increase the rendering performance, thanks also to a harder clipping done in way to reduce the number of draw-calls. Clipping is a computer graphics rendering technique that cut the rendering of objects that are on the borderline of the frustum, or better in our case on the border line of the camera plane.

5.3.6 Fixed Foveated Rendering

Normal rendering consider each area on the screen with the same importance, and calculates all of them with the same resolution. This computer graphics solution is not used by human visual system. Our eyes have a visual field around 120 degrees of arc, but only a very limited arc around 18 degrees is visualized by the human eye in full resolution. This solution gives humans a greater concentration and resolution on the center view. This area is called **Macula**, and it is where there is a higher density of cone cells. A cone cells (or cones) are photoreceptor cells positioned on the retinas of all vertebrate eyes. So, most of human view is peripheral, and it have less importance for our brain, especially if there are no moving objects inside it [8]. Otherwise, if not all objects in the peripheral view are static, instinctively the brain change the attention on the area where the motion is perceived. However, this change is not done through a resolution variation, in that is fixed, but will produce a head or eyes motion that will change the center of the view. The human

⁷<https://docs.unity3d.com/Manual/StaticObjects.html>

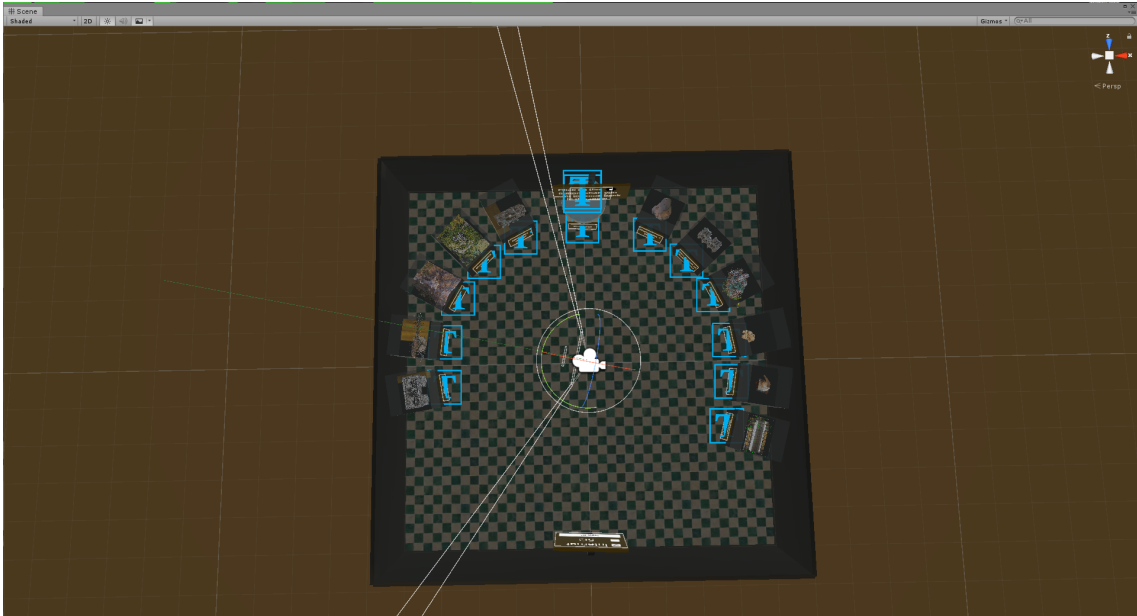


Figure 5.6: Our Menu Hall rendering with all visible Game Objects.

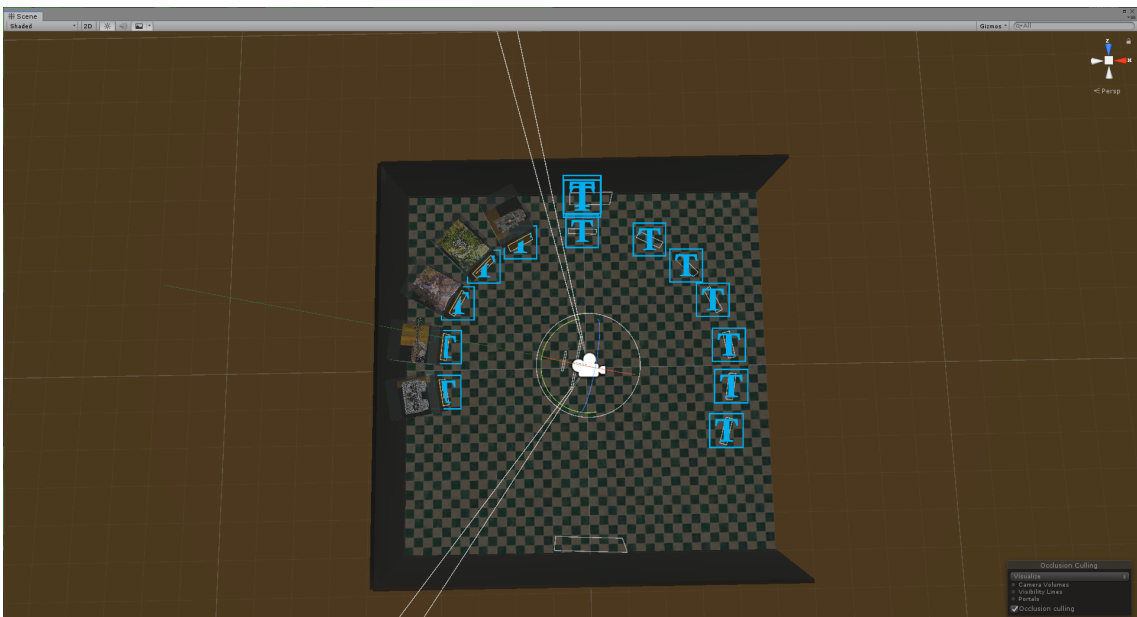


Figure 5.7: Occlusion culling rendering of our Menu Hall.

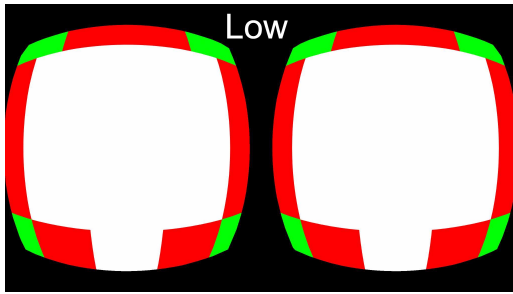


Figure 5.8: Low FFR.

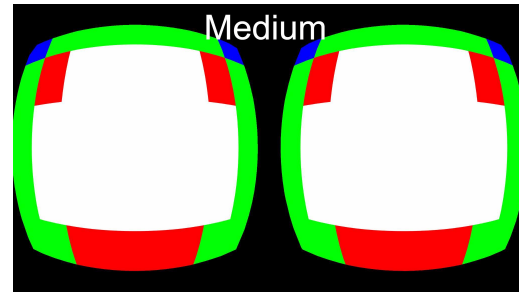


Figure 5.9: Medium FFR.

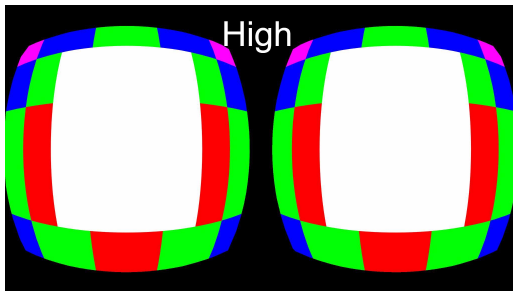


Figure 5.10: High FFR.

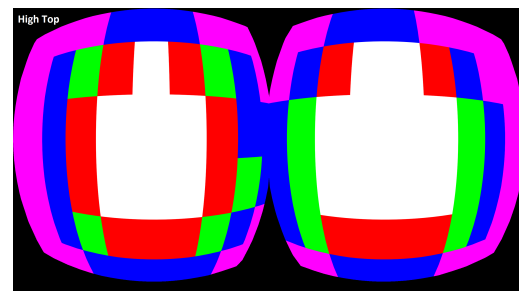


Figure 5.11: High Top FFR

vision principle is at the base of Oculus's Fixed Foveated Rendering⁸ (FFR) where the pixels at the edges of the screen are rendered with a lower resolution than the center. It is possible to activate this rendering system by code with four modes in Unity applications, from a Low FFR to a High Top FFR. The differences between the modes are due to the grade reducing rendering power that each peripheral area have. For example, Low FFR (Fig. 5.8) renders in the red areas only 1/2 of the pixels and 1/4 in the green areas respect the standard pixel resolution. Instead, High Top FFR (Fig. 5.11) renders the magenta areas with a resolution 1/16 and blue areas with 1/8 of the standard resolution.

