Ca' Foscari University of Venice

Master's Degree programme

in Economics and Administration of Arts and Culture

3D Reconstruction for Cultural Heritage: Enabling Access to the Coats of Arms of Bo Palace for the Visually Impaired

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To my grandmother, Magdalena

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Introduction

Preservation and accessibility of cultural heritage are fundamental aspects of our collective identity and history. In recent years, advancements in digital technology have revolutionized the way we document, preserve, and share cultural artefacts. One innovative approach to enhance accessibility of heritage objects is through 3D reconstruction techniques.

Nowadays it is essential for art and culture to be more inclusive and accessible to everyone, including individuals with disabilities. This inclusivity is vital for personal growth, fostering empathy, and building social responsibility. By ensuring that cultural experiences are accessible to all, society can support the personal maturation of individuals and encourage a deeper understanding and appreciation of diversity. This approach not only enriches the lives of those with disabilities but also enhances the cultural fabric of the entire community. This thesis aims in fact to enhance accessibility to cultural heritage for people with visual impairments estimated to be, as of 2010, 285 million people worldwide, with 39 million of them being blind (Pascolini, D., & Mariotti, S. P. 2012).

More specifically this project focuses on broadening access to the Coats of Arms on display at Palazzo Bo, the historical location and nowadays museum of the University of Padua, through 3D reconstruction. Coats of Arms, emblematic symbols of lineage, identity, and authority, offer unique insights into the history and culture of their respective contexts. However, traditional methods of preservation and display may limit accessibility for individuals with visual impairments or those unable to physically visit heritage sites. By employing 3D reconstruction technology, we aim to overcome these barriers and provide inclusive access to coats of arms, fostering greater engagement and understanding of our shared cultural heritage.

Chapter 1 provides a comprehensive overview of 3D reconstruction which involves capturing the shape and appearance of physical objects using various techniques and technologies. From the fundamental principles underlying 3D reconstruction to the diverse methods employed, this chapter focuses on the intricacies of capturing the shape and appearance of objects in three dimensions. By delving into the various methods such as stereo vision, structured light scanning, and photogrammetry, it lays the groundwork for digitisation of the Coats of Arms.

Furthermore, the chapter explores the multifaceted applications of 3D reconstruction across diverse fields, from archaeology and architecture to gaming and virtual reality. By examining the role of 3D modelling software and its significance in different industries, it underscores the versatility and transformative potential of digital reconstruction techniques.

In Chapter 2, we embark on a journey into the realm of 3D modelling within the field of cultural heritage, where cutting-edge technologies intersect with centuries-old artefacts to unlock new dimensions of understanding and accessibility. Defined by the International Council of Monuments and Sites (ICOMOS) as *"the tangible and intangible legacy of the past transmitted from generation to generation",* cultural heritage serves as a testament to the richness and diversity of human experience. We uncover the transformative impact of 3D reconstruction on cultural heritage preservation, restoration, and dissemination. Through case studies and examples, we witness how 3D modelling technologies enable scholars, conservators, and enthusiasts to document, analyse, and visualize historical sites and monuments with unprecedented precision and detail. From the Digital Michelangelo Project's meticulous digitization of Michelangelo's masterpieces to The Angkorian Temples Project's ambitious reconstruction of Cambodia's ancient architectural wonders, we travel through continents and eras, witnessing the power of technology to bridge gaps in time and space.

Moreover, we explore the vital role played by 3D reconstruction in enhancing accessibility for visually impaired individuals, as exemplified by initiatives such as the Omero Tactile Museum and innovative VR applications for archaeological sites.

Chapter 3 deals with the history of Palazzo Bo, a place which served as an academic institution and also as a vibrant cultural and intellectual hub, its architectural evolution and its chambers and spaces. Within its walls, iconic figures like Galileo Galilei left lasting legacies in fields ranging from astronomy to philosophy. Covering Palazzo Bo’s walls from top to bottom are the Coats of Arms, each of them tells a story of scholarly achievement, representing rectors, council members, and captains of student nations who once graced these hallowed halls. From the intricate frescoes of the Old Courtyard to the majestic portraits of the Sala dei Quaranta, every corner of Palazzo Bo bears witness to the intellectual fervour and cultural diversity that defined its past.

Chapter 4 outlines the detailed process of reconstructing a reduced 3D printed wall of Palazzo Bo’s Coats of Arms, focusing on the acquisition, post-processing, and printing phases. Throughout this chapter, each stage of the reconstruction process is meticulously documented, providing insights into the technical methodologies, challenges encountered, and innovative solutions implemented. From the initial data acquisition using two structured light scanners (EinScan Pro HD and Revopoint POP 3) through the 3D reconstruction using the Geomagic DesignX Software and the final 3D printing of the models through FDM and SLA printing technologies.

Chapter 5 presents a concise overview of the preliminary survey conducted with two visually impaired individuals to evaluate the feasibility of the project. Through ten carefully crafted questions, the survey aimed to gauge the effectiveness and potential impact of the final 3D printed models of the Coats of Arms of Palazzo Bo. The chapter briefly outlines the objectives of the survey and provides insights into its findings, offering valuable implications for the refinement and enhancement of the project to better serve visually impaired visitors.

Chapter 1: 3D Reconstruction

The process of acquiring the shape and appearance of an existing physical object is known as 3D reconstruction: capturing the component's geometrical traits and physical measurements makes object reconstruction possible.

This technology is commonly used in various fields such as:

- Computer vision, for example a computer vision system for the estimation of apple volume and weight by using 3D reconstruction (Baohua Zhang et al. 2020).
- Robotics, for example a 3D reconstruction-based robot line laser hand-eye calibration method (Mingyang Li et al. 2020).
- Medical imaging, for medical diagnosis three-dimensional geometric reconstructions of individual anatomical structures became indispensable (Stefan Zachow et al. 2007).
- Archaeology, the destructive nature of excavation can be mitigated by using the techniques of 3D digital modelling (Suma Dawn and Prantik Biswas, 2019).
- Architecture, three-dimensional reconstruction of indoor environments is fundamental for many applications, such as navigation guidance, emergency management, building maintenance and renovation planning (Zhizhong Kang et al. 2020).

The process typically involves capturing multiple images or using specialized sensors to gather data from different viewpoints, then using algorithms to process this data and create a 3D model that accurately represents the shape and appearance of the original object or scene.

There are several methods and technologies used for 3D reconstruction (*see Figure 1*), including stereo vision, structured light scanning, laser scanning, and photogrammetry. Each method has its own advantages and limitations, and the choice of method depends on factors such as the desired level of detail, accuracy, portability and available resources:

- **Level of detail**: applications such as medical imaging or forensic analysis need meticulous attention to detail, so laser scanning or structured light techniques are favoured for their ability to capture features with precision. Industries like architecture or virtual reality often seek moderate detail levels, in this case photogrammetry or stereo vision methods offer a balance between detail and cost-effectiveness. On the other hand certain applications, like construction monitoring or basic terrain modelling, prioritise simplicity over fine detail so basic stereo vision or entry-level photogrammetry may suffice in these cases.

- **Accuracy**: aerospace and precision manufacturing sectors demand utmost precision, so laser scanning or structured light systems excel in delivering precise measurements and detailed surface data. Cultural heritage preservation, archaeology, or virtual reality experiences require reasonable accuracy without extreme precision, so photogrammetry or stereo vision methods can provide satisfactory results while being cost effective. Then projects like gaming may prioritize visual appeal over precise measurements so consumer-grade cameras or depth sensors offer cost-effective solutions for generating rough 3D models.
- **Budget**: organizations with substantial financial resources can invest in top-tier technologies like laser scanning. While costly upfront, these methods offer unparalleled accuracy and detail. Projects operating within limited budgets often rely on photogrammetry with off-the-shelf cameras or stereo vision setups. These options strike a balance between affordability and quality. While hobbyists or small businesses with tight budgets may opt for open-source software and DIY approaches using consumer-grade cameras. Despite limitations, these methods offer accessible avenues for 3D reconstruction.
- **Portability**: some applications require the ability to capture 3D data in various locations, often outdoors or in remote environments. In such cases, portability becomes a critical factor. Methods like photogrammetry, which only require a digital camera or drone, are highly portable and versatile. They allow for on-site data capture without the need for bulky equipment or specialized setups. Additionally, handheld 3D scanners that use structured light or laser technology are becoming more compact and portable, enabling fieldwork in diverse environments. In environments where portability is less of a concern, such as controlled indoor settings like laboratories or studios, the choice of method may prioritize other factors like accuracy or detail. Laser scanning systems, while highly accurate, are often bulkier and require more setup time, making them less suitable for frequent relocation.

Overall, the choice of method involves weighing these factors against the specific needs of application.

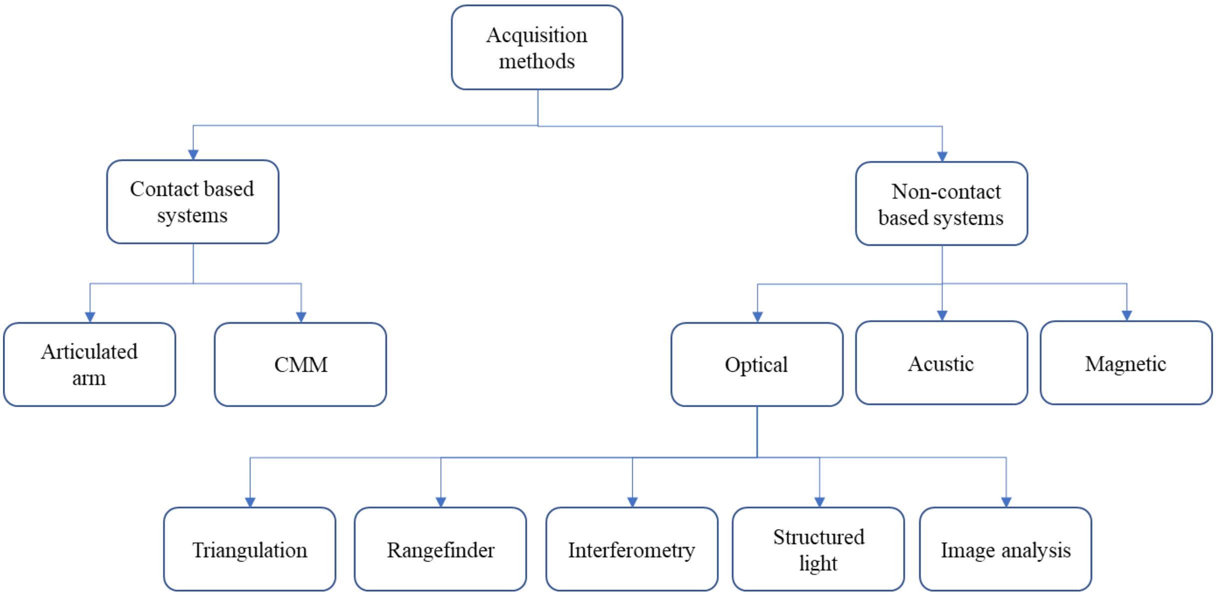

Figure 1 - Classification of 3D reconstruction techniques

Overall, 3D reconstruction plays a crucial role in various fields by enabling virtual representation, analysis, manipulation, and visualization of physical objects and environments. The reconstruction can also be the starting point for reverse engineering, a process used to recreate complex structures through inspecting and measuring objects in order to understand how they work and how they have been made. The knowledge gained through this process can help to:

- Understand the composition of the object;
- Modify the object itself and upgrade it;
- Create something similar to that object;
- Engineer something better than that object.

Reverse engineering is useful to understand and make better decisions about an object through taking the object itself apart in order to understand how its made and how it works.

Nowadays the most common measurement technique used for 3D reconstruction is structured-light. In fact during the past few years the costs of three-dimensional (3D) scanning equipment has decreased while Internet bandwidth increased making it possible for larger audiences to employ the use of 3D models.

In the following section we will first discuss the most diffused acquisition techniques, then we will focus on other aspects such as the modelling softwares.

1.1 Acquisition Techniques

3D reconstruction techniques fall into two general categories: contact-based systems and non-contact-based systems. In the following, we analyse both alternatives and present some related technologies.

1.1.1 Contact based systems

3D reconstruction techniques based on contact have been around for about 40 years. The more conventional approaches for data collection are contact based techniques such systems require contact between the surface and a measurement tool, typically a probe or stylus. Measurements based on contact guarantee the best results in terms of accuracy and quality of surface finish but on the other hand they are really time consuming because we need to acquire one point at a time (S. Martinez-Pellitero et al. 2008).

The coordinate measurement machine (CMM) was the first and remains the most widely used technique. The CMM uses a contact probe, an extremely sensitive pressure-sensing instrument that is triggered by any touch with an object (*see Figure 2* and *Figure 3*).

Figure 2 - example of CMM method

Figure 3 - example of CMM method

Other contact methods include touch probes are handheld devices equipped with a small stylus that physically touches the surface of the object to record its coordinates in 3D space. These devices are commonly used in metrology and quality control applications where high precision is required.

Advantages of contact methods are high accuracy and insensitivity to colour and transparency, disadvantages count slow data collection, distortion of soft objects by the probe, high costs and lack of portability. At the same time insensitivity to colour means that texture cannot be acquired and for some projects this could be a disadvantage.