5.3.7 Our Adaptive Fixed Foveated Rendering

In our application we have customized Fixed Foveated Rendering system to be activated only when a significant drop in performance is detected. Indeed, a much intense use of this technique could be perceived by the users through the presence of different rectangular area on the screen that divided the resolution areas, especially if in the scene there is a great illumination. In this way the developer risks making users lose the feeling of illusion previously created. For this reason FFR system must be balanced very well, to avoid this unintended result. In our application we have adopted FFR solution (Fig. 5.12), completely avoiding the rendering problems presented before, like the color flickering, and the lag problems. However, to prevent that FFR system being noticed by users, we have not used it in all scenarios of our application, but customized it in way to be activated only when is necessary with a manually mange system. In this way it was possible to increase fps and the performance, reducing significantly the GPU workload.

⁸<https://developer.oculus.com/documentation/quest/latest/concepts/mobile-ffr/>

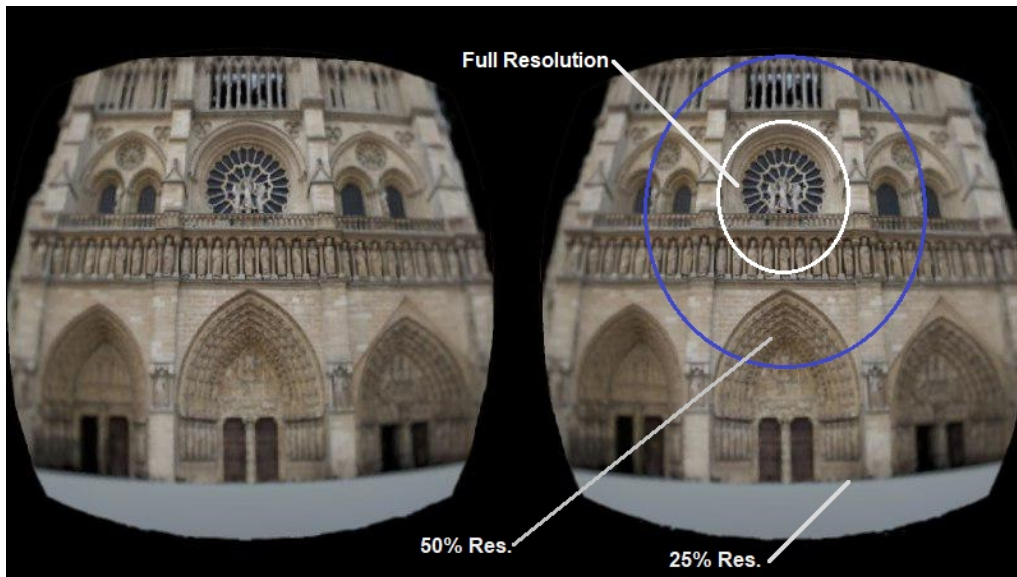


Figure 5.12: Our Adaptive Fixed Foveated Rendering, during its working inside our application with The Face of Notre Dame.

5.3.8 AssetBundles

The way followed by Unity to reduce loading times, consists to loading all possible objects in the RAM memory at the start of a scene. This solution, with some devices like PC or console, does not create some particular problem, thanks to the large RAM memories that we have today. Instead other times, can bring to critical performance, like happen on standalone HMD and smartphone with limited RAM. In our case we have found this limitation, as explained before, and for this reason a traditional Unity's memory management could not be used to produce the application required. For this reason, we decided to follow an AssetBundles solution. An AssetBundle⁹ is an archive file that contains assets that a Unity's project can load at run time. An AssetBundle can reference to a lot of different Unity's objects, for example, Materials¹⁰ (that define how a surface should be rendered, by including references to the Textures it uses, tiling information, Color tints and more), Textures¹⁰ (bitmap images) and Prefabs¹¹ (a Unity's way to create, configure, and store an complete object with all its components, property values, and childs as a reusable Asset). The AssetBundle archive is a container, like a folder, containing resources that must be generated in a specific way, so that they can be subsequently loaded into the cache and used at run time. Normally, we recognize a pre-generative phase, in which it is possible to compress objects in different ways to reduce the size of the memory and consequently get less download and upload time in the cache, during use.

⁹<https://docs.unity3d.com/Manual/AssetBundlesIntro.html>

¹⁰<https://docs.unity3d.com/Manual/Shader.html>

¹¹<https://docs.unity3d.com/Manual/Prefabs.html>

5.3.9 Our AssetBundles Use

In our application, other than have used assetbundles like resource files (chunks of binary data stored separately) to allow Unity to efficiently load them from external internet server on the HMD, we implemented a manually upload and unload system in RAM memory, in way to have always a minimum possible consumption. Normally, the loading/unloading of assetbundles, in the memory, is automatically managed by Unity, with a cleaning phase that is executed only in some specific cases. Instead, our assetbundles management system is designed to clean the memory every time the main menu scene starts, in way to be sure to have always all possible space available for a new download. Thanks to our manage system we were able to resolve the RAM memory challenge.

5.4 Summary

In this chapter, we have described the technologies used for the application development. We also discussed the challenges that were tackled during the implementation. At the end, we present an in-depth discussion of the solutions adopted in the development of the application, like our application architecture, our PCX importer extension, our adaptive Occlusion Culling, our adaptive Fixed Foveated Rendering, and our manual memory resource management system.

Chapter 6

Our Application

In this chapter we detail the flow of the application and provide in an illustrative way all actions and scenarios in which users can find themselves. All the images of this chapter are taken directly from the VR demo application which we have realized.

6.1 Our application as a supporter of photogrammetry and cultural heritage

Our application is a support for cultural heritage, as it reproduces a virtual museum that allows users to admire different cultural heritages from different parts of the world in a single application. The models used within the application are all obtained from archaeology/architectural surveys or from photos of tourists through photogrammetry. To obtain the models used, the following procedure was performed. The first step was to collect, on the site of the monument, an adequate number of images with different views for all the different faces of the monument (normally around a few GB of images). Of course, in this case, the image quality is a key feature to get a good result. Secondly, all the images were processed by a photogrammetry software in which for each pair of images and for each common point the 3D coordinates are calculated and a vertex is generated within the 3D model. In addition to the vertex coordinates, to obtain a more realistic model, the color of each vertex was also saved. In this way a first 3D model of point clouds is produced. The two previous points did not execute directly by us, as we selected available online models. Third, from the first model obtained a new solid model (for example an OBJ or FBX) was developed using another 3D modeling software, using a polygonal reconstruction algorithm. Fourth, a texture has been generated from the enormous quantity of original images to texturize the new 3D solid model. At this point the architects usually start a manual reconstruction job, to reduce the high-poly model that is generated and to perfect the small errors that can be produced by software development. We did not rework the 3D models, in order not to miss the explanations of the reconstructions that can be performed on the models, but, due to the rendering limitations, we have reduced the number of polygons with



Figure 6.1: Museum Hall.

an automatic reduction algorithm. In our application users can view both models mentioned above, a point cloud model that provides a more abstract feeling and the high polygon mesh generated by the point cloud itself.

6.2 Structure of the Experience

The application always starts from an initial lobby, structured so as to remember a room of a museum, where users must decide their first step between three different scenarios:

- **Tutorial:** where users have the opportunity to learn the main actions and interactions that they can perform during the experience.
- **Monument exploration:** where users can explore the different buildings offered by the application, moving inside them thanks to different teleport spots.
- **Interactive cultural heritage:** where users can move, rotate and zoom the small cultural heritage, such as columns, statues, etc.

6.2.1 The Hall

In the initial scene (Fig. 6.1) users will find several showcases containing the cultural heritage monuments. This hall was designed to recreate a familiar environment like a museum or an art gallery to involve them in a better experience. In this case users can only look around and done two different actions described below.



Figure 6.2: Network selection panel.



Figure 6.3: Panel use to insert a new IP during the experience.

Network Selection

On behind them, users will find a panel (Fig. 6.2) that give possibility to select which network connection use. The two possible network selections are: (i) an external connection where the download is done from a common internet cloud service (like OneDrive or GoogleDrive); (ii) a private network, in this case represented by the 5G label. If users select the private network, they have the possibility to insert the server's IP directly at run time. The insertion is possible thanks to a keyboard that will appear after have selected the "New IP" button (Fig. 6.3), subsequently, after have inserted the new IP, users must confirm it with the use of "OK" button. This solution resulted very useful whenever was required to change the models download position, or if they were available on different servers.

Monuments Selection

In this case, users with a simple point and click (using the back trigger button of the controller) on the glass of the case, or on the brass panel (where the monument's name is written), can select a monument. After the selection, an animated ring will appear on the selected case with writing in the middle "Loading..", to show that the download of the monument has begun. The scene will change automatically only when the download is completed showing the selected cultural heritage.