1.1.2 Non-Contact based systems

3D reconstruction technologies based on not-in-contact acquisition techniques enable for the acquisition of highly precise models of objects, while maintaining their integrity and minimizing the possibility of potential damage. They work projecting energy sources (such as sound, laser, microwave or light) onto the surface of an object, then the transmitted or the reflected energy is observed. We can distinguish three types of non-contact based systems: optical, acoustic and magnetic.

The geometric data can be computed in different ways such as triangulation, time of flight, wave interference information and image processing algorithms. In the following we discuss the main structured-light techniques.

Structured-light techniques require the projection of a light pattern at a known angle onto the surface of the object (*see Figure 4*), then an image of the resulting pattern, reflected by the surface, is captured. A light pattern can be a single point, a line of light or a grid or more complex coded light. Structured light systems are easily employed in a variety of contexts and there are a huge number of structured light techniques, we will now analyse some of them.

Figure 4 - Example of instrument based on structured light technique

A basic example of a structured light technique is laser scanning which uses a laser line which is swept through the scene (*see Figure 5*). 3D points are then computed via triangulation of its intersection with the observed line in the captured image.

The same principle is applied by frame coding techniques, where the laser line is replaced by a specific sequence of patterns projected all over the scene.

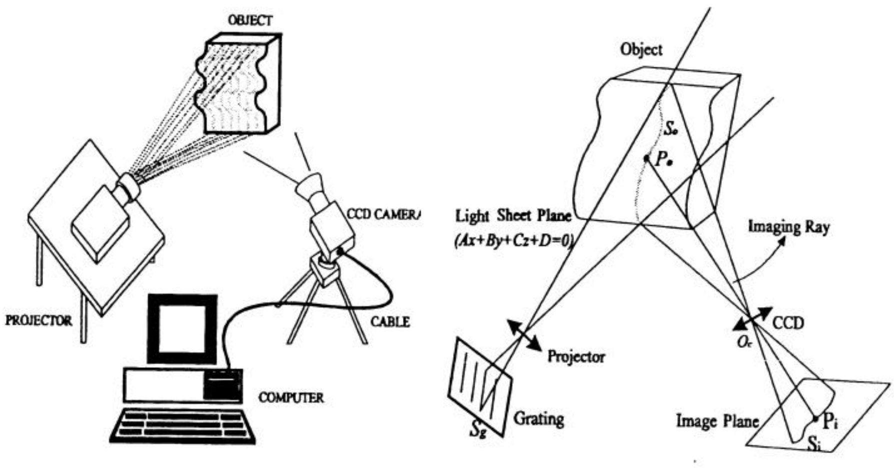

Figure 5 - Triangulation Principle

The advantages of structured-light systems are the high speed of data acquisition (up to millions of points per second) and availability of colour and texture information, disadvantages count high sensitivity to environmental conditions (light, shadows…) and surface reflectivity, shiny materials can partially absorb the projected pattern indeed.

The **interferometry** technique consists in the projection of structured light patterns onto a surface in order to produce shadow Moiré effects (*see Figure 6*). It is an optical phenomenon that occurs when two repetitive patterns overlap or are superimposed, creating a new interference pattern. This interference pattern can produce visual artefacts such as bands, waves, or grids that weren't present in the original patterns. The light contours produced by the Moiré effects are captured through an image and studied to determine the distances between the lines which is proportional to the height of the surface, this way the surface coordinates can be calculated.

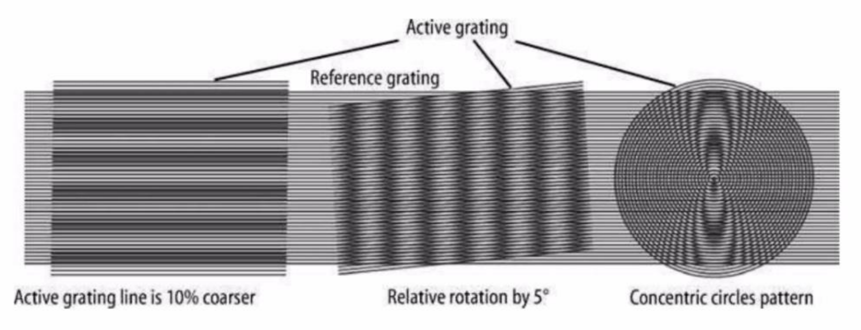

Figure 6 - Moire effect

Interferometry gives accurate results with small objects, but has limitations with larger objects as detail and precision are sacrificed for range.

The Time of Flight (TOF) system works through measuring the time that a light pulse takes to travel to the object and back (*see Figure 7*). The accuracy of the TOF technique depends on the duration of the emitted light pulse and the speed and sensitivity of the detector. Shorter and faster light pulses and more sensitive detectors result in higher accuracy in TOF distance measurements. The main disadvantage of the TOF technology is that scanners are large, and they do not capture an object's texture, but only its geometry.

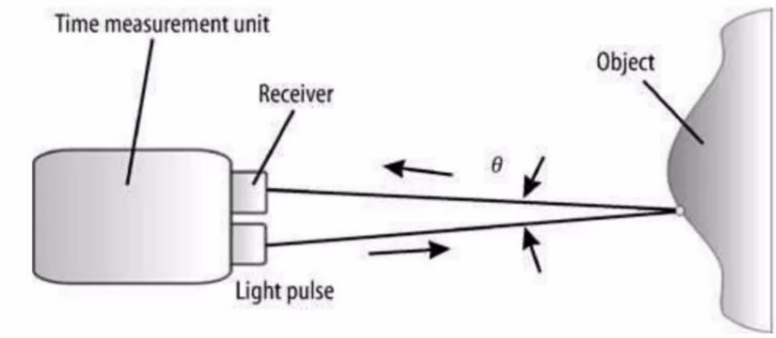

Figure 7 - Working principle of time-of-flight method

In passive approaches coordinate data is obtained by evaluating photographs and reconstructing a three-dimensional model of the object. The use of image frames for 3D reconstruction makes it comparable to active structured-light methods; however, passive methods do not project structured light sources onto the object in order to acquire data. Some examples of passive methods are shape from shading, shape from stereo, shape from motion, shape from focus/defocus, shape from silhouette.

A passive method we cited is shape from stereo (SfS), a technique used in computer vision and 3D reconstruction to estimate the depth or three-dimensional structure of a scene. SfS relies on having two or more photos of a subject obtained from slightly different angles (*see Figure 8*). To capture these photos, a stereo camera system is used, in which two cameras are placed apart to simulate the distance between human eyes. Finding corresponding spots or features between the images is the first stage in Shape from Stereo. The goal of this procedure, called correspondence matching, is to locate picture areas or pixels in the left image that match the corresponding spots in the right image. Once comparable points have been found the disparity map, a two-dimensional image where each pixel value represents the disparity or depth difference at that place, is computed. The three-dimensional structure of the scene can be rebuilt using the depth measurements derived from the disparity map. There are several ways to depict this reconstruction: as a point cloud, depth map, or 3D mesh representation.

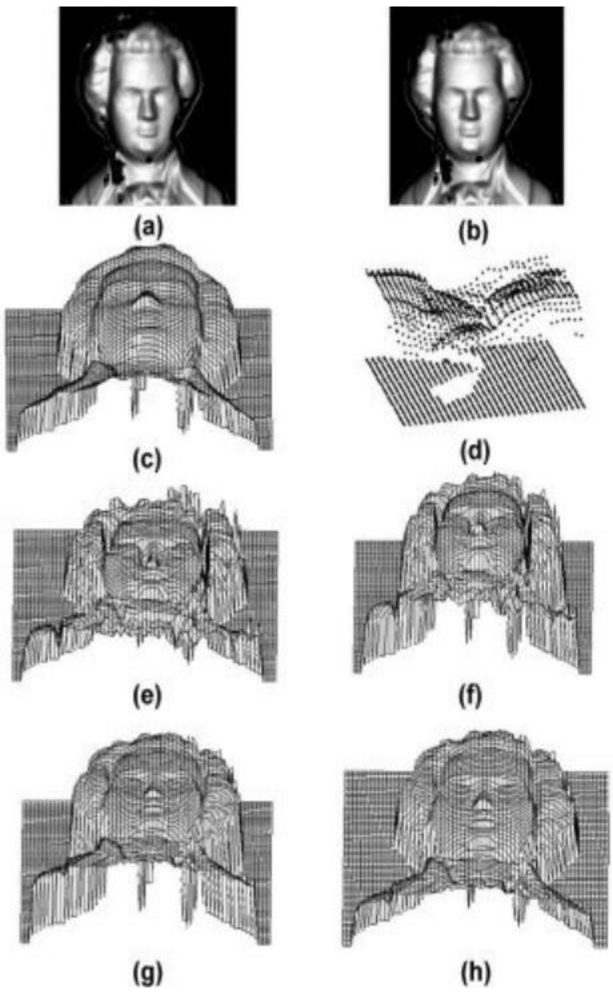

Figure 8 - Stereo images of Mozart (a) and (b)

Acoustic (active sonar) and microwave radar (radio detecting and range) are examples of **non-optical methods.** These 3D reconstruction methods work on the basis of measuring the time delay between incoming and returned signals to determine an object's distance from the sensing device.

Mariner's ability to avoid obstacles and navigate has significantly improved with the advent of sonar technology, which are typically employed in 3-D underwater mapping. Sonar range sensors are cheap; however they do not have fast acquisition speeds or great accuracy. Determining the focal point location is frequently problematic, as is acoustic interference or noise.

Advantages of non-contact based methods

- No physical contact,
- Fast digitising of volumes,
- Good accuracy and resolution,
- Ability to detect colours,
- Ability to scan highly detailed objects, where probes may be too large to accomplish the task.

Disadvantages of non-contact based methods:

- Possible limitations for transparent or reflective surfaces,
- Lower accuracy,
- High sensitivity to environmental conditions.

1.2 3D Reconstruction: the process

Creating a 3D reconstruction is a multifaceted endeavour involving several sequential steps to achieve a comprehensive 3D mesh representation of an object. These steps collectively form a structured pipeline (L. Gomes et al. 2014).

This pipeline typically comprises five essential stages: acquisition (*see Figure 9*), pair-wise registration, global registration, mesh generation, and texture generation.

Figure 9 - Data Acquisition

Numerous technologies have been proposed over the past few decades, each catering to specific scenarios and demands, but no single sensor best suited for all applications, instead different situations call for tailored solutions. The most important properties of a sensor to consider are:

- Quality: probably the most important characteristic when digitizing complex sculptures or sites, the accuracy and resolution of a sensor directly influences the faithfulness of the resulting model.
- Price: the cost of sensors can vary significantly from a few hundred Euros to 100k Euros. Given that the budgets allocated to digital preservation missions can often be constrained, it becomes crucial to factor this into consideration.
- Portability: Challenges such as lack of electricity and limited accessibility to certain cultural heritage sites are common hurdles. Consequently, it is important to address how the device handles these issues as well.
- Acquisition time: cultural heritage sites often contend with heavy foot traffic from visitors and local workers, among other constraints, which can impose time limitations on acquisition processes. Consequently, faster devices are deemed more appropriate for such scenarios.
- Flexibility: flexibility in sensor design is crucial when it comes to dealing with the diverse characteristics of artworks, sensors should be designed to accommodate various sizes of artworks, from small sculptures to large installations; artworks can be made from a wide range of materials and in different shapes and in many cases it's important for sensors to be non-invasive to preserve the integrity of the artwork.

This pipeline serves as a general framework for 3D reconstruction, but the specific steps and techniques may vary depending on factors such as the nature of the artefact or site, available resources, and desired level of detail.

Here's the pipeline for 3D reconstruction (M. Ioannides et al. 2023):

I. Data Acquisition:
   - Photogrammetry: Capture multiple images of the artefact or site from different angles using high-resolution cameras.
   - 3D Scanning: Utilize laser scanners or structured light scanners to directly capture 3D point cloud data of the object or site.
   - Drone Imaging: For larger sites or inaccessible areas, drones equipped with cameras or LiDAR sensors can be employed to capture aerial imagery or point cloud data.

II. Pre-processing:
   - Image Alignment: If photogrammetry is used, images need to be aligned accurately to ensure proper reconstruction. This may involve feature detection and matching techniques.
   - Noise Reduction: Clean up the acquired data to remove any noise or artefacts that might affect the quality of the reconstruction.
   - Point Cloud Registration: If multiple scans are taken from different viewpoints, register the point clouds to ensure they are aligned correctly.

III. Surface Reconstruction:
   - Mesh Generation: Convert the point cloud data into a surface mesh representation (*see Figure 10*). This can be achieved using surface reconstruction algorithms.
   - Mesh Refinement: Refine the mesh to improve its quality and remove any imperfections or holes.