6.2.2 The Tutorial

The use of the tutorial is intended to help users to learn all the different action and interaction that they can execute inside the experience. To begin the tutorial, users must select the pedestal in the middle of the first scene (Fig. 6.1) with on the top a big yellow question mark and on the bottom the label "Tutorial". After the selection, the tutorial will start and users will find themselves in another room of the museum.

The tutorial is divided into three different parts:

1. in the first step users will learn how to change, between the point cloud model and the polygonal model. The instructions that users must perform are written on a panel (Fig: 6.4) in front of them. When users consider themselves ready, they can close the canvas with the appropriate button on the bottom, and try to perform the interaction. The sub-phases in this part of the tutorial are three. First, users will change from a point cloud model to a solid model (Fig. 6.5). Second (after the succeed of the first) they must go back to the point cloud model (Fig. 6.6). Finally, after these two actions, users will find, at the right of the model, a button "Next" to go to the tutorial second phase (Fig. 6.7).
2. on the second step users will learn how to interact with the little monuments. Also in this case on a panel are described all the steps that they must do to

select and use the different actions. Before to learn how to perform interactions, users will be followed, through a series of panels, to allow them to learn how to open the interaction menu (Fig. 6.8), select an action (Fig. 6.9) and confirm it (Fig. 6.10). This menu is present only during the scenes whit little cultural heritages (columns, statues and capitals) and it is attached on the controller. It appears, when closed, like a green little parallelepiped, instead, when open, seems a horizontal palette with an animated arrow on the top that will show which action is selected. After that, users will learn how to rotation (Fig. 6.11), move (Fig. 6.12) and zoom (Fig. 6.13) the interactive cultural heritages. Only after they has performed all the available interaction, a "Next" button will appear to give to users the possibility to go to the last tutorial phase.

3. in the last step is explained to users how teleport into the buildings. This is possible thanks to teleport spots represented by an animated green cube. After having read the instructions and closed the new instruction panel, users can try to teleport near a painting placed at the end of the room (Fig. 6.14). After their teleport, they will find at the right of the painting a new canvas that describes (Fig. 6.15) which action to be performed to return to the main menu.

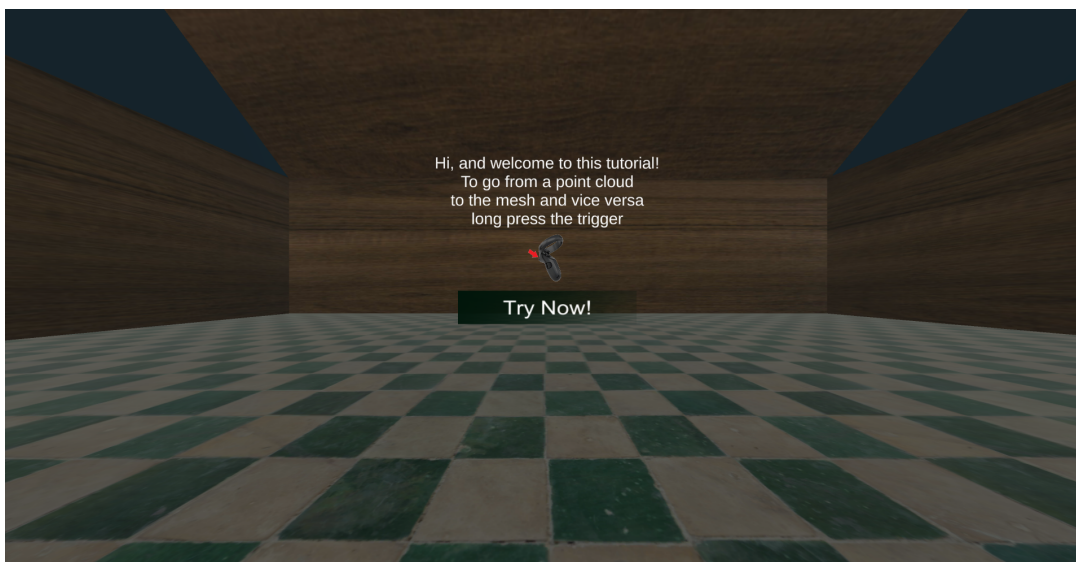


Figure 6.4: Instructions panel of the first tutorial phase.

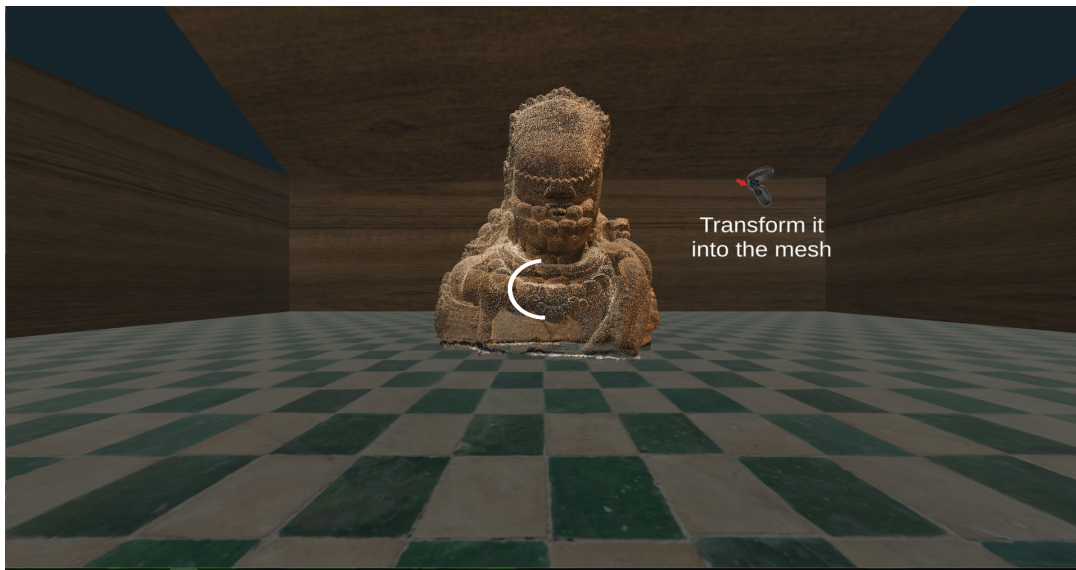


Figure 6.5: First tutorial phase, from point cloud to solid model.

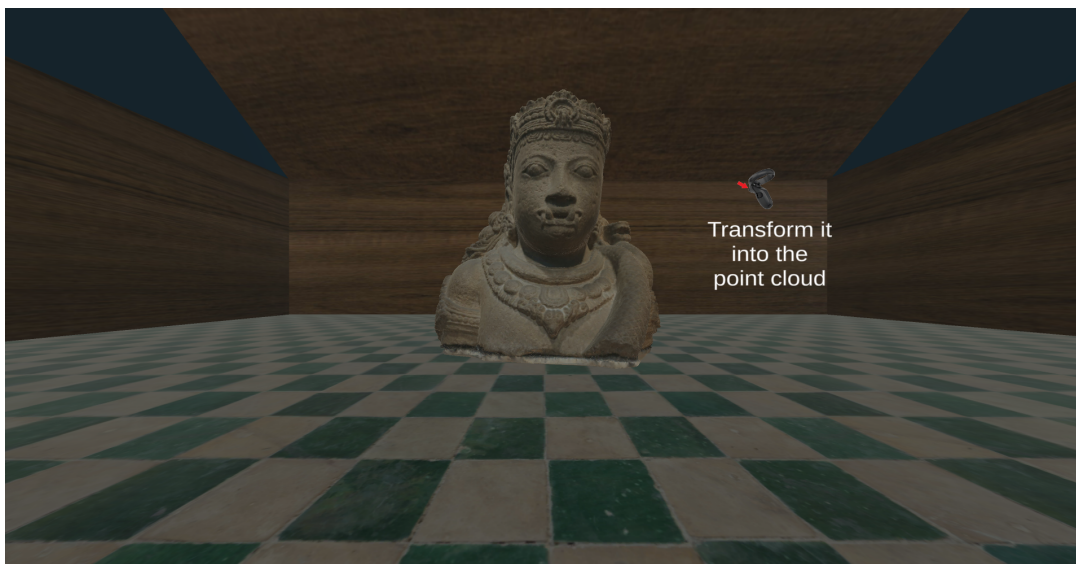


Figure 6.6: First tutorial phase, from solid model to point cloud.



Figure 6.7: Point cloud model, at the end of first tutorial phase, after two model changes.



Figure 6.8: Explanation panel on "how to open the menu" during the tutorial second phase.