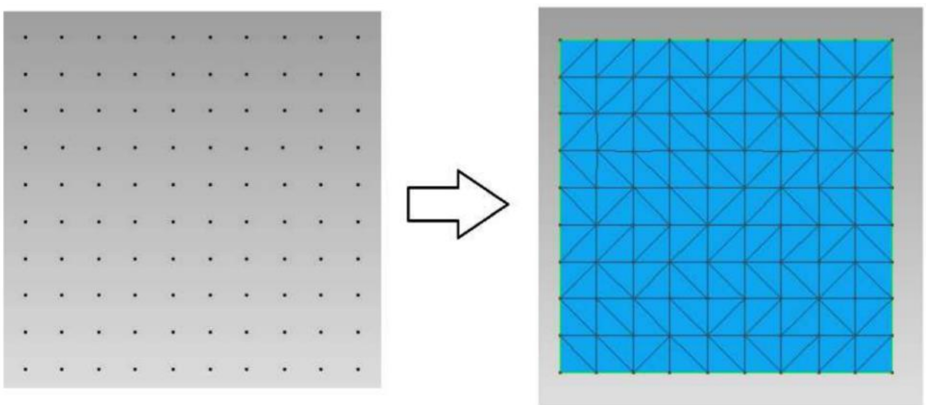

Figure 10 - Mesh creation from cloud of points

IV. Texture Mapping:

- Texture Projection: Project the acquired images onto the reconstructed mesh to apply realistic textures. This involves texture mapping techniques to ensure proper alignment and blending.

V. Model Refinement:

- Geometry Correction: Perform any necessary corrections or adjustments to the geometry of the reconstructed model based on reference measurements or expert input.
- Texture Enhancement: Enhance the texture quality by applying filters or adjusting color levels to improve visual fidelity.

VI. Post-processing:

- Mesh Optimization: Optimize the mesh structure to reduce its complexity while preserving important details.
- Compression: Compress the data to reduce file size while maintaining visual quality, especially important for online dissemination and storage.

The first step in a 3D reconstruction process involves choosing the relevant portion of the object, then raw data is produced, usually a point cloud data file, using the appropriate measurement tools for data gathering. A point cloud is a collection of 3D points or data coordinates that take the form of a cloud: most applications require point clouds to be transformed into an appropriate format before they can be used, such as a polygon mesh or non-uniform rational B-spline (NURBS) surface models (S. Münster et al. 2016).

The main methods for converting a point cloud data into a model rely on the creation of segments that fit into the model or a triangular polyhedral mesh. To capture the component topological features using the point cloud data, a triangular mesh must first be constructed using triangles to approximate the surface. A larger file size will result from adding more triangles, which will also improve the surface presentation. Typically, the triangulation software file is written in Standard Triangulation Language (STL), more commonly known as STL format. The triangular mesh is polished up to eliminate unnecessary vertices (connected points) and smooth surface curvatures.

The original point cloud data are divided into patches with well-defined boundaries in the segment technique. Then using the proper mathematical modelling techniques, parametric modelling or quadric functions, these discontinuous surface patches will be smoothed. The simulated model will then be constructed by fitting each patch into a specific area of the part surface.

1.3 What is 3D modelling used for?

By 3D model we refer to the numerical representation of any object under arbitrary viewpoints and lighting conditions in order to simulate its appearance in novel environments (*see Figure 11*). Furthermore, the models need to be editable to enable using the physical objects as the starting point for redesigning new objects with computer modelling systems. Both the surface and the geometry should be editable - i.e. the colours of the surfaces can be changed and the object can be stretched

Figure 11 - "The work of God",real object vs 3D model

The characteristics of a range scanner that we need to know are its accuracy and its scanning resolution. Accuracy concerns how close the measured value is to the true value; its importance is given by the fact that 3D models are built from points acquired from many different points of view so we need to understand the reliability of each point to combine them correctly.

Machine vision systems based on 3D triangulation are employed in a range of industries from the games market and automotive manufacturing to e-commerce, virtual museums, and archaeology (M. Lo Brutto et al. 2012).

Gaming and Virtual Reality

The most well-known use of 3D modelling is in video games development. 3D models are used in video games to create objects, locations, people, and even entire universes. Any successful game must focus on creating an immersive experience and 3D modelling is a great approach to do this.

Within the gaming industry virtual reality gaming is a rapidly developing field in which 3D modelling is also very important. With virtual reality games, a player can explore whole three-dimensional environments and immerse themselves in the game like never before.

3D printing

In order to make a physical replica of an object a computerized 3D model of the thing must first be created. This process is known as 3D printing. This technology allows to print an physical object from a digital file. There are a number of useful uses for 3D printing that go beyond producing tiny figurines and trinkets printed at home.

For instance, 3D printing is extensively used in the medical industry, for example it has been used to create personalized prosthetics and implants for individuals in need, as well as anatomically accurate models for surgical planning. In certain circumstances medical practitioners may also utilize 3D modelling to demonstrate to patients how their bodies will look after surgery, so they know what to expect.

Architecture and Engineering

3D models are used by builders, engineers, and architects to plan buildings and other huge constructions such as bridges. But they also plan out smaller items like furnishings and appliances for the house using the 3D modelling technique. Additionally, the 3D method can be used by professionals in the building, engineering, or design fields to show clients what their finished structure would look like.

This is especially helpful when pitching or talking with project stakeholders about the final result. Modern building design requires 3D modelling because it may reveal potential weaknesses in building structures in a manner that 2D designs are unable to.

More precisely, engineers utilize computer software known as CAD (computer-aided design) to design new machinery and structures and to verify if their drawings are accurate using 3D models. When it comes to design 3D modelling also enables architects to plan ahead beyond the custom of manually drawing architectural blueprints.

Product Design

When designing a new product, product designers use computers to generate a three-dimensional model of the final product before beginning to assemble it from metal or plastic components.

Product designers can create a virtual 3D model of the product before it is manufactured, allowing them to identify any problems and make necessary changes. Merely observing the object's dimensions in comparison to other products could significantly impact the production process.

When presenting product concepts to investors 3D modelling is very useful since it shows the items from all angles, making it possible for stakeholders to see the finished product precisely and easily. A major step in the correct way is to embrace sustainability in product design, as it is less wasteful than continuously producing prototypes and mock-ups.

Animation

Animators use computer software to make characters move around on screens to create animated films. Animators use 3D models to produce a streamlined, unified look in films and television series. 3D modelling is utilized to create scenery, characters, objects, and more during the whole animation process. But animation is not the only application for the capacity to animate. It's also great for special effects in non-animated movies.

E-Commerce

3D modelling is used for online product visualisation, augmented and virtual reality and configuration to increase engagement and sales. These products are referred to as 3D eCommerce or immersive eCommerce models. By offering an enhanced online buying experience over conventional 2D graphics, these 3D models hope to change the way consumers engage with products on the internet.

Customers may interact with products in a more immersive and engaging way when using 3D models in eCommerce, which has many advantages. 3D models for eCommerce give customers more flexibility to examine and assess things than 2D pictures do, enabling them to make better judgments and eventually lowering the amount of returns. Furthermore, higher conversion rates and happier customers might result from the integration of 3D models into eCommerce platforms.

Virtual Museums

Users' impressions of real-world experiences can be enhanced by fusing computer-generated virtual surroundings with real scenes through the application of VR technology. Virtual reality (VR) technology may be used to build museums and show off its benefits in a variety of areas, such as image processing for interactive and museum exhibition design. Virtual reality technology and museums work well together in fact 3D models can enhance museums' objectives of education and communication.

The Internet is becoming more and more important in the distribution of museum objects. More visitors may now learn about a wide range of topics thanks to the digitization of several prestigious museums' collections.

Throughout history museums have served as the primary hubs for the diffusion of cultural heritage. Museums have been digitizing their content more and more in recent years, to the point that it is now typical for every museum to have free digital information available online. This can include three-dimensional artefacts or simply images of the pieces accompanied by comprehensive descriptions. Virtual museums are also quite widespread; these could be digitally-only built museums or just digital representations of real museums.

There are many different kinds of virtual museums that can be used as a practical tool for network content distribution. Initially, the process of digitizing museums involved taking pictures of the objects and uploading those pictures together with their descriptions to the internet. Virtual museums later emerged as digital reproductions of pre-existing spaces. These digitalisations were movies, or a sound-assisted virtual tour that described the entire museum. Additionally, these movies can be made 360-degree interactive, allowing users to spin their heads while using the mouse, the device, or virtual reality glasses and gazing sideways.

Some virtual museums are made possible by Google Maps technology, allowing visitors to explore the area and take in the many rooms. The three-dimensional panorama can be viewed by the user by navigating between viewing locations situated at the centre of each room. To expand the data, there are additional panels with pictures or further information.

Other technologies, like photogrammetry, 3D scanning, or the use of 360-degree cameras that add a multitude of points of view, enable the construction of virtual tours of existing museums.

At the same time there are virtual museums that are digital environments that depict artworks in a virtual setting rather than being exact replicas of the actual thing. Models that exclusively display two-dimensional artwork are common and simple to make in this kind of museum. Numerous network applications enable the integration of photos into 3D spaces and if needed the addition of more data. The user can zoom in on each painting in the virtual setting, which is a three-dimensional room, to acquire more specific information that is either textual or supplemented by more photographs. You can enlarge the image to see the painting in far greater detail than you would in real space. These virtual museums are frequently made exclusively for internet usage and are not replicas of actual museums.

Additionally, there are totally virtual museums with 3D objects that are not duplicates or recordings of real museums or objects, but rather they are made specifically for this application. Compared to just digitizing an existing area and its objects, creating these digitized exhibition spaces demands a far larger investment. To achieve this the pieces to be exhibited must be created in three dimensions and an interaction that permits the visitor to move around the space appropriately must be included. This is typically done with displays that consist solely of documentation or historically accurate replicas of goods, such clothing, of which there aren't many real examples or which are challenging to keep and display.

1.4 Modelling softwares

There are lots of tools for 3D modelling: 3D modelling software stands as a crucial tool for transforming imaginative concepts into vivid, tangible models.

Blender:

Blender is a free and open-source 3D computer graphics program that is suitable for professional use. Blender can be used to create 3D printed models, animated movies, artwork, interactive 3D apps, visual effects, and video. Animating, 3D modelling, camera tracking, compositing, match moving, raster graphics editing, rendering, rigging and skinning, sculpting, soft body simulation, texturing, UV unwrapping, and video editing are a few of Blender's features.

SketchUP:

Although it was initially developed for use in architectural design, this 3D modelling program is today utilized for a variety of drawing tasks. This tool's primary functions include surface rendering in different "styles," drawing layout capabilities, and rendering that is almost photo-realistic thanks to third-party plugin programs.

SolidWorks:

SolidWorks is a computer-aided engineering (CAE) and computer-aided design (CAD) application for solid modelling that creates assemblies and models in accordance with the designer's purpose using geometric or numerical parameters. With the help of the program's "design intent" tool, the user may determine which criteria are most crucial to maintaining the integrity of the design and ensuring that it adapts appropriately to changes. SolidWorks uses geometric characteristics from your sketch, such as arcs, conics, lines, and points, to form the model and generate views. Typically, you start with a 2D sketch to develop a model.

ZBrush:

Industry-wide ZBrush is the go-to program for digital sculpting. Its versatile toolkit extends far beyond digital sculpting; for example the Spotlight tool can be used to add texture or retrieve a reference image. Practically anyone with experience in 3D modelling can make excellent use of almost every function in ZBrush.

Maya:

Even Maya's "light" game development version (Maya LT) includes all the key tools for producing 3D objects, such as modelling, rigging, animation, and texturing. Set driven keys, PSD file compatibility, animation layers, and cluster deformers are more features that Maya provides.

Geomagic:

The most complete reverse engineering program available, Geomagic Design X (*see Figure 12*), combines history-based CAD with 3D scan data processing to enable the production of feature-based, editable solid models that work with CAD programs.

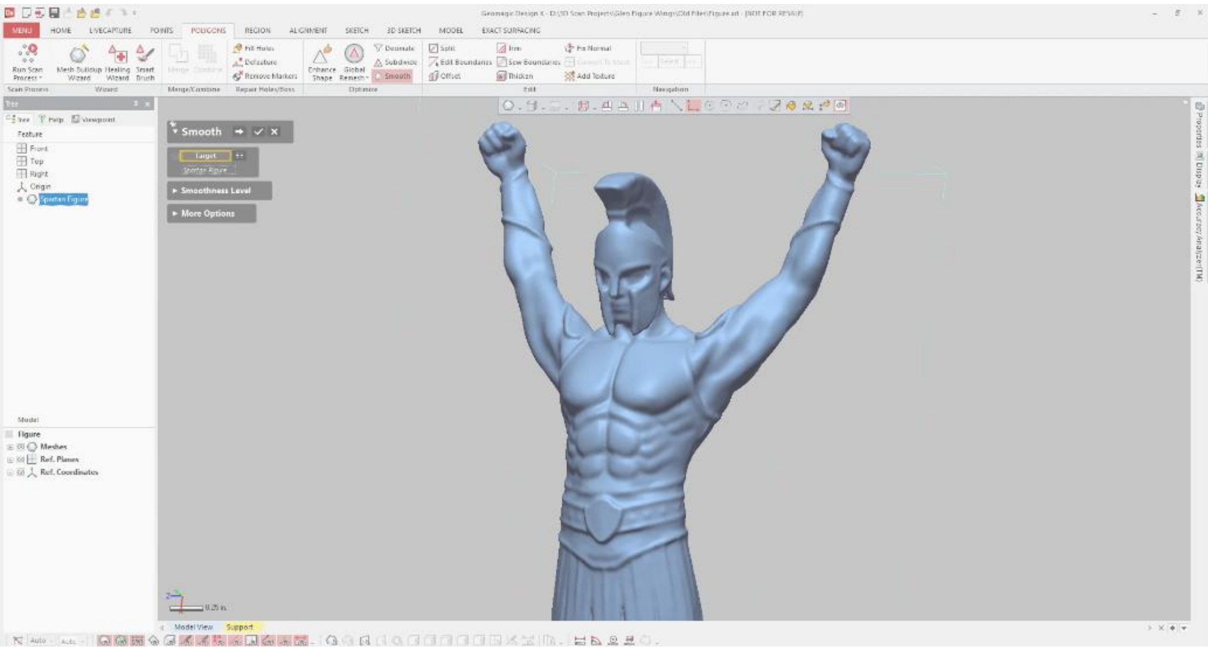

Figure 12: Geomagic DesignX

Chapter 2: 3D modelling in the field of Cultural Heritage

Cultural heritage encompasses the tangible and intangible artefacts, traditions, practices and knowledge that are inherited from past generations and preserved for future generations (*see Figure 13*). It includes a wide range of elements that hold cultural, historical, artistic or spiritual significance to a particular group of people or society (R. Harrison et al. 2010).