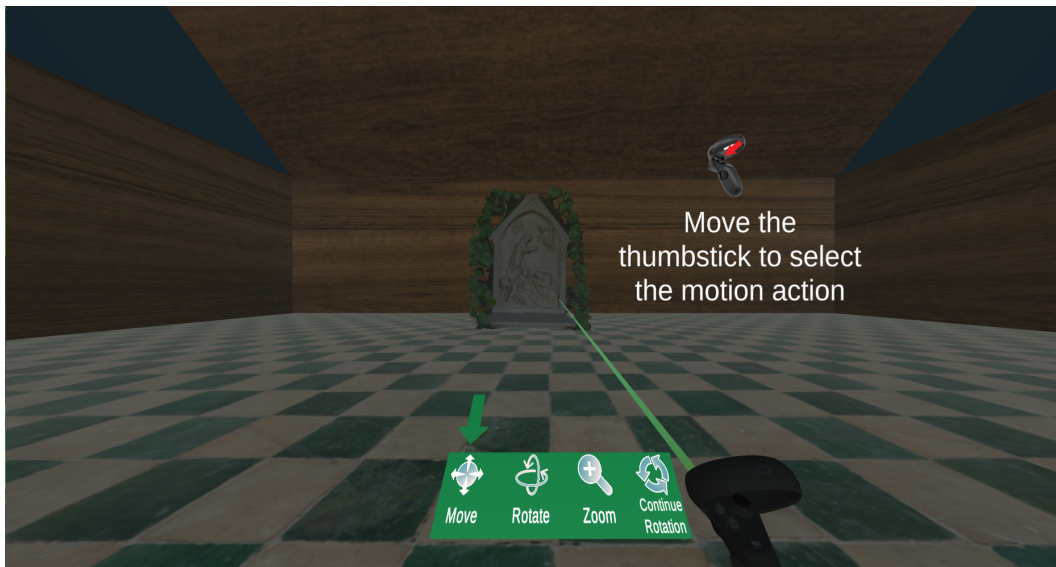


Figure 6.9: Explanation panel on "how to select an action" during the tutorial second phase.



Figure 6.10: Explanation panel on "how to confirm an action" during the tutorial second phase.

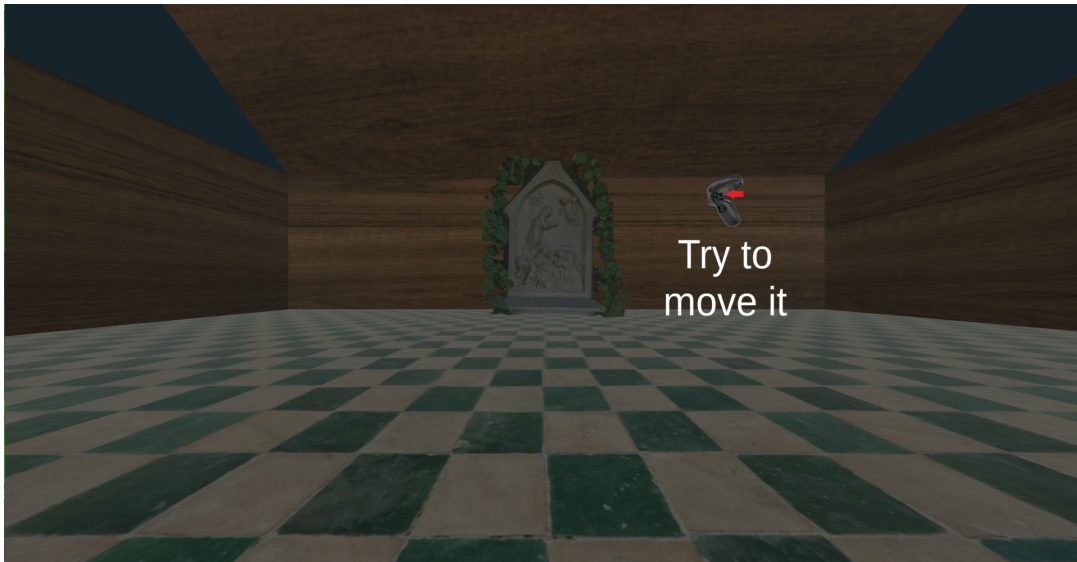


Figure 6.11: Moving the object in the tutorial second phase.

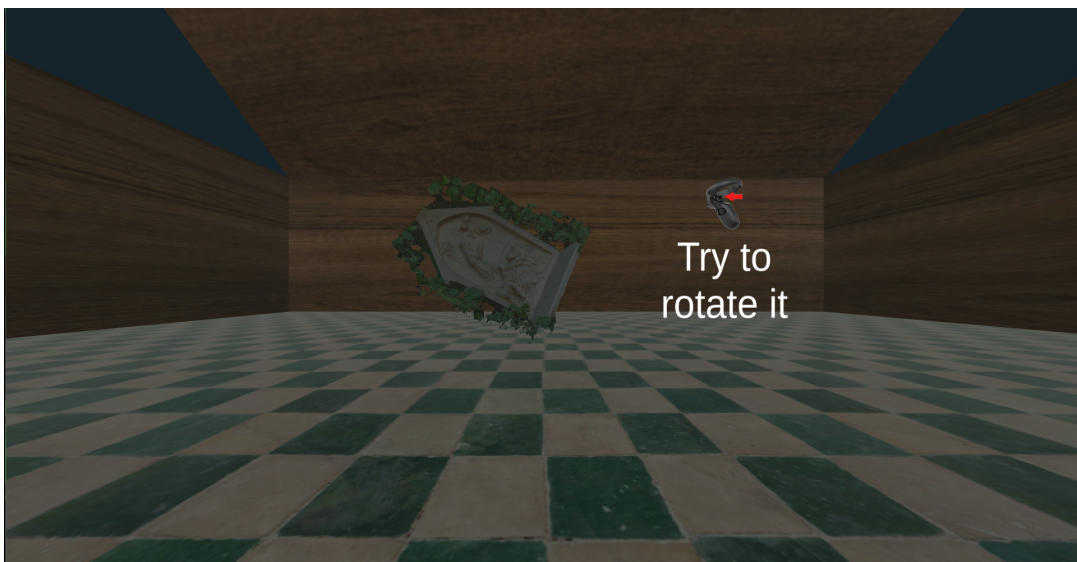


Figure 6.12: Rotating the object in the tutorial second phase.

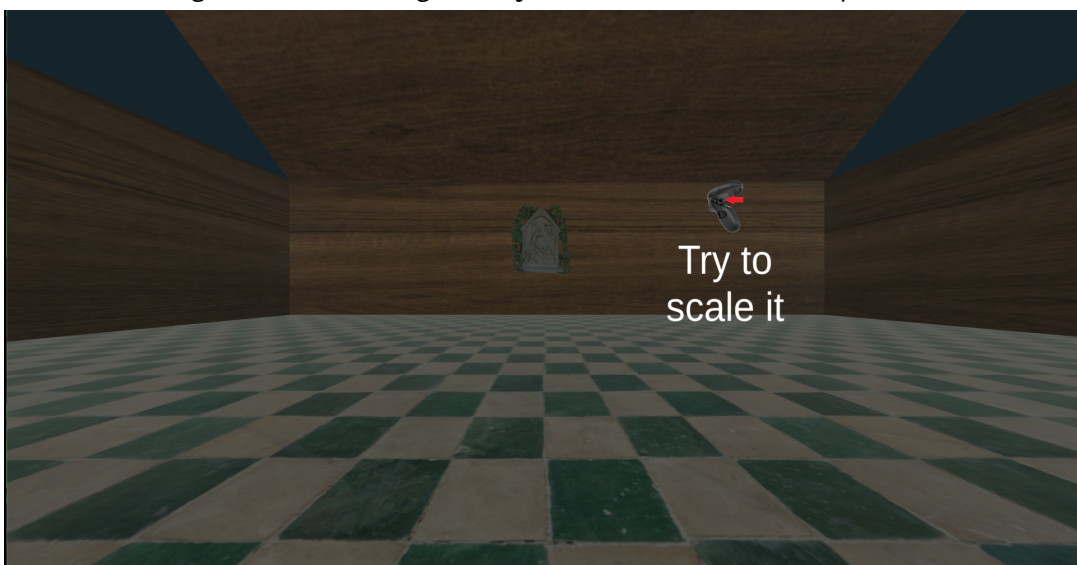


Figure 6.13: Zooming the object in the tutorial second phase.

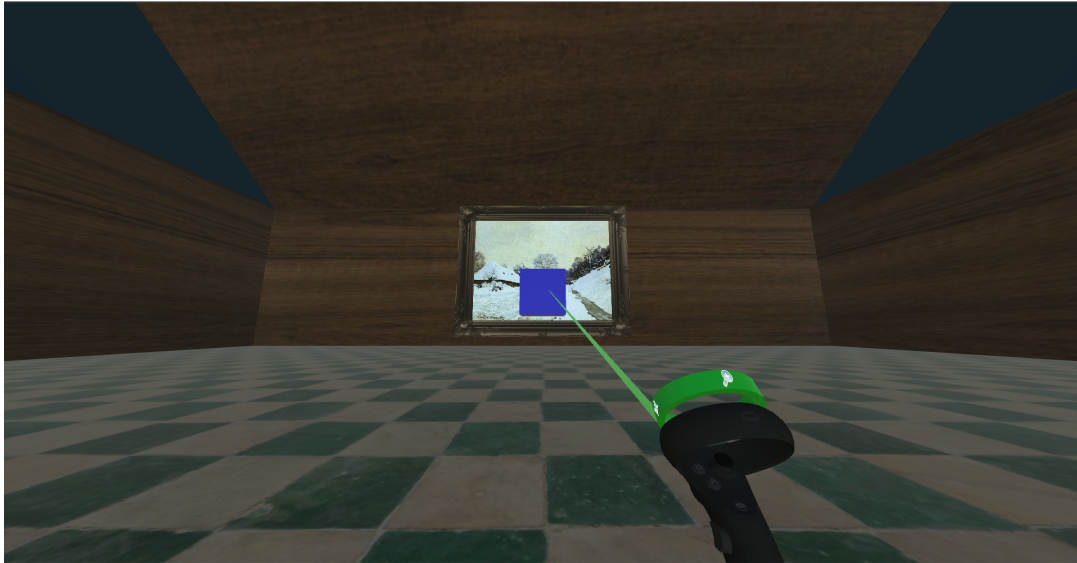


Figure 6.14: Teleport in the tutorial third phase.



Figure 6.15: End of tutorial.

6.2.3 The Monuments Exploration

We present to users this scenario whenever is selected a "large" building. Normally, these buildings are not presented in a completely real scale, this to avoid too high distances and annoying travel period to users. For this reason we have used a little bit lower scale, without departing too far from the real one.

Navigation spots

In VR applications one of the major problems is users locomotion. In this type of application is impossible to carry out a continuous movement like in video game, this because for most of the users may create a motion sickness problem. Where motion sickness is a conflicting inputs from visual and vestibular afferent that produce sickness and postural instability [2]. Different studies have demonstrated that

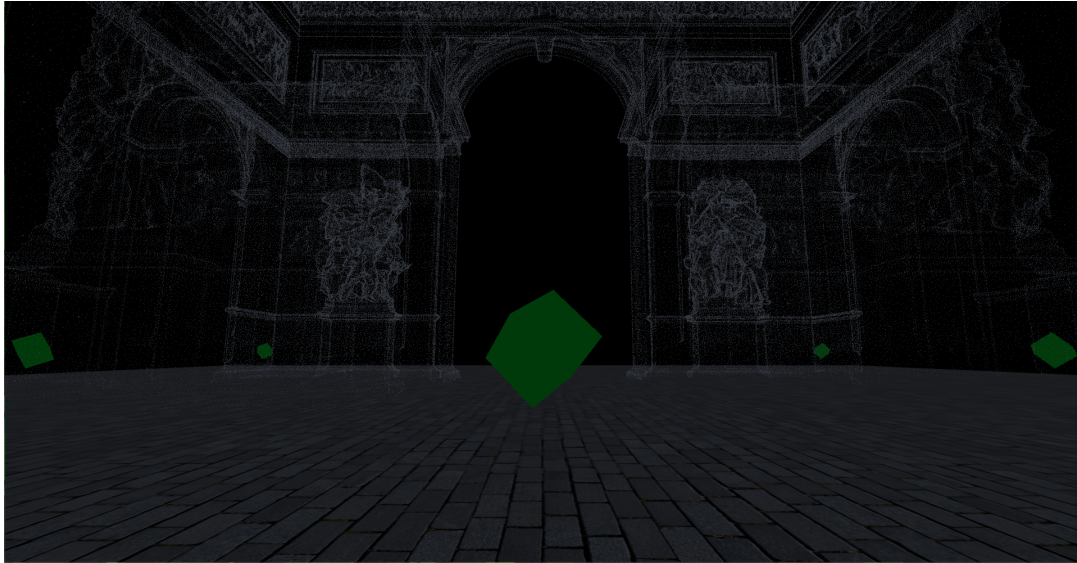


Figure 6.16: Teleport Spot.

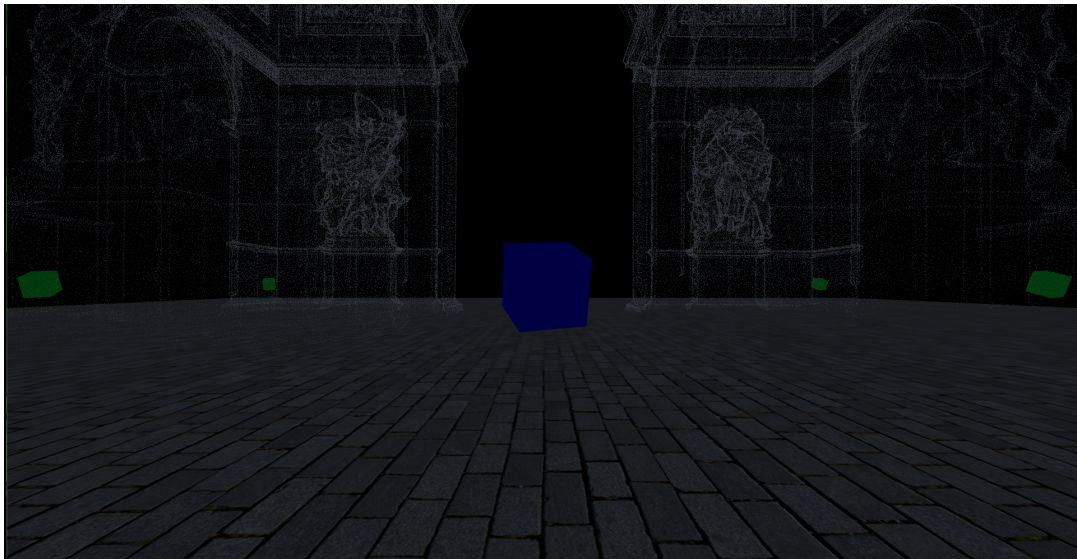


Figure 6.17: Focus Teleport Spot.

this incoherent visual–vestibular conflict (VVC) can be induced by VR applications when a great miss-match between users’ bodies and their vision is recognized. This sickness is perceived by users not only during the application use, but can also continue later, bringing to the users the desire to no longer use the VR applications. This is the worst scenario for a VR developers. For this reason different locomotion solution were designed during the years to avoid motion sickness. Within the application, to avoid motion sickness, but to allow users to move, a teleportation solution was adopted. Users can change their position simply point and click, with the use of the back trigger button of the controller, on the teleport spots (Fig. 6.16). These spots are represented by green cubes and are animated by a continuous rotation to attract the attention of the users. Additionally, the cubes change his colour (Fig. 6.17) each time are spotted with the laser pointer, this help for a better users’ interaction.

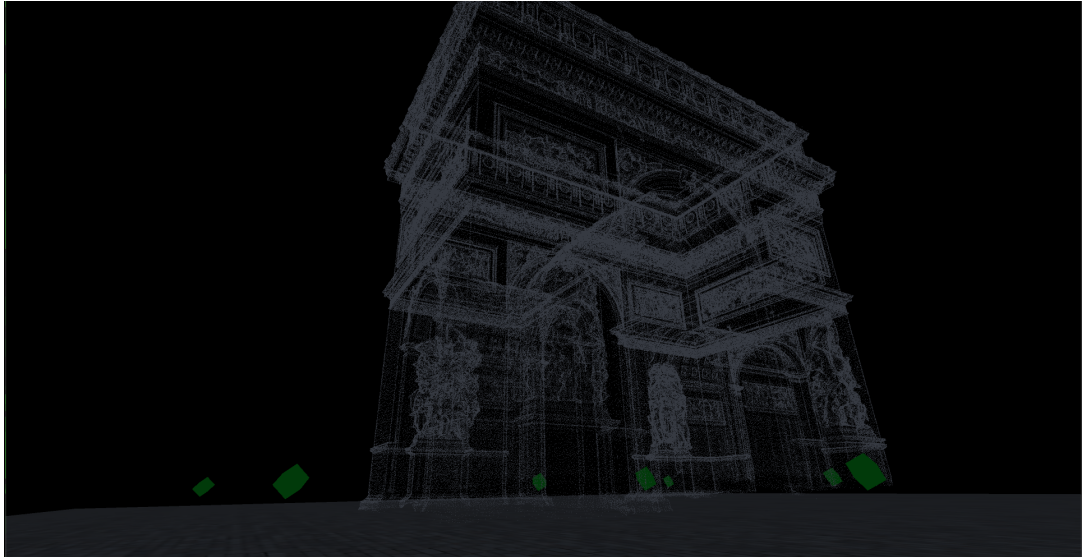


Figure 6.18: Point cloud model.