Figure 13 - Forms of cultural heritage

Photogrammetry has been used for a long time to gather texture information and three-dimensional (3D) data on cultural heritage objects. The field of cultural heritage was first exposed to imaging spectroscopy in the 1990s when a multi-spectral imaging system built around a Vidicon camera was utilized to map and identify the pigments in paintings.

By the considerable advancements in electronics, computers, and information technologies, including digital cameras, parallel processing, and storage capacity, old approaches are constantly replaced by new techniques in digital photogrammetry. Terrestrial laser scanning devices are quite common these days and have been utilized for 3D modelling and visualization as well as documentation of cultural heritage objects.

Understanding what restoration materials have been used in the preservation of artworks is crucial as is studying the materials and artistic techniques used to create them. This will give curators, scholars, conservators, archaeologists, and conservation scientists effective tools for learning about artefacts and archaeological objects. The investigation of these materials can employ both invasive and non-invasive methods, each with unique benefits and drawbacks. Invasive procedures should be avoided while working with cultural qualities since they need samples, or micro-samples, from the items being studied. Nevertheless, compared to non-invasive methods, these procedures provide more precise information for identifying purposes. In scientific research programs non-invasive imaging techniques are typically used for a preliminary screening and thorough evaluation of the surface, followed by non-invasive analytical spot techniques and, if necessary, a complementary phase with micro-invasive techniques that are focused on examining a small number of suitable, selected points as a final step (L. Piroddi et al.).

The process of recording and conserving historical sites and monuments in three dimensions has commenced thanks to international organizations like ICOMOS (International Council of Monuments and Sites), CIPA (Comité International de la Photogrammétrie Architecturale), and ISPRS (International Society for Photogrammetry and Remote Sensing). On the one hand, an increasing number of businesses are creating digitisers (cameras, lasers) that are more accurate, versatile, and efficient. However, information technology (IT) is creating sophisticated software to process vast amounts of scanned data in the future. This allows the scientist to use the data for restoration and/or replica manufacture in CAD systems, and in certain situations, directly in the production line. The 3D reconstruction, visualization and animation in the area of culture heritage is based on the cooperation between different fields of study such as computer science and photogrammetry.

There are different 3D reconstruction technologies utilized for cultural heritage preservation, we will discuss some of their methods, applications, and significance.

- **Photogrammetry**

Photogrammetry is a widely used technique that involves capturing multiple overlapping images of an object or site from different angles. These images are processed using specialized software to create a 3D model by identifying common points and calculating their positions in 3D space. Photogrammetry is versatile and can be applied to various scales, from small artefacts to entire archaeological sites. It offers high accuracy and detail, making it suitable for creating precise replicas of cultural artefacts and monuments.

- **Laser Scanning (LiDAR):**

LiDAR (Light Detection and Ranging) technology employs laser beams to measure distances to objects and surfaces. It generates highly accurate 3D point clouds by scanning the target area from multiple vantage points. LiDAR is particularly useful for capturing intricate details of complex structures such as buildings, sculptures, and landscapes. It enables archaeologists and conservationists to conduct virtual reconstructions and analyse features that may not be visible to the naked eye.

- **Structured Light Scanning:**

Structured light scanning involves projecting patterns onto the surface of an object and capturing the deformation of these patterns with a camera. By analysing the distortion of the projected patterns, the system calculates the object's geometry and texture. This method is efficient for capturing fine details with high resolution, making it suitable for digitizing delicate artifacts and artworks. Structured light scanning is non-contact, minimizing the risk of damage to fragile cultural objects during the digitization process.

- **Drone Imaging:**

Drones equipped with cameras or LiDAR sensors are increasingly used for aerial mapping and surveying of cultural heritage sites. Aerial imagery and LiDAR data captured by drones provide comprehensive coverage of large areas, facilitating the documentation of archaeological sites, landscapes, and monuments. Drones offer mobility and accessibility, enabling researchers to explore inaccessible or remote locations without disturbing the environment. Integrating drone-based data with other 3D reconstruction techniques enhances the accuracy and completeness of cultural heritage documentation.

3D reconstruction technologies play a crucial role in cultural heritage preservation by digitizing and safeguarding artefacts and sites from natural deterioration, human activities, and conflicts.

The recent advancements have given rise to the issue of standardization and compatibility. The multitude of scanners on the market today and the variety of software that is available to the general public mean that hardware and software frequently don't function well together. For this reason, there is a current need for standardization in the IT and cultural heritage domains.

2.1 Cultural Heritage applications

3D reconstruction offers significant advantages to Cultural Heritage, serving as a valuable tool for monitoring degradation phenomena and restoration efforts, as well as preserving and archiving multimedia representations of artworks. Additionally, it plays a crucial role in enhancing accessibility for individuals with disabilities, ensuring that cultural treasures can be experienced and appreciated by everyone (Barone, S., Paoli, A., & Razionale, A. 2012).

The preservation of cultural heritage in digital form has grown substantially over the last two decades. This technology serves multiple purposes:

i. Protection Against Loss: it safeguards the shape and appearance data of objects from potential loss caused by natural disasters or accidents;
ii. Wider Dissemination: digital collections can be disseminated widely through virtual museums, allowing them to reach a broader audience beyond physical limitations;
iii. Replica Creation: digital preservation facilitates the creation of replicas, enabling accurate reproductions of cultural artefacts for various purposes;
iv. Forgery Detection: it aids in the detection of art forgery by providing detailed digital records for comparison and analysis.
v. Geometric and Texture Information: digital preservation enables the collection of specific geometric or texture information that may be challenging to obtain directly from the real objects, enhancing research and conservation efforts (Gomes, L., Regina Pereira Bellon, O., & Silva, L. 2014).

In addition to research focusing on the preservation of cultural heritage through 3D reconstruction, there are also projects dedicated to restoration efforts. One such project proposed a paper on a 3D reconstruction methodology specifically tailored for the restoration of historical buildings. This methodology leveraged the combined capabilities of a total geodetic station, incorporating its speed, range, and precision. The aim was to provide archaeologists with a technological solution that is relatively low-cost, enabling them to reconstruct "Neoria," a Venetian building situated by the old harbour at Chania, Crete, Greece. This innovative approach aimed to enhance restoration efforts by providing detailed and accurate 3D reconstructions, facilitating the preservation and restoration of historical landmarks (L. Ragia, F. Sarri and K. Mania, 2015).

The integration of digital technologies such as laser scanning, photogrammetry, computer vision-based techniques, and 3D geographic information systems (3D GIS) presents significant potential for documenting and analysing specific aspects related to the preservation status of historical structures. In a notable case study, the investigation concentrated on the northern section of the double atrium house of Caecilius Iucundus (North House of Caecilius Iucundus) in Pompeii. This study utilized advanced digital methods to capture detailed information about the architectural features, conditions, and changes over time within this historical site. By employing these digital tools, researchers aimed to enhance their understanding of the preservation needs and challenges associated with the structure, ultimately contributing to more effective conservation and management strategies for Pompeii's cultural heritage (Campanaro, D. M., Landeschi, G., Dell’Unto, N., & Leander Touati, A.-M. 2016).

3D reconstruction serves as a valuable tool for digitising cultural and artistic objects, as it can accurately capture the 3D shape of an object without the need for physical contact with its surface. This capability is invaluable for research and study, especially when physical access to the artwork is restricted due to factors such as its shape, height, or placement within a room. Moreover, digitization enables the exploration and examination of artworks in ways that may not be feasible in person, including the ability to virtually "touch" them. This not only enhances accessibility but also deepens understanding and appreciation of cultural and artistic heritage (Pieraccini, M., Guidi, G., & Atzeni, C. 2001).

Archaeological sites and museums frequently present challenges for individuals with physical disabilities, stemming from mobility limitations, inadequate accessibility features such as ramps, and remote locations. Nevertheless, recent advancements in virtual reality (VR) technologies have ushered in new opportunities for improving accessibility. By leveraging VR, individuals can virtually explore archaeological sites and museum exhibits from the comfort of their own homes, overcoming barriers associated with physical limitations and geographical constraints. This innovative approach not only enhances accessibility but also fosters inclusivity by ensuring that everyone, regardless of physical ability, can engage with and appreciate cultural heritage.

Pappa, G., Ioannou, N., Christofi, M., & Lanitis, A. (2018) have introduced a VR application that reconstructs the archaeological site of Choirokoitia in Larnaca, Cyprus. This virtual reconstruction meticulously replicates the current state of the site by leveraging real data obtained from photographs captured at the actual location. Users have the opportunity to navigate through the archaeological site virtually, gaining access to historical information about significant points of interest. This innovative approach not only tackles accessibility challenges but also delivers an immersive and educational experience for all users (Kosmas, P., Galanakis, G., Constantinou, V., Drossis, G., Christofi, M., Klironomos, I., Zaphiris, P., Antona, M., & Stephanidis, C. 2020).

Another noteworthy project involves the utilization of a 3D laser scanner for the survey of San Martin’s Church, located in Plaza Juan Bravo, in the historic city centre of Segovia, Spain. The objective of this project was to develop a platform that integrates augmented and virtual reality technologies to enhance digital accessibility for disabled individuals. By incorporating cartographic products, such as maps and architectural models, into the platform, users can experience an immersive and interactive exploration of the church and its surroundings, regardless of physical limitations. This initiative represents a significant step forward in leveraging technology to promote inclusivity and provide equal access to cultural heritage sites for all individuals (Mancera-Taboada, J., Rodríguez-Gonzálvez, P., González-Aguilera, D., Finat, J., José, J. S., Fernández, J. J., Martínez, J., & Martínez, R. 2011).

2.2 Cultural Heritage for the visually impaired

The importance of accessibility and inclusivity in the cultural heritage sector has long been recognized., in fact in 1909 the American Museum of Natural History in New York City created a special room dedicated to visually impaired visitors where they could handle and examine taxidermy specimens. Six decades later, in the 1970s, there was a global upsurge in the number of art shows designed for viewers with low vision and blindness in mind. Because sculpture is intrinsically more tactile than two-dimensional artworks like paintings, sketches, and photographs, sculpture was the subject of many of these shows.

Fascinating examples of facilitating access to art for visually impaired individuals include the Typhlological Museum in Zagreb, which opened its doors in 1953, and the Omero Tactile Museum in Ancona, established in 1993.

The Typhlological Museum counts a selection of paintings and sculptures by academic sculptors, but the majority of the collection comprises artwork created by self-educated blind sculptors (*see Figure 14*). Collecting these artworks and featuring them in both permanent and rotating exhibitions, like the Tactile Gallery, serves the museum's mission to unveil the creative talents of blind artists, challenging misconceptions about the artistic abilities of the blind community. Moreover, another museum’s objective is also to motivate and inspire blind visitors to explore their own artistic potential in this field.

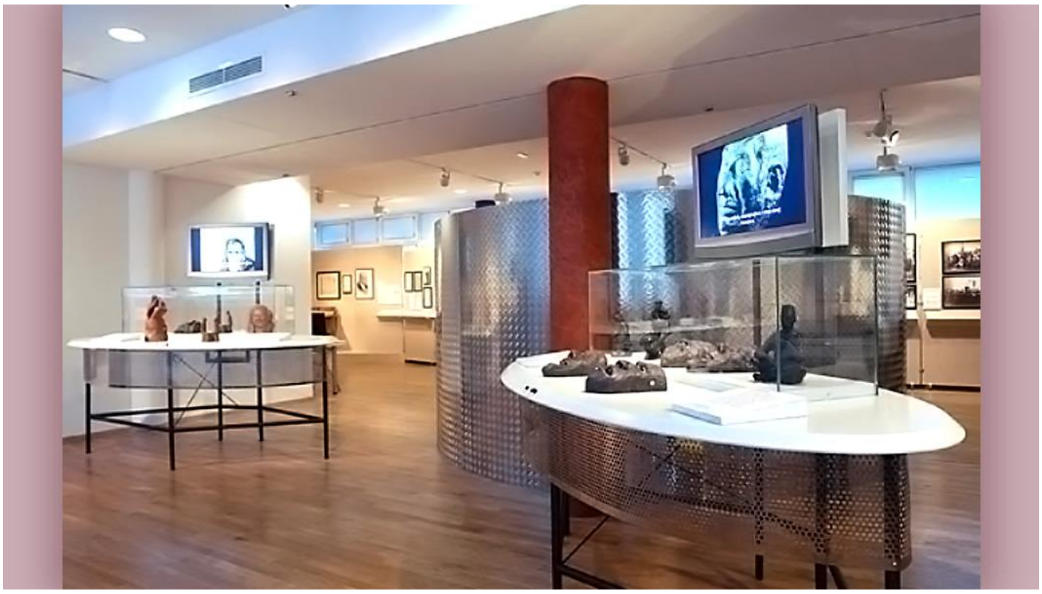

Figure 14 - The Typhlological Museum, Zagreb

The Omero Tactile Museum on the other hand offers a rich collection features a diverse array of copies and casts of genuine archaeological discoveries and artistic masterpieces (*see Figure 15*), including artworks such as the Winged Victory of Samothrace, the Venus de Milo, and Michelangelo's Pietà. Architectural replicas of iconic structures like the Parthenon, the Leaning Tower of Pisa, and Saint Peter's Basilica are also showcased, alongside original sculptures crafted by contemporary artists. Organized into four sections, each corresponding to a distinct period of art history:

i. Greek-Roman art
ii. Romanesque-Gothic art
iii. Renaissance art
iv. Contemporary art

Figure 15 - The Omero Tactile Museum, Ancona

2.3 Relevant Case Studies

We will now explore some case studies and examples of 3D reconstruction in the field of cultural heritage and we will discuss some of them more specifically in the next subchapters.