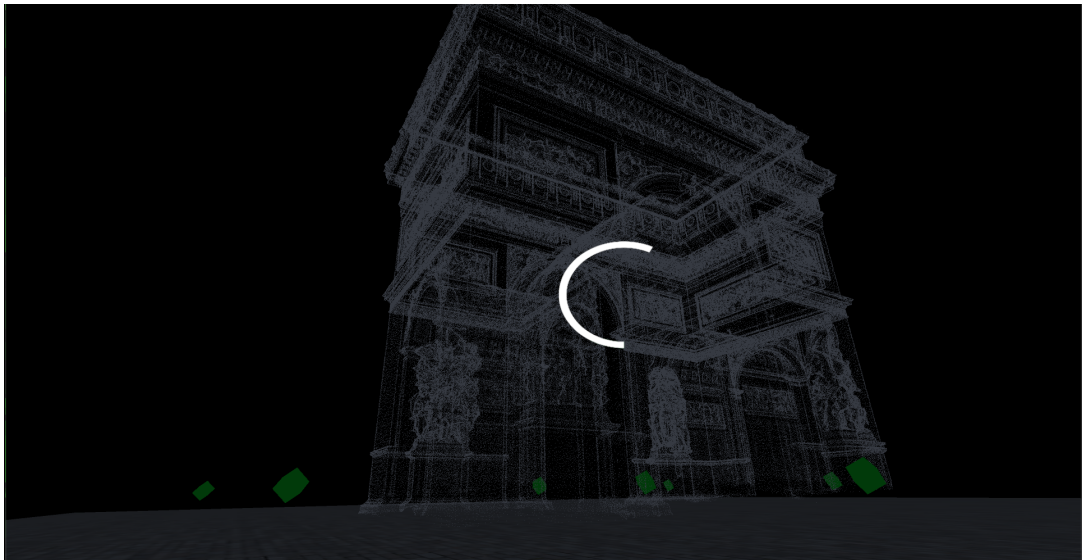


Figure 6.19: Changing the model.

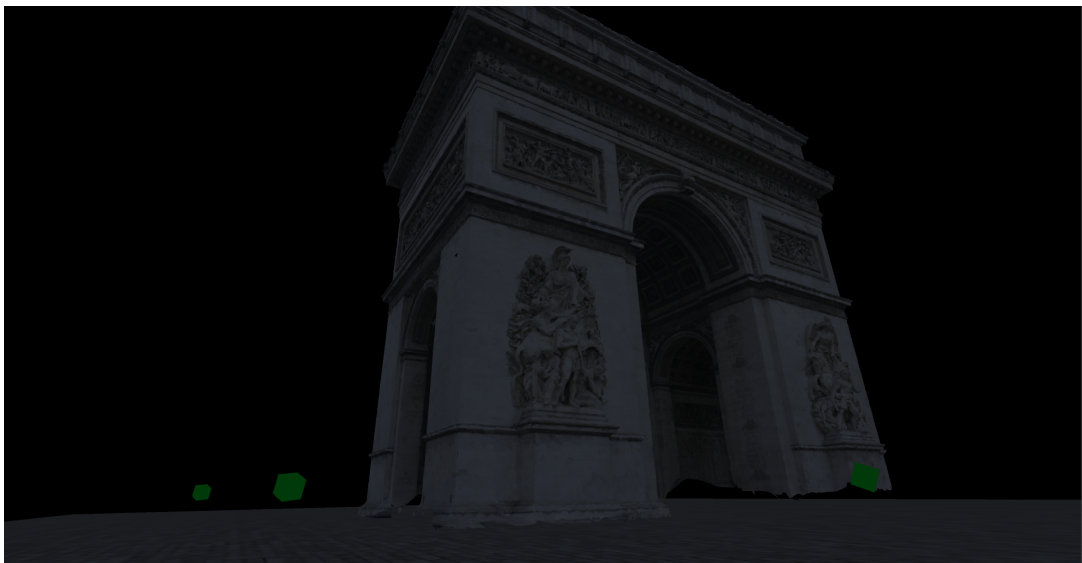


Figure 6.20: Solid model.

Change of Models

The models shown within this application are of two different types, as explained in section 6.1. During the application design phase as requirement, we decided to give to users the possibility to change between these two 3D models to allow them to notice the differences between them, and also to give to a professor the opportunity, in the case of academic use, to explain the different technical aspects between the models. We have implemented this interaction using a long press on the controller's back trigger button. To show to users the progress of the change between the models, a white circular loading bar (Fig. 6.19) appears during this phase. Upon completion of the circular bar, the operation will be completed and the user simply will have to release back trigger button to confirm the operation. Of course, if users do not wait for the process completion, the change will not be performed and the previous model will re-show.

6.2.4 The Interactive Cultural Heritage

This other scenario (Fig. 6.21) is offered to users whenever a small cultural heritage is selected. In this case users will find themselves on a new museum room, without the possibility of motions, and in front of them the selected cultural heritage. In this case, thanks due a special "palette of action", users can interact with the monument with four different actions.

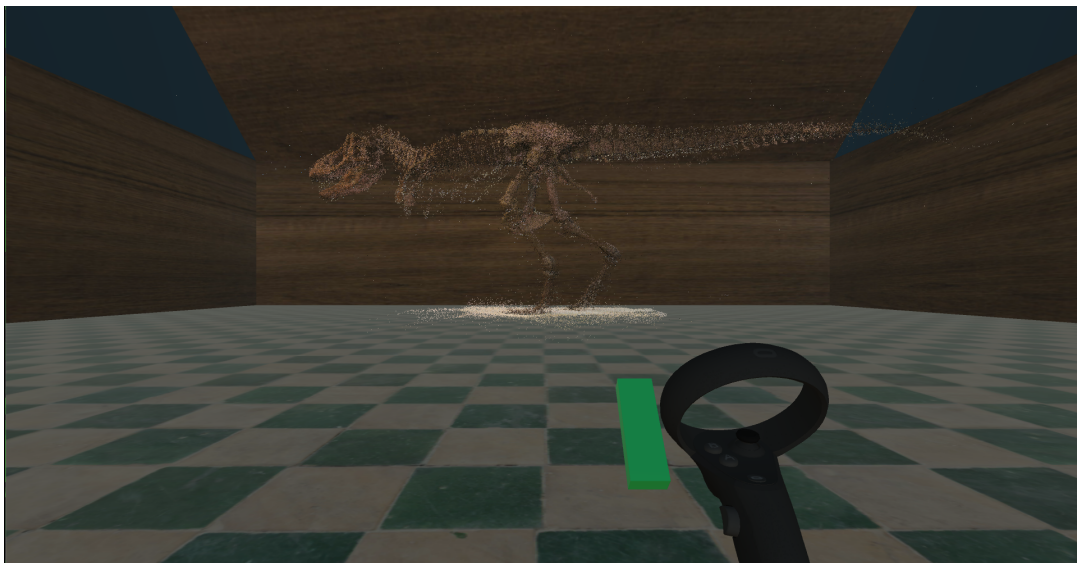


Figure 6.21: Example of an interactive scene of a small cultural heritage, with the closed interaction menu attached to the left side of the controller.

Palette of actions

This "palette of actions" is presented to users in two possible forms, depending on whether the menu is open or closed, and it is placed on the left side of the controller. When the palette is closed, it can remember a small green parallelepiped, instead, once open it with the appropriate controller button, it remembers horizontal green

palette, with the four possible actions displayed on it.

The four possible actions are:

- **Continue rotation** (Fig. 6.23): when users select this interaction, the model will start automatically rotate on itself with a fixed speed.
- **Manual rotation** (Fig. 6.24): in this case, unlike the previous one, it is the users who with the use of the controller thumbstick to control the rotation of the monuments.
- **Move** (Fig. 6.25): this interaction give to the users the possibility to move the monuments on the x/y plane. Also in this case to perform the action users must use the controller thumbstick.
- **Zoom** (Fig. 6.26): this last case is used by users whenever they want to reduce or increase the size of the model. In this way it is possible to better observe the details or resize the model so as to have a complete view of it. Also in this case, users must manipulate the controller thumbstick to perform the action.

At the beginning of the scene the menu is always presented closed. Once the menu button (the controller's grasp side button) (Fig. 6.22) has pressed by users, the menu will open through an animation, showing the active action through an animated arrow in the upper part of the palette. The first action proposed is always the movement and is positioned on the left border side of the palette. To modify the action, users must holding down the controller grasp button, and moving sideways the controller thumbstick, in way to change the arrow' position. After selecting the desired action, users can confirm it by simply releasing the grip button. Each action is represented on the palette by a symbol and a description placed at the bottom of the image, to provide users with a better explanation of the action.

6.3 Summary

In this chapter, we explained how our VR application is related with photogrammetry and why is possible to consider it a virtual heritage application. In the second part, we introduced the application structure with all offered scenarios to the users. These possible scenes are: (i) the hall, where users start the experience; (ii) the tutorial, where they learn the different possible interactions; (iii) the little interactive monuments' scenes, where users can rotate, move and zoom the heritages; (iv) the big cultural heritages' scenes where users can explore several available buildings, moving through different teleport spots.



Figure 6.22: Interaction menu open, with a red arrow indicating the controller menu button.



Figure 6.23: Continue Rotation.

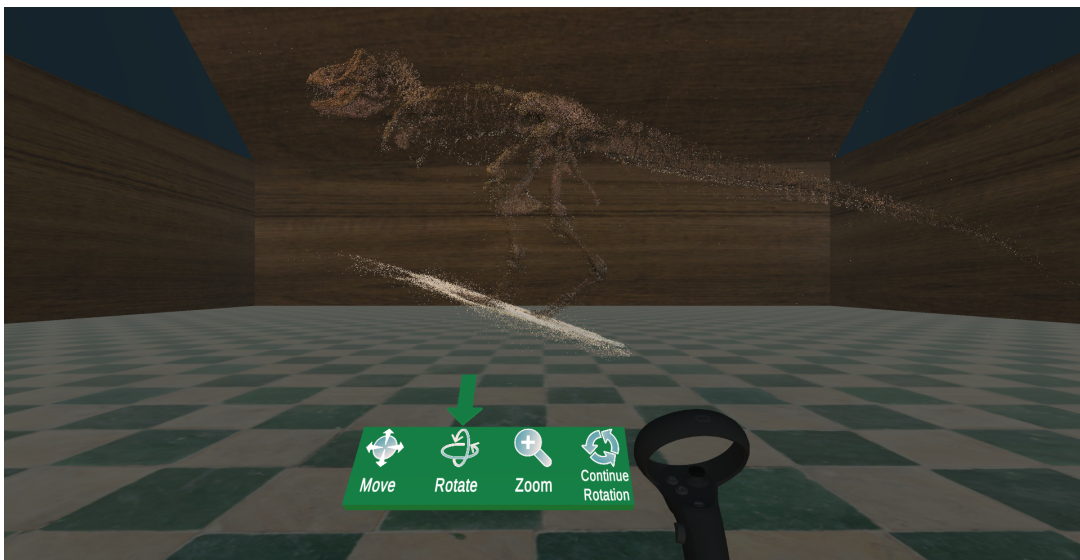


Figure 6.24: Manual Rotation.



Figure 6.25: Object Motion.



Figure 6.26: Zoom.

Chapter 7

Experimental Results

In this chapter we present the questions and results of the evaluation of our application that we have performed with the Master students attending the course of Video Game Design and Programming at Politecnico di Milano.

7.1 The Questionnaire

To carry out our evaluation, we have prepared a online Google Docs¹ questionnaire to collect the questions results. The form comprised 22 questions, reported in the 7.1 table. It was specified in the questionnaire that, when answers ranged from 1 to 5, 1 meant “I completely disagree” or “Very poor” and 5 meant “I completely agree” or “Very good”. After a couple of preliminary requests, to understand the type of users subject to the questions (such as the age and degree of use of video games), the requests were designed in a targeted way to understand if there were potential critical aspects in the application. The first questions were designed to understand the level of feeling that users have had in general with the application, with the adopted locomotion, and with recreated environments. For this reason, specific questions were asked, to comprehend if the application brought the user to perceive motion sickness. In second part, the demands were used to comprehend if users completely learned all the possible interactions, after executing the tutorial, and if the interactions with the ”palette actions” menu were easy to manage. The last questions were designed to see, if for users, the application could have an use in a university course and to have a general application evaluation by users.

Table 7.1: Questionnaire filled by the students for the experience’s evaluation.

Id	Question	Answer Type
Q1	Sex	Male/Female
Q2	Age	One out of: <ul style="list-style-type: none">• Less than 18 years old• Between 18 and 30 years old• Between 30 and 50 years old

¹<https://docs.google.com/>

		<ul style="list-style-type: none"> • More than 50 years old
Q3	Experience with using videogames	One out of: <ul style="list-style-type: none"> • Not at all • Less than 2 hours per week • Between 2 and 4 hours per week • 7 hours per week • More than 7 hours per week
Q4	Have you always felt comfortable in the virtual environment?	One out of: <ul style="list-style-type: none"> • Yes • No, I did not feel comfortable at the beginning but after some minutes I did well • No, I felt comfortable at the beginning but after some minutes I did not feel well • No, I never felt comfortable
Q5	Have you felt comfortable during the experience as a whole?	Range 1-5
Q6	Moving and activating commands in the virtual environment was easy	Range 1-5
Q7	I understood within a reasonable amount of time what I could do in the virtual environment	Range 1-5
Q8	Please add any comment/suggestion you deem useful. In particular, we would like to know what made you feel uncomfortable	Open
Q9	How would you rate the usability of the controller?	Range 1-5
Q10	How would you rate the usability of the virtual environment?	Range 1-5
Q11	How would you rate the usability of the teleport cubes?	Range 1-5
Q12	How would you rate the usability of the menu on the controller?	Range 1-5
Q13	How would you rate the usability of the overall experience?	Range 1-5
Q14	Please add any comment/suggestion you deem useful	Open
Q15	How easy was it to understand the meaning of the tutorial?	Range 1-5

Q16	How easy was it to understand the meaning of the connection between point cloud and mesh?	Range 1-5
Q17	In your opinion, could this kind of experience enrich a traditional university or high school lecture?	Range 1-5
Q18	Would you appreciate lessons with this kind of support?	Range 1-5
Q19	Please add any comment/suggestion you deem useful. In particular, we would like to know what was MOST UNCLEAR to you	Open
Q20	How the experience worked overall (what it is about, where to go, what to do...)	Range 1-5
Q21	Overall, did you enjoy the experience?	Range 1-5
Q22	Please add any comment/suggestion you deem useful	Open

7.2 Evaluation and Results

We carried out the evaluation with the students of the Master in Computer Engineering and Design who attended the course of Video Game Design and Programming at the Politecnico di Milano. Each student received a brief introduction to the experience and its scientific basis. Subsequently, one user at a time tested the application with use of the HMD. Each student was asked to start the experience from the tutorial (6.2.2), in order to learn the interactions of the application. After that, the students were free to select and visit any monument available in the application, for a total time of use of about 15 minutes. In the end, users were asked to fill out the online form described above to evaluate the VR app with their own opinion.

The application was tested by 27 students (5 females and 22 males) all between 18 and 30 years old. Most of them video game players (Q3), with a good number (fifteen to be precise) of players with more than 7 hours of play per week; four between 4/7 hours per week; two that played from 2 to 4 hours per week; two less than 2 hours per week; while four students did not play video games (Fig. 7.1).

Motion sickness can be a major issue for virtual reality. In our case most of the students had no problems with the virtual environment (Q4) (Fig. 7.2), always feeling at ease without perceived motion sickness. Two of them have answered that at first did not feel at ease, but after a few minutes of use they have changed their sensation. Only one person felt comfortable at the beginning, but after a few minutes she did not feel well, perhaps due to an initial perception of motion sickness. This person later (in answer Q8) wrote that she normally wears prescription glasses (not

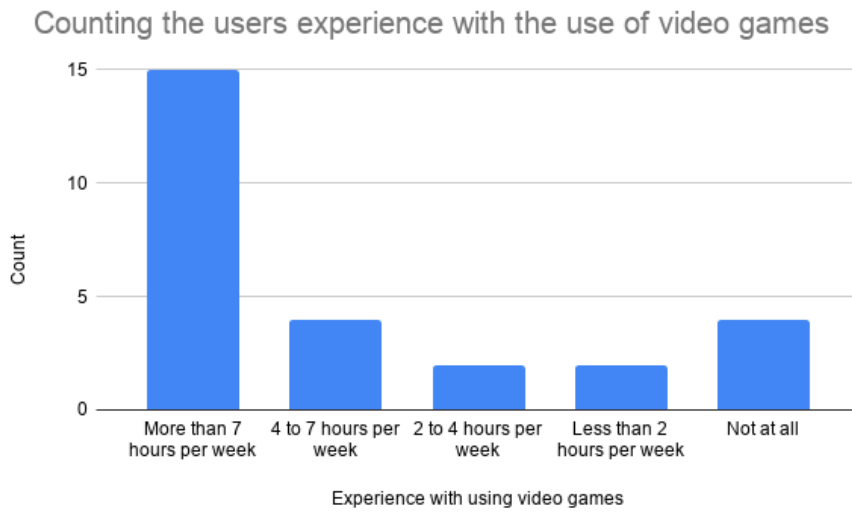


Figure 7.1: Bar chart that describes the interaction that each user has with the world of video game.