The Digital Michelangelo Project (M. Levoy et al. 2003) presents a comprehensive account of the digitization process applied to ten Michelangelo statues (*see Figure 16*), two building interiors, and 1163 fragments of an ancient marble map in Italy. The project employed triangulation laser scanners, time-of-flight laser scanners, and digital cameras. Notably, the paper addresses the significant challenges encountered in handling the large sculptures and datasets, with the largest dataset comprising two billion polygons. Section 3 of the paper specifically delves into the issue of managing large datasets.

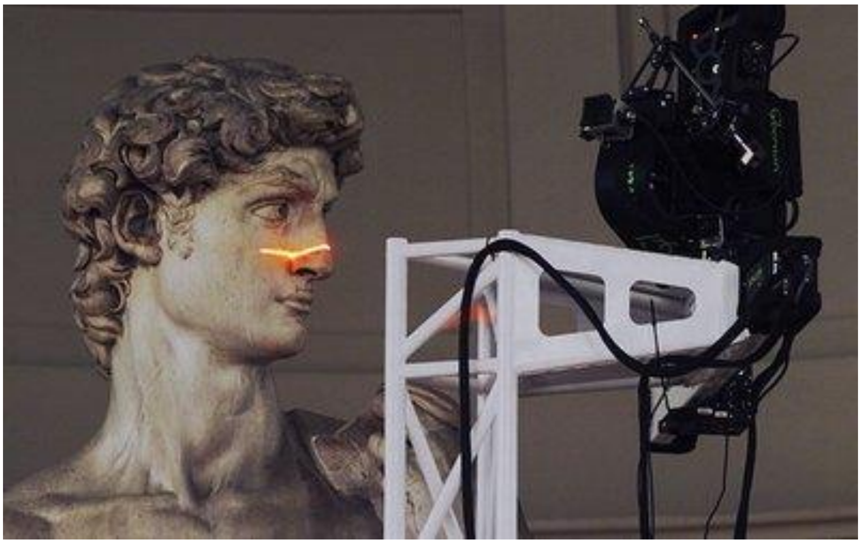

Figure 16 - The Digital Michelangelo Project

Another noteworthy endeavour is *The Great Buddha Project* (Miyazaki, D. et al. 2001), which outlines the complete pipeline and obstacles encountered in digitally archiving and restoring three large Buddha statues measuring 2.7, 13, and 15 meters in Japan (*see Figure 17*). The primary sensor utilized in this project was a time-of-flight laser scanner. The paper discusses various challenges and their solutions, including those related to outdoor scanning environments and the development of a novel algorithm for registration and integration. These contributions significantly enhance the understanding and practice of digitizing monumental cultural artefacts.

Figure 17 - The Great Buddha Project

Additionally, there's *The Minerva Project* (R. Fontana et al. 2002), focusing on the Minerva of Arezzo, an ancient 1.55-meter-tall bronze statue situated in Italy (*see Figure 18*). The project aimed to create a 3D model to monitor variations during the statue's restoration process. Employing a high-resolution 3D triangulation laser scanner posed a challenge due to the extensive data involved (approximately one million points in each of the 119 range images) given the limitations of RAM size and processing power of computers at the time.

Figure 18 - The Minerva Project

The Eternal Egypt Project (H. Rushmeier, 2006) is an expansive historical initiative aimed at constructing a digital guide and virtual museum showcasing artefacts from ancient Egypt (*see Figure 19*). This project utilized a time-of-flight range sensor and IBM Research's Pro/3000 Digital Imaging System for high-quality colour images. The virtual collection comprises more than 2000 2D scans, 16 3D models, and four navigable environments.

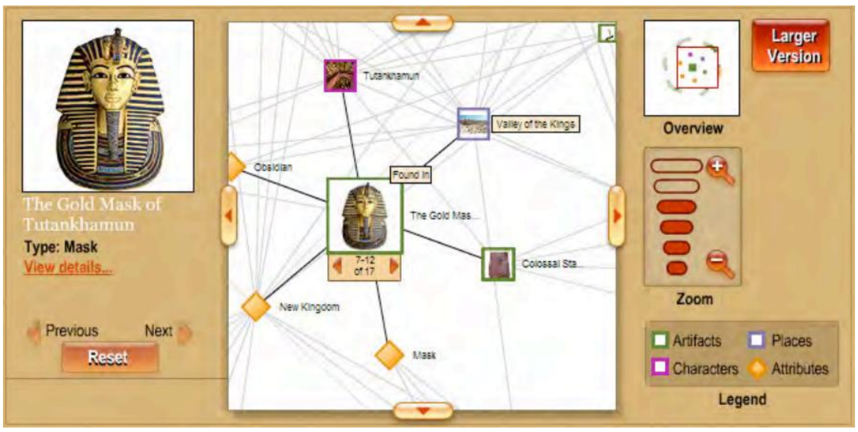

Figure 19 - The Eternal Egypt Project

Lastly, The *Angkorian Temples Project* (T. Sonnemann et al. 2006) presents the reconstruction of a vast area containing over 1000 historical structures in Angkor, Cambodia, using aerial images (*see Figure 20*). Based on photogrammetric 3D modelling, this project offers compelling results for documenting the archaeological landscape of large cultural heritage sites.

Figure 20 - The Angkorian Temples Project

The Forum of Augustus (D. Ferdani et al. 2020) is another example of 3D reconstruction, but this time the aim of the work is to develop a videogame (*see Figure 21*), in fact due to the thriving video game industry, the realm of technology applied to cultural heritage is now exploring fresh avenues for disseminating heritage and studying the past through innovative edutainment models. “A Night in the Forum” is an Educational Environmental Narrative (EEN) Game designed for PlayStation® VR, immersing players in the Augustan Rome era. Its primary aim is to elucidate the intricacies of Imperial Rome's administration. Grounded in the principles of "environmental storytelling" and "learning-by-doing," the game provides an experiential journey into the depths of Roman governance.

Figure 21 - A Night in the Forum, PlayStation Videogame

During the Covid-19 pandemic there has been a renewed emphasis on reorienting attention towards fostering inclusivity, sustainability, and safety measures within the cultural heritage field. The case study of *The Museo d'Arte Orientale di Torino* (R. Spallone et al. 2021) is an example of the use of 3D acquisition and reconstruction in order to offer new ways of visiting cultural sites and museums through the exploitation of virtual reality (*see Figure 22*). The case study revolves around two Japanese statues and suggests their visualization with their respective weapons virtually reconstructed. It utilizes virtual reality (VR) to reconstruct the interior space of a temple that is deemed philologically compatible with the statues' location within a statuary complex.

Figure 22 - The Museo d'Arte Orientale di Torino Project

We will now analyse more in depth some of the case studies cited above.

The Digital Michelangelo project

This case study introduces a hardware and software solution devised for digitising large, delicate objects in non-laboratory environments, capturing both their shape and colour. The scholars utilized laser triangulation rangefinders, laser time-of-flight rangefinders, digital still cameras, and a suite of software to collect, align, merge, and visualize scanned data. The project involved digitizing ten statues by Michelangelo, including the renowned David, two building interiors, and all 1,163 surviving fragments of the Forma Urbis Romae, a colossal marble map of ancient Rome.

The primary technical objective of the Michelangelo project was to establish a 3D library comprising as many statues as could be scanned within a single year, capturing intricate details using advanced computer technology and scanning techniques. Special emphasis was placed on capturing Michelangelo’s chisel marks, as the artist often intentionally left the surface of his statues rough. To achieve a realistic appearance of curved surfaces under varying lighting conditions, the computer models needed to accurately depict the bumps and textures of the statues geometrically. Furthermore, Michelangelo's chisel marks on his unfinished statues, such as St. Matthew and the Slaves, offer insights into his artistic process. Through the use of computer modelling, it became feasible to segment the statue's surface based on the chisels used to sculpt each area, providing a deeper understanding of Michelangelo's labour techniques and artistic vision (*see Figure 23*).

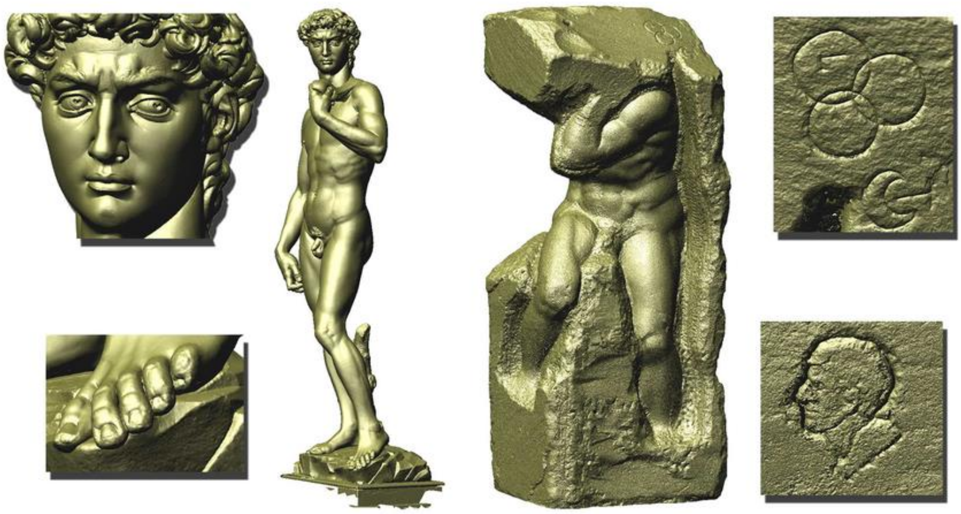

Figure 23 - The David and Atlas Statues

In addition to capturing geometry, scholars aimed to capture colour information, specifically by calculating the surface reflectance of each point on the scanned statues (*see Figure 24*). Extracting reflectance is a more complex process than simply capturing colour, but it offers several advantages, including the ability to relight the statue during the rendering process and providing valuable scientific insights. This is particularly important for old statues and sculptures, which may be coated with a mixture of marble veining, filth, waxes, and other compounds used in earlier restorations, as well as experiencing aging and discoloration over time.

The primary hardware component used in this study was a laser triangulation scanner and motorized gantry customized for digitizing large statues. For instance, scholars scanned the David under both white light and ultraviolet light separately to gain insights into the statue's history and composition. This comprehensive approach allowed for a thorough examination of both the geometry and colour characteristics of the scanned objects, enhancing our understanding of their preservation and artistic significance.

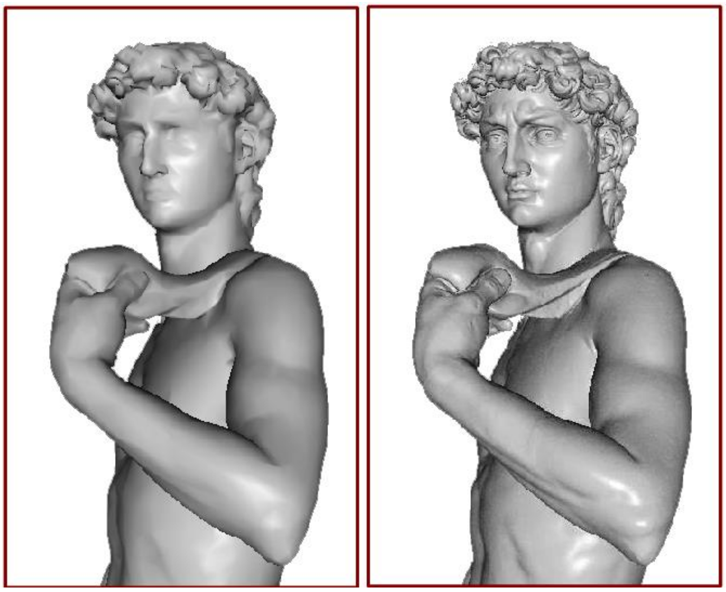

Figure 24 - Simplified polygonal model vs high quality image

Preserving the integrity of the sculptures was paramount throughout the project. Laser triangulation, a non-contact digitizing technique, ensured that the artwork was only exposed to light. However, careful management of heat and light levels was essential to prevent any potential harm to the art. A 5 mW red semiconductor laser served as the scanning beam, directed into a line 20 cm wide at the surface of the statue and moved continuously during scanning.