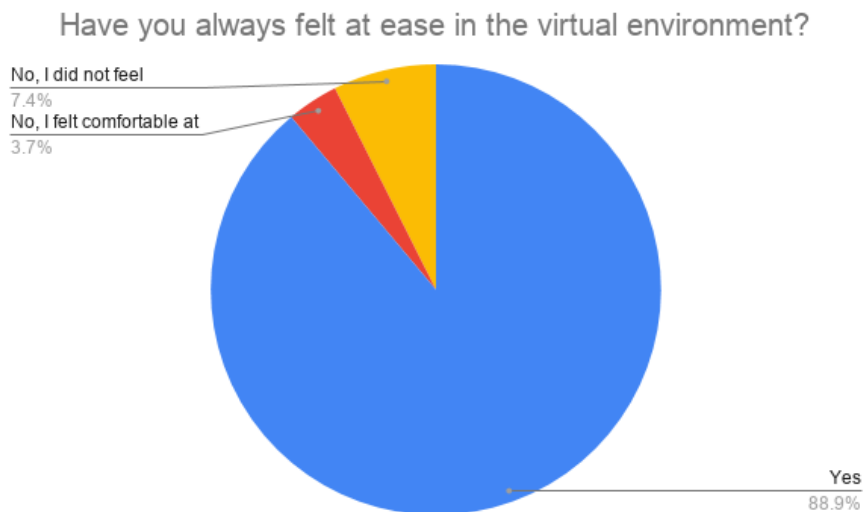


Figure 7.2: Pie chart on the result of feeling of the users, during the application test.

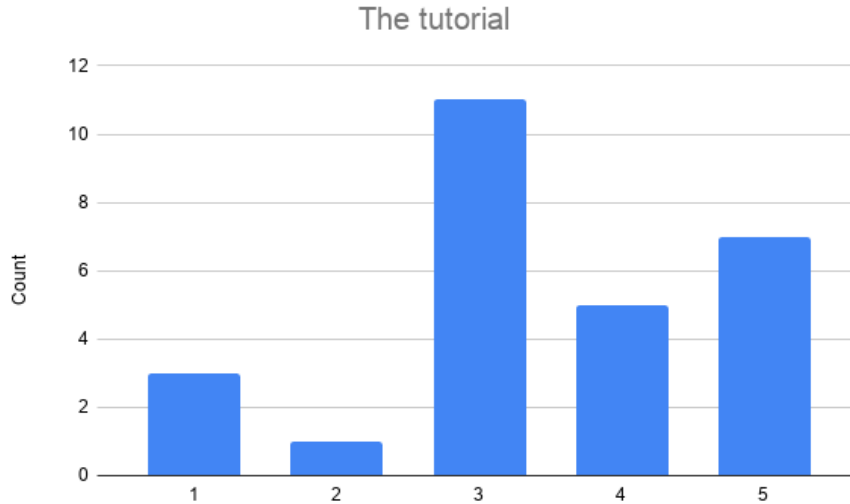


Figure 7.3: Column chart of users' overview on the tutorial.

worn during the test) and is very susceptible to light brightness, elements that can amplify motions sickness perception in some subjects. Other students in answer Q8 have written, even there did not feel uncomfortable, that sometimes did not match themselves with the scale of buildings and with own height. All other answers at this question were referred to the interactions, for these reason will described later. In the quantitative questions, on the feeling inside the virtual environment (Q5, Q6, and Q7), have received an average of 4.56 for Q5, 4.22 for Q6, and 4.48 for last one.

The students, instead, have rated the usability of the controller, teleport spots, and the "action palette" menu, for the quantitative questions (from Q9 to Q13) with averages of (Q9) 4.37, (Q10) 4.26, (Q11) 4.15, (Q12) 4.48, and (Q13) 4.48. In open answer Q14, including the answers given in question Q8 on interactions, the main requests or observations that appear more frequently are: (i) confusion on when it is possible or not to move, rotate and zoom the cultural heritages; (ii) increase the size of the teleport spots, for a larger interaction spot; (iii) a request of a more realistic movement, such as walking around in the virtual environment. After these answers/requests, we can affirm that the interaction with the "palette actions", using the lateral grasp button, button turned out to be a good solution, while the size of the teleport spots may have to be resized. Finally, the last written request (iii) in Q14, although possible with the used HMD, is not applicable in that it would require very large and variable free spaces in which users can move.

The tutorial question (Q15) has received an average grade about of 3.45 (Fig. 7.3). This is our lowest value compared to all other averages. Furthermore, some users, at Q18 open, question wrote that it is not easy to remember the "walls of text" that describes in each part of the tutorial the different steps to learn the interaction. Although we have structured the tutorial so that after each instruction panel, the user is followed step by step with other simpler additional panels to learn all the parts of the different possible interactions with littler passages, the tutorial is resulted to be our critical part that must be redesigned to be more user friendly.

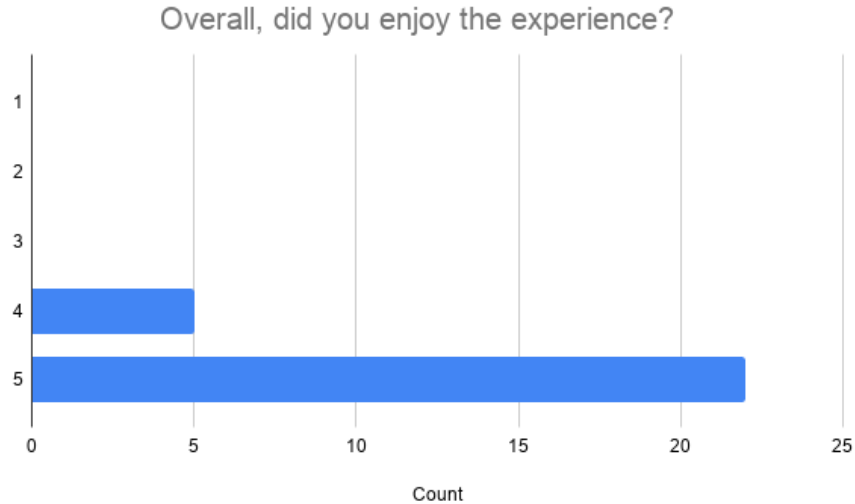


Figure 7.4: Bar chart of users' overall overview on the application.

The questions Q17 and Q18 about the students opinion to bring our application in a university course has received an average of 4.52 and 4.85, getting a good result about.

The general questions Q20 and Q21 on the application achieved a good result with an average of 4.6 and 4.85, with grades no lower than four for question Q21 (Fig. 7.4). Finally, in the last open question we received some interesting requests. For example, a student suggested that it would be interesting to add some information on photogrammetry surveys and historical information on buildings, as well as having the opportunity to observe completely the structures (both internal and external parts).

Concluding, from the results our application would seem to have been appreciated by the students during the tests. Surely, these tests showed us the weaknesses of the application that will be considered for improvements and corrections, for future. Overall, we are satisfied with the results obtained.

7.3 Summary

In this chapter we presented the evaluation form done for our application, listed all the questions done. Next, we discussed the results obtained, from the final test, with the students attending the course of Video Game Design and Programming at Politecnico di Milano. The application was appreciated by the students, with good average results in almost all quantitative questions. Additionally, we received some interesting suggestions that can be used as ideas for future developments. In general, we were satisfied by the result obtained by our application.

Chapter 8

Conclusion

We designed, developed and validated a Virtual Reality application that allows people to explore cultural heritage monuments. Our application targets both people with some knowledge about of architectural/archeological surveys (such as architects or civil/ambient engineering students) and people with other backgrounds. The application can provides support for lectures of “Tecniche Innovative del Rilevamento” and “Advance Survey and Representation Techniques” courses of Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente at Politecnico di Milano, but can also be used like a virtual exhibition for a museum.

The target platform was the standalone Head-Mounted Display (HMD), Oculus Quest. These devices don't needed to be plugged to a computer, but belong a limited computational and rendering power. For this reason, we have adopted several customized solutions to obtain the application, such as our extension on the 3D point cloud models importer, our adaptations on two rendering techniques and our manual memory resource management system. The resulted application shows up like a virtual museum where users can select, visit, observe and interact with different famous cultural heritage pieces.

We carried out a final evaluation of our application with the students who attended the Video Game Design and Programming course of the Politecnico di Milano. Each student was given about 15 minutes to try the experience and was subsequently asked them to complete an online questionnaire for their evaluation. Overall, the results (reported in the chapter 7) proved to be very satisfactory, with good reviews from the students, and showing interesting suggestions.

As future developments, we plan to increase the number of possible monuments to visit and add information both on the models reconstruction phases, and on historical knowledge, in order to create an even more functional application on both aspects.

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