Additionally, a 250 W incandescent bulb powered by a fibre-optic connection served as the white light source, effectively preventing heat from reaching the scan head by dispersing the light into a broad disk 50 cm wide at the surface of the statue. Compared to ambient lighting, minimal energy deposition occurred on the statue in both situations.

To mitigate the risk of inadvertent contacts between the scanner and the monument, researchers implemented various methods. Pressure-sensitive motion cutoff switches were installed on the rails of the horizontal and vertical translation tables, replacing software motor controls to plan the motions of the scan heads. Additionally, one member of each scanning team was designated as a spotter, and foam rubber was used to encase the scan head to reduce the potential for harm in case of accidental contact.

After acquisition, scans underwent a comprehensive post-processing pipeline to create a polygon mesh. Scans from different gantry positions were aligned interactively and automatically as part of the range processing pipeline. A volumetric technique was employed to merge the scans, and space carving filled in any gaps, resulting in a solid irregular triangle mesh as the output of the pipeline.

The Digital Michelangelo Project's tangible output comprises a collection of 3D geometric models, with the scholars' objective being to freely distribute these models to the scientific community.

The Minerva Project

The Minerva of Arezzo is an antiquated bronze statue housed in the Museo Archeologico in Florence. Before the restoration process began a full 3D digital model of the Minerva was assembled. During the restoration process more and more 3D models were created in order to record the changes that transpired throughout the restoration procedure, up until the ultimate acquisition of the completely restored artwork (*see Figure 25*).

The aim of the project was to keep track of all the variations that occurred during the restoration process and at the same time to show how 3D techniques could be used to design and introduce new tools for the diagnostics of archaeological objects. 3D measurements have been realised by means of a high-resolution laser scanner and in order to compete with the extremely expensive commercial devices, the instrument, developed at INOA (Institute for Applied Optics), is built from low-cost commercial components.

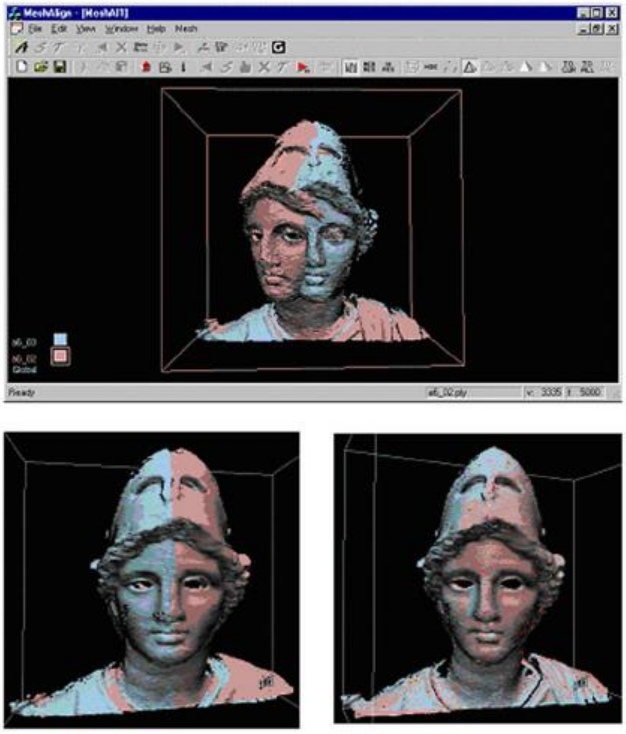

Figure 25 - The MeshAlign Tool of The Minerva Project

Discovered in Arezzo in 1541, the Minerva is a bronze statue believed to date back to the 3rd century B.C. While the lower portion of the statue underwent full repair using wood and plaster, the right arm, from the shoulder down, was integrated in bronze in 1785. In 2001, the Minerva project commenced at the Florence Restoration Centre of the Soprintendenza Archeologica, overseeing the restoration of the Minerva statue.

Prior to the restoration process, the entire Minerva statue underwent 3D scanning. Complex objects like this are typically modelled using a series of partially overlapping range scans. In this case, each range map sampled an area of approximately 30×30 cm^2. A comprehensive digital representation of the Minerva was created, resulting in a reconstructed mesh consisting of 26 million triangle faces.

This 3D model of Minerva serves as the sole depiction of the sculpture's form before restoration (*see Figure 26*).

Figure 26 - Probable different position of the Minerva statue's right arm

During the restoration process, the right arm and the lower wooden and plaster portion will be removed. The 3D model can then be utilized to replicate and accurately position the missing parts or to preserve evidence of any potential shape changes that may occur. The 1785 restoration of Minerva is incorrect. Both the recovery process and the original preservation state of the statue, which was most likely restored in the fifteenth century, are not well documented. The right arm of the Minerva was repaired with plaster in the past; this is evidenced by a printing from the beginning of the 18th century. The forearm was raised to hold a lance, a recurring feature for the warrior goddess who was wearing a Corinthian helmet. The scholars decided to use a simulation program in order to visualize the two most likely initial positions of the right arm through the acquired 3D model.

The Minerva project demonstrated that even in 2001 the 3D technology was already sufficiently developed to be used in the field of cultural heritage.

The Angkorian Temples projects

The UNESCO World Heritage site of Angkor, located in Cambodia, is home to over 1000 historical structures spread across a vast area in the northern lowlands surrounding the Tonle Sap Lake. This area served as the centre of the Khmer empire from 800 to 1327 A.D. boasting remarkable architectural and cultural achievements.

The objective of this project was to explore the feasibility of creating true-to-life 3D models of the complex historical buildings at Angkor from aerial imagery using structure-from-motion techniques (*see Figure 27*). By harnessing advanced imaging techniques and computational methods, researchers aimed to capture the intricate details and architectural nuances of these ancient structures. This endeavour sought to bridge the gap between modern technology and historical preservation offering a novel approach to documenting and understanding the rich heritage of Angkor. Through meticulous analysis and processing of aerial images the project aimed to produce high-fidelity 3D models that would not only serve as accurate representations of the original buildings but also provide valuable insights into their construction and spatial relationships. In fact, scholars hoped to overcome logistical challenges and access areas that may be difficult to reach on the ground thereby expanding the scope and depth of their investigations.

Figure 27 - Scenes from Virtual Angkor

Ultimately this work sought to contribute to the preservation and appreciation of Angkor's cultural heritage by providing researchers, historians, and the general public with detailed and immersive reconstructions of its architectural wonders. By combining cutting-edge technology with a deep respect for history, the project aimed to unlock new avenues for exploration and understanding of one of the world's most iconic archaeological sites.

The Virtual Angkor project represents a pioneering effort to reconstruct the magnificent city of Angkor when the Khmer empire held significant power and influence. This ambitious endeavour is the result of a collaboration among archaeologists, historians and virtual history specialists hailing from Australia, Cambodia, and the United States. Through cutting-edge technology the project transports users into a three-dimensional world where they can explore Angkor's renowned bas-reliefs up close, witness bustling marketplaces teeming with goods from diverse regions and observe animated crowds and processions traversing the city's sprawling complex.

Designed with educational purposes in mind the virtual environment of Angkor serves as an invaluable tool for classrooms nowadays: it enables educators to captivate students by providing them with a firsthand encounter with history, without the constraints of physical travel. By immersing students in a historically accurate rendition of Angkor, teachers can inspire curiosity and further exploration of the Khmer civilization. This virtual reconstruction serves then as both a gateway to the past and a springboard for deeper investigation and learning.

Chapter 3: Palazzo Bo and its history

Palazzo Bo is one of the most iconic buildings in Padua, Italy, with a rich history dating back to the Middle Ages (*see Figure 28*). It was originally constructed in the 13th century as a university building, in fact the official foundation of Padua University dates back to the year 1222, although even before its establishment, the city had "schools" for the study of law (M. Nezzo).

Figure 28 - Palazzo Bo, Padova

The university's inception was prompted by the migration of teachers and students from nearby Bologna University. This move was a response to perceived violations of academic freedoms and the neglect of privileges promised to teachers and students. Unlike universities founded by papal or imperial decree, Padua University emerged from specific events and favourable cultural circumstances. Its founding principles of academic freedom endured over the centuries, initially safeguarded by the free City Commune in the 13th century, then by the Da Carrara rulers in the 14th century, and later by the Republic of Venice, which governed Padua from 1405 to the late 18th century. The University's motto, Universa Universis Patavina Libertas (Freedom of Thought for Everyone), reflects this commitment.

Originally focused on law, the university gradually expanded to encompass other disciplines. In 1399, it was divided into two branches: *Iuristarum* for civil and canon law, and *Artistarum* for medicine, philosophy, theology, grammar, dialectics, rhetoric, and astronomy. The university initially operated as a self-governing body of students, organized into *nationes* based on their regional or ethnic origin. These *nationes*, in turn, formed two larger groups: the *citramontani* (Italians) and the *oltramontani* (non-Italians). Students played a central role in university affairs, approving statutes, electing rectors, selecting teachers, and funding their salaries through contributions from attendees. Teachers were subsequently appointed and remunerated by public authorities.

The 15th century marked a period of significant growth and prosperity for Padua University, extending for several centuries. Designated as the sole *Gymanisum Omnium Disciplinarium* for the Venetian Republic, Padua enjoyed exceptional religious tolerance and intellectual freedom, fostering its international renown. The university's contributions to the rapid advancement of philosophical thought and other disciplines during this era were profound. During this period, Padua emerged as a significant centre for scientific thought, boasting influential schools of medicine and anatomy.

Notably, Galileo Galilei, a luminary of his time, imparted his wisdom at Padua for eighteen years, leaving indelible marks on astronomy, physics, and mathematics. As a result, Padua became a magnet for students from across Europe, playing a pivotal role in the burgeoning scientific revolution.

Palazzo Bo served not only as an academic institution but also as a vibrant cultural and intellectual hub. It hosted lectures, debates, and gatherings that shaped the course of European thought. The university's prestigious reputation attracted scholars from various disciplines, fostering a spirit of intellectual exchange and innovation.

In the annals of scientific history, this era at the university is noteworthy for several milestones. Gian Battista Da Monte's pioneering approach to clinical medicine, conducting teachings at the patients' bedside, stands out as a revolutionary practice in Europe. Furthermore, the establishment of the world's first public university Botanical Garden in 1545 and the advent of anatomical studies for medical advancement signify Padua's progressive ethos. The construction of the world's inaugural Anatomy Theatre in 1594-95 underscored Padua's commitment to innovation in medical education.

Beyond the realm of science, Padua's influence extended into philosophy and jurisprudence. Philosophy began to liberate itself from the constraints of scholasticism, in fact Elena Lucrezia Cornaro Piscopia made history in 1678 as the world's first woman to earn a university degree when she successfully obtained her degree in philosophy at Padua.

Despite challenges such as the fall of the Venetian Republic in 1797 and the tumultuous political landscape preceding Italian Unification in 1866, Padua University persevered, albeit facing financial constraints and restrictions on intellectual freedom. Nonetheless, it continued to fulfil its educational mandate at a regional level. During moments of national significance, such as the local uprising of February 1848 and the First World War, Padua University played active roles. Chancellor Concetto Marchesi and Vice-Chancellor Egidio Meneghetti emerged as influential figures during these turbulent times. True to its motto of freedom of thought, the university remained a bastion of resistance against Fascism and Nazi occupation, earning the esteemed Gold Medal of Military Valour for the sacrifices made by its students and faculty.

3.1 Architectural Evolution

Architecturally Palazzo Bo is a blend of medieval and Renaissance styles. It features a beautiful courtyard, elegant arcades, and impressive frescoes decorating its interior walls. Over the centuries Palazzo Bo underwent several architectural changes reflecting the evolving needs of the university.

During the early decades of the sixteenth century, the numerous educational "schools" scattered across the city's neighbourhoods found a unified home in the Palazzo Bo. Situated in close proximity to the traditional street lined with butcher's shops, the building took its name from the sign of the renowned *Hospitium Bovis* (Ox Inn), which occupied one of the noble residences constructed in this area from the late thirteenth century onward. The transformation of these existing structures into spaces for university purposes commenced in 1494 and reached completion in the early seventeenth century.

In the 16th century the renowned architect Andrea Moroni added the famous Anatomical Theatre to the building. This theatre was used for anatomy lectures and demonstrations, making the University of Padua a pioneer in medical education.

During the Napoleonic era in the late 18th and early 19th centuries, the University of Padua underwent significant changes. The Palazzo Bo became the headquarters of the Napoleonic University of Padua for a brief period.

A new phase of renovations for the Palazzo Bo commenced in 1889, culminating in its present-day configuration between 1938 and 1942. This later stage of development included the addition of the New Court, overseen by architect Ettore Fagiuoli under the directive of Chancellor Carlo Anti. The interior decor and furnishings of the refurbished structure were masterminded by the renowned architect Gio Ponti.

The Old Court (*see Figure 29*): Commenced in 1546, this masterpiece is attributed to Andrea Moroni, a preeminent architect of Padua during the mid-sixteenth century. Representing one of the Renaissance's finest architectural achievements, it features a double loggia characterized by two tiers of columns - Doric in the lower order and Ionic in the upper. Adorning the walls and vault of the portico are the coats of arms of rectors and councillors from the *Universitatis Iuristarum* and the *Universitatis Artistarum* spanning the years 1592 to 1688. However, in 1688, the Venetian Republic prohibited further additions to the Bo's memorials, partly to discourage ostentation and partly to prevent the destruction of existing ones. The Great Hall of the university also boasts original crests as part of its adornment.

Figure 29 - Palazzo Bo: the old court

The Great Hall (*see Figure 30*): from the sixteenth to the eighteenth century, this building served as the esteemed venue for "The Great School of Jurists" and hosted academic lectures. Notable figures like Galileo Galilei imparted their knowledge within these walls, leading to the hall being dedicated to his memory. Following a period of use as a drawing studio in the early nineteenth century, the space underwent restoration from 1854 to 1856, transforming into the university's Great Hall. Decorated during this restoration, the ceiling frescoes by Giulio Carlini feature a central allegory portraying Wisdom and other disciplines.

In 1942, architect Gio Ponti undertook renovations, giving the end wall its current appearance. This area now serves as the seating location for the University Senate during significant events such as the commencement of the academic year and the conferral of honorary degrees. Adorning the wall is the university's ancient motto: “Universa Universis Patavina Libertas”.

Figure 30 - Palazzo Bo: the Great Hall

The Sala dei Quaranta (*see Figure 31*): Named for the forty (quaranta) portraits adorning its walls, this gallery showcases distinguished foreigners who once studied at Padua. Painted in 1942 by Giangiacomo dal Forno, these portraits are not intended to be precise likenesses but rather symbolic representations. Among the notable figures depicted are Antonio Augustin, the Spanish ambassador to Philip II and various popes; Michel de L'Hospital, Chancellor of France and adviser to Catherine de Medici; Thomas Linacre, physician to Henry VIII of England and a lecturer at Oxford University; William Harvey, the English physician renowned for his groundbreaking work on the circulation of blood and a key figure in the English medical tradition; Olof Rudbeck the Elder, a Swedish professor of botany, anatomy, and medicine at the University of Uppsala who advocated for the establishment of a botanical garden akin to that in Padua; Thomas Bartholin, a Danish physician pivotal in the advancement of medical education in Denmark; Nicholas of Cusa, a renowned fifteenth-century German philosopher and cardinal; Werner Rolfinck, a German advocate for the study of anatomy and chemistry in his homeland; Peter Vasiljevic Postnikov, a Russian scholar dispatched by Peter the Great to study medicine at Padua; Stefan Báthory, a Hungarian nobleman who ascended to the throne of Poland in 1576; Giovanni Capodistria, a Greek statesman appointed dictator/president of the Greek government in 1828; and Emanuele Sciascian, an Armenian physician at the imperial court of Constantinople who spearheaded the establishment of medical education in Turkey.

In the Sala dei Quaranta, there's also the podium, which legend has it was erected by Galileo's students so he could lecture in the "great hall of jurists," now known as the Great Hall. None of the other chambers were spacious enough to accommodate the large audiences that flocked to his lectures. This podium remained in the Great Hall until the mid-nineteenth century. Galileo taught at Padua University for eighteen years, from 1592 to 1610, a period he later reminisced as one of the happiest of his life. Revered by his students and shielded by the Venetian government, he laid the groundwork for the modern scientific method during his tenure here.

Figure 31 - Palazzo Bo: Sala dei Quaranta

The Medicine Hall and Anatomical Theatre (*see Figure 32*): One of the most ancient and aesthetically pleasing instructional spaces within the building is the Medicine Hall, this room now serves as the venue for public discussions on degree theses presented by students of medicine and other disciplines. While it once hosted lessons in anatomical theory, its origins predate the establishment of the university in this location. The exquisitely preserved coffered ceiling and the characteristic medieval frieze adorning the walls offer glimpses into its storied past. Originally part of one of the three fourteenth-century patrician residences that once graced this site, this room belonged to the Da Carrara family. These structures formed the nucleus of the site later occupied by the *Hospitium Bovis*.

The Anatomical Theatre was constructed in 1594 for the renowned anatomy professor Gerolamo Fabrici d'Acquapendente, this structure is rumoured to have been designed based on suggestions from Fra Paolo Sarpi. It holds the distinction of being the earliest permanent anatomy theatre globally, as prior to its establishment, temporary structures were erected for autopsy attendees. Remarkably, it remains the oldest surviving anatomy theatre to this day (A. Porzionato et al.).

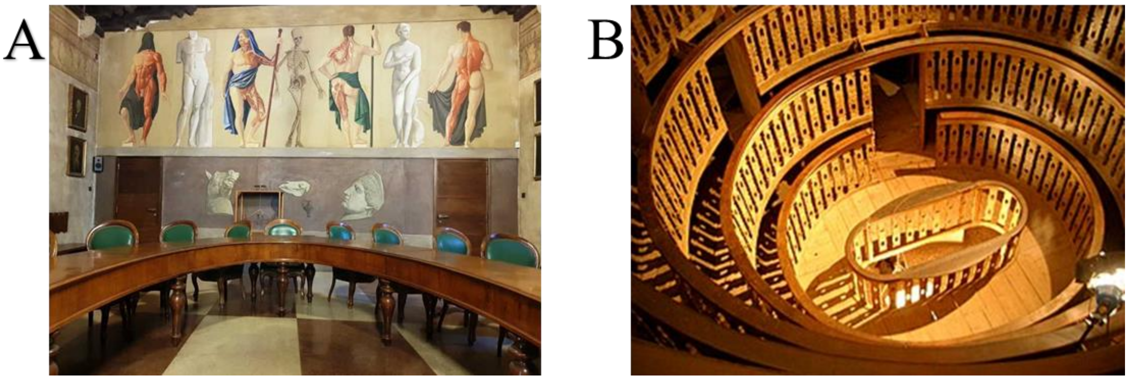

Figure 32 - Palazzo Bo. A: Medicine Hall; B: Anatomical Theatre

Fashioned from wood, the theatre takes the shape of an inverted cone with an elliptical ground plan. It comprises six concentric tiers of seats encircling the central anatomy table. The banisters and balustrades, intricately carved from walnut, add to its aesthetic appeal. Originally, the windows were solid panels, and torches provided illumination during anatomy lessons. It wasn't until 1844, as part of the modifications initiated in 1842, that they were opened up to function as proper windows.

The theatre ceased educational activities in 1872 but underwent restoration in 1991-92. Adjacent to it lies a small room, once utilized for preparing bodies for dissection, now housing an exhibition that sheds light on its storied history.

In conclusion Palazzo Bo stands as a testament to the enduring legacy of the University of Padua and its contributions to education, science, and culture. From its medieval origins to its modern-day significance, it continues to inspire generations of scholars and visitors alike.

3.2 Coats of Arms

The Old Courtyard and various rooms of Palazzo Bo are adorned with over three thousand heraldic coats of arms (*see Figure 33*), depicted in frescoes and carved in stone. These coats of arms represent students who held prestigious academic positions, such as rectors of the two *Universitates*, their deputies, council members, and captains of the *nationes* (student nations). Their presence reflects the diverse and rich cultural geography that shaped the student body, influenced by pan-European interactions. Students were organized into *nationes* based on their ethnic and geographic origins, further divided into groups known as *Citramontani* and *Oltramontan*i.

In the university's early days students wielded significant administrative power, including approving statutes, electing rectors and selecting professors.

The oldest frescoed coats of arms, dating back to the late sixteenth century, adorn the vaults. Initially painted by Francesco Falzapato, they were later redone by the painter Dario Varotari between 1581 and 1590.

The coats of arms were created between the mid-sixteenth century and 1688, the year during which the Venetian Republic discontinued the practice due to architectural issues.

Figure 33 - Coats of Arms

Chapter 4: 3D Reconstruction of a wall of coats of arms at Palazzo Bo

This thesis centres on the scanning of selected coats of arms located in Palazzo Bo, with a particular emphasis on those adorning the Great Hall (refer to *Figure 3*. This decision was strategically made to mitigate challenges associated with the fluctuating weather and lighting conditions that could affect the scanning process. By focusing on indoor locations such as the Great Hall, where environmental factors can be more controlled, the accuracy and consistency of the scanning results can be ensured.

Figure 34: Coats of Arms of the Great Hall

The project delves into preserving and democratizing access to cultural heritage, in fact we aim to reconstruct and recreate through a 3D printer a sort of reduced wall of Coats of Arms which people can explore through touch.

The decision to employ 3D printing technology to reproduce these coats of arms is then purposeful: not only it provides a tangible representation of these historical symbols, but it also opens up avenues for exploration, especially for visitors with visual impairments.

The first step of this project was to visit Palazzo Bo and choose an emblematic object which could represent best the museum and at the same time talk to the museum's staff in order to understand which were the needs of the visually impaired who visited the museum.

Following our initial discussion, we concluded that utilizing coats of arms was the most suitable choice for this project, primarily for two reasons:

1. Coats of arms are omnipresent throughout the museum, adorning every wall and hall, so they are the most distinctive and prevalent feature.
2. The museum staff faced challenges in articulating the significance of the coats of arms to visually impaired visitors.

After selecting the most emblematic objects for our project, we convened for another meeting to decide which coats of arms to scan. We opted for the coats of arms located in the Great Hall, as we noticed ample access to power outlets for our 3D scanners and PCs in that area. Additionally, architects assessed the lighting conditions in the Great Hall to ensure they were ideal for seeing the coats of arms accurately.

In the following, we will describe the tools and the acquisition process.

4.1 3D scanning tools

We settled on two different 3D scanners which both utilise structured light technology: they project a light pattern onto an object through a specialized projector and then they detect the reflected light utilising cameras. These 3D scanners are non-contact measurement tools that transform pairs of images (one for each camera) into surface information through a point cloud.

EinScan Pro HD

The first 3D scanner we used is the EinScan Pro HD (Shining 3D, Hangzhou, China), a multifunctional handheld structured light 3D scanner (*see Figure 35*). It can capture the point cloud simply by manually moving the device while projecting the light pattern onto the surface to be evaluated, automatically aligning the newly acquired points with the already detected cloud, or by moving the object while the scanner remains stationary.

Figure 35 - EinScan Pro HD

At the bottom, the scanner features a projector, positioned at the centre, and two cameras placed at the extremes of the projector. Each camera is positioned in the centre of four bright LEDs. In the back (*see Figure 36*) the scanner has two buttons for exposure adjustment and a button with the *play* logo, which with a single click activates the "start and stop" scanning command; with a double click it activates the ability to adjust the exposure using the two buttons just described. The scanner also features a USB port through which a provided camera for texture detection can be connected.

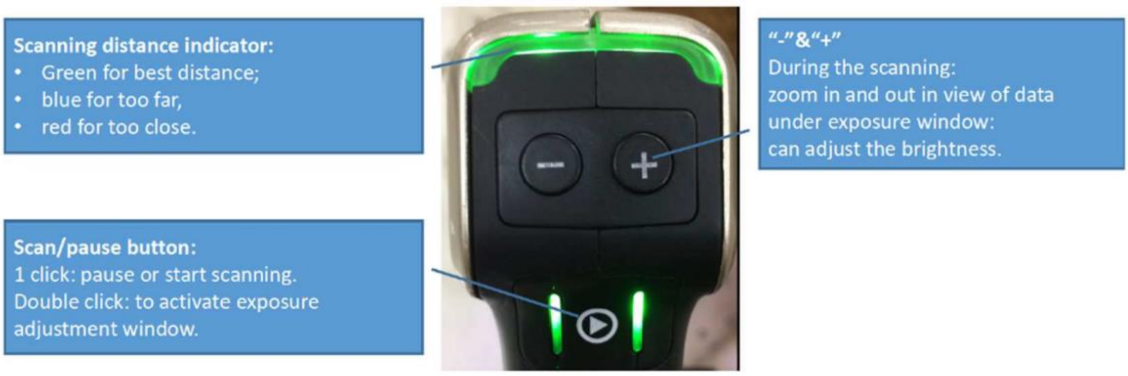

Figure 36 - EinScan Pro HD: detail

The scanner comes equipped with the Industrial Pack accessory, which includes essential tools for efficient scanning. This accessory comprises a tripod, a rotating table, and the necessary power supply. Additionally, circular adhesive markers are provided with the scanner. These markers feature two concentric circles: one inner circle made of reflective material and an outer circle in black. These markers serve as reference points for aligning different shots during the scanning process, particularly useful for objects lacking distinctive features or for scanning large objects.

The accompanying software (*see Figure 37*) of the scanner is ExScan Pro, which allows to manage the scanner's functions and settings. Upon launching the software, it is possible to identify the scanner's functions:

- Handheld HD Scan
- Handheld Rapid Scan
- Fixed Scan

The division between Handheld and Fixed functions indicates that new point acquisition occurs either through manual movement of the scanner or by keeping the scanner stationary while moving the object, usually through the use of the rotating table.

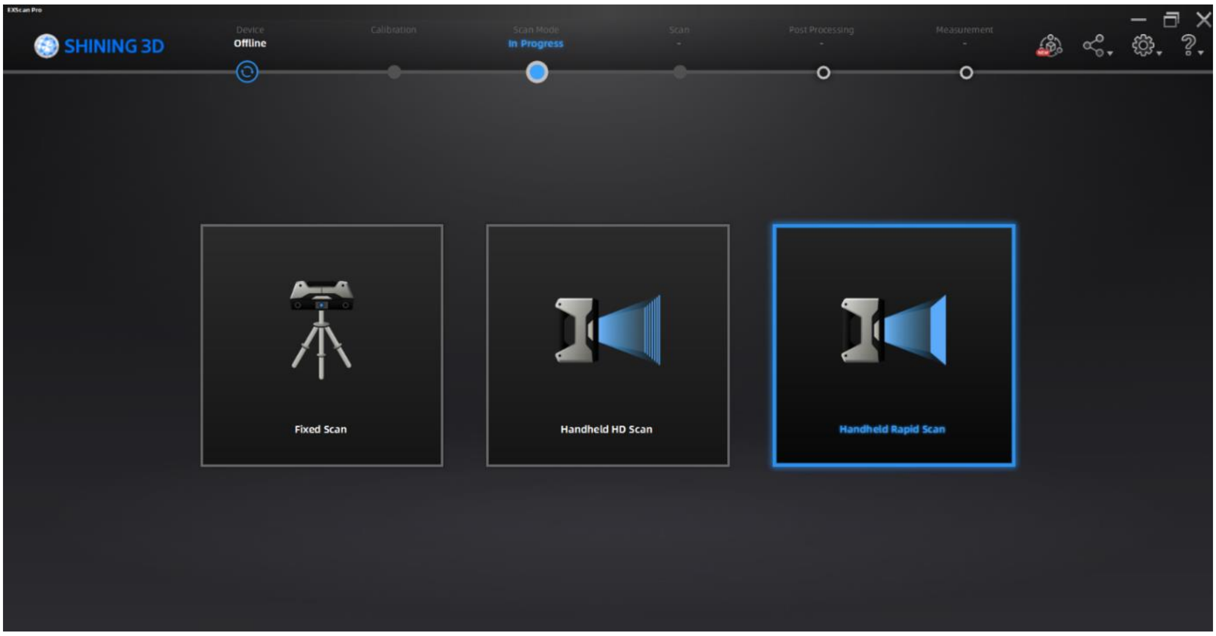

Figure 37 - Preliminary work interface of the EXScan Pro Software

The Handheld HD Scan function allows the tool to achieve a higher accuracy, up to 0.045 mm. The object is sampled at a frequency of 10 fps, capturing 3000 points per second. In High Detail operation mode, this function offers a reduced scanning area compared to others. It is specifically designed to detect objects rich in features and of smaller dimensions.

The Handheld Rapid Scan function is the fastest among the scanner's freehand modes, but it has lower resolution compared to the HD mode. It allows scanning objects ranging in size from 30 to 4000 mm. The maximum scanning accuracy is 0.1 mm.

The Fixed Scan function allows for high resolution (0.24 mm) to detect objects ranging from small sizes (30 x 30 x 30 mm²) to medium sizes. The resolution is fixed and cannot be changed. In this mode, the relative position of the scanner and the objects remains fixed during scanning. To obtain the surface of an object, multiple individual scans are required, which will be aligned later.

Alignment can be achieved through features, markers, or manually through selecting two sets of corresponding points present in two distinct point clouds to serve as reference for alignment, for fixed scanning without a rotating table. Additionally, alignment can be performed using textures.

Revopoint POP 3

The second scanner used is the Revopoint POP 3 (Revopoint 3D Technologies Inc., Shenzhen, China), another handheld structured light 3D scanner (*see Figure 38*). On the front of the scanner there are two cameras for triangulation, one camera for texture and the projector of the light pattern.

Figure 38 - Revopoint POP 3 Scanner

In the back the scanner (*see Figure 39*) features three touch-screen buttons to increase or decrease exposure and to start or pause the scans.

Figure 39 - Revopoint POP 3 key functions

The POP 3 has a single frame precision up to 0.05mm, a scanning speed up to 18fps and a working distance of 150mm-400mm. The main features of this scan are its compact size and compatibility with mobile devices which, together with it being lightweight, make it a powerful and flexible on-the-go tool. In fact the POP 3 comes with a bundle of tools to make it portable: a tripod, a power bank, USB type C cable, 2-in-1 mobile cable and a phone holder.

The Revopoint POP 3 can as well be used manually by moving the device or by moving the object while the scanner remains stationary thanks to the mini turntable which comes with its bundle.

The software accompanying the scanner is Revo Scan (*see Figure 40*), which enables for 3D scanning and for post-processing to generate point cloud, mesh and texture models. When launching the software there are two functions we can choose from:

- Feature mode: designed for scanning objects with distinctive shapes, like sculptures, and readily recognizable features (POP 3D Scanner, User Manual).
- Marker mode: tailored for scanning objects featuring extensive, smooth surfaces or regularly repeating patterns, which might challenge the POP's internal pattern recognition capabilities. Typically, flat planes such as boards or symmetrical objects like balls or bowls are well-suited for scanning with this mode (POP 3D Scanner, User Manual).

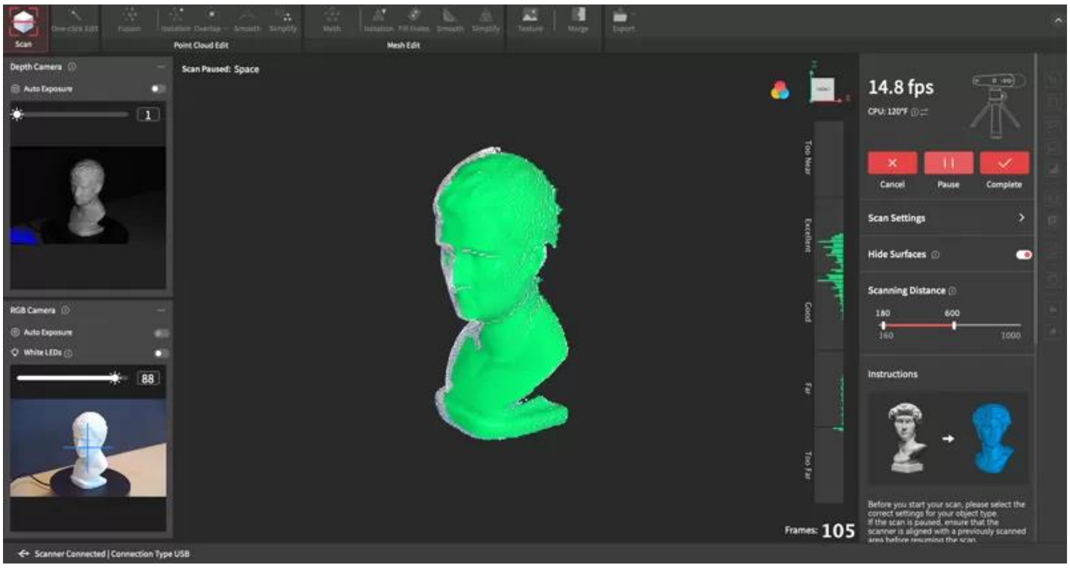

Figure 40 - Work interface of RevoScan 5 software

The main difference between these two devices is their prices, which affect consequently their performance: the EinScan PRO HD costs around 14.000Euro while the Revopoint POP 3 costs about 700Euro.

4.2 Process Pipeline

After the preliminary steps described above the work was divided into four main steps (*see Figure 41*):

1. Data acquisition
2. Post processing
3. Preparing the model for 3D printing
4. 3D printing.

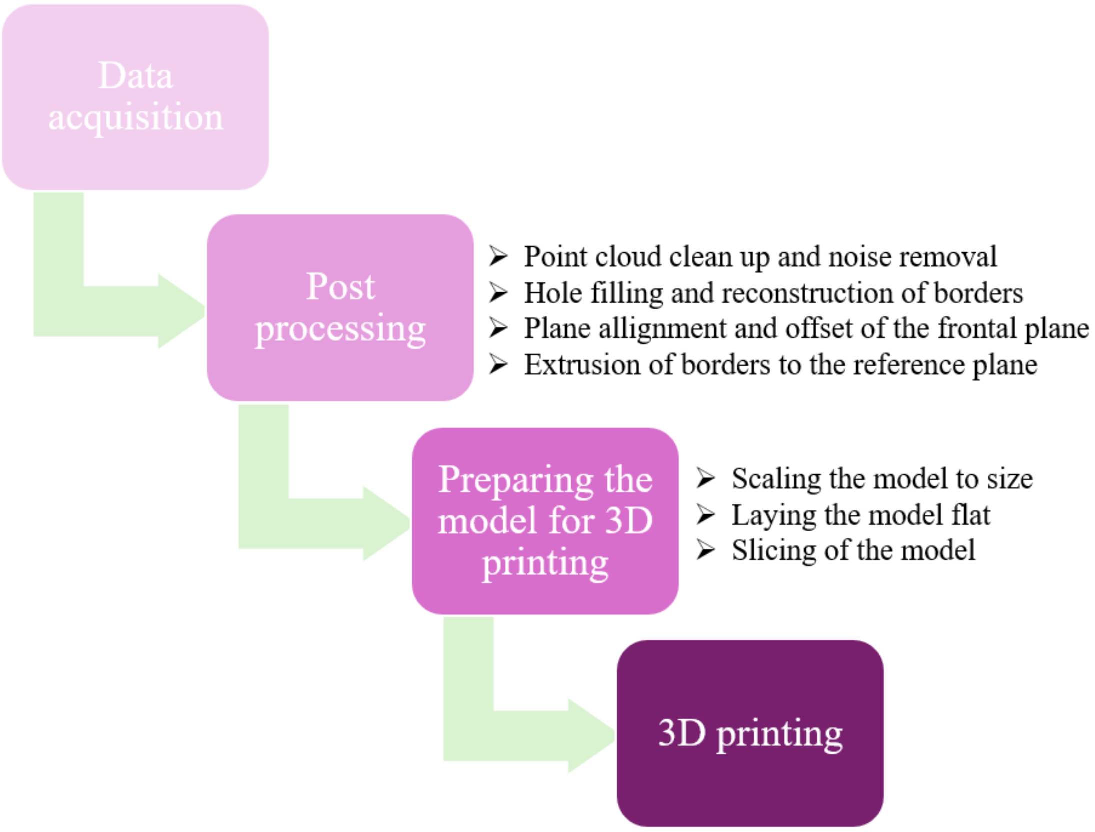

Figure 41 - Process workflow

4.2.1 Data Acquisition

In March 2023, our first data acquisition visit to Palazzo Bo took place (*see Figure 42*). Using the Einscan Pro HD, we obtained data for four coats of arms, while the Revopoint POP 3 was utilised to capture data for three coats of arms. This process took approximately five hours.

Figure 42 - Acquiring visit to Palazzo Bo

Three out of the four coats of arms obtained using the EinScan Pro HD were captured utilizing the Handheld Rapid Scan mode, while one was acquired through the Handheld HD Scan mode.

Following the acquisition phase, the raw data goes through an important step called post-processing. This stage is essential for fine-tuning the data and turning it into a representative mesh that depicts the scanned model accurately. Post-processing has two main goals: mesh optimization and error elimination.

4.2.2 Post Processing

After data acquisition with a structured light scanner, the initial result is a point cloud. This point cloud represents the surface geometry of the scanned object, consisting of a dense collection of points in three-dimensional space. However, to create a surface 3D model, this point cloud must undergo post-processing to transform it into a mesh.

The post-processing stage involves several steps, including noise reduction, point cloud alignment, and surface reconstruction. These processes help to refine the raw data and eliminate any inaccuracies or redundancies.

In this study, the software used for post-processing was Geomagic Design X® (Oqton (3D Systems), Inc., South Carolina, US). Geomagic Design X is a tool designed for converting 3D scan data into editable solid CAD models. It integrates comprehensive tools for point cloud processing, including filtering, smoothing, and alignment, making it possible to handle complex datasets efficiently.

Figure 43 illustrates a raw point cloud acquired using the EinScan Pro HD scanner. Initially, the point cloud included extraneous details not relevant to the main subject, such as parts of the background wall and adjacent sections of another coat of arms. Utilizing the advanced features of Geomagic Design X, these unnecessary elements were meticulously removed. This post-processing step allowed for a cleaner and more focused representation of the coat of arms, highlighting its intricate details without the distraction of unrelated components. The use of Geomagic Design X significantly enhanced the clarity and precision of the final model, ensuring that only the relevant features of the coat of arms were retained and emphasized.

Figure 43 - Raw point cloud acquired with EinScan Pro HD

Figure 44 showcases a clean point cloud of the acquired coat of arms, illustrating the successful removal of noisy clusters.

Figure 44 - Clean point cloud

The next step in the post-processing procedure consists in meshing the point cloud to obtain a “defect-free and watertight model from raw 3D scan data” as reported in the tools menu of Geomagic Design X. Once obtained a mesh model (*see Figure 45 A*) it is necessary to use the Healing Wizard tool which detects abnormal poly-faces in a mesh and cures them. In fact upon aligning and combining 3D scan data that was acquired from many directions using a 3D scanner into a single mesh, anomalous polyfaces such folded polyfaces, dangling polyfaces, and tiny noisy clusters could appear. The Healing Wizard tool is useful in fixing these flaws in order to maximize the mesh. The following action requires filling in missing holes with poly-faces based on feature shapes of the mesh (*see Figure 45 B*).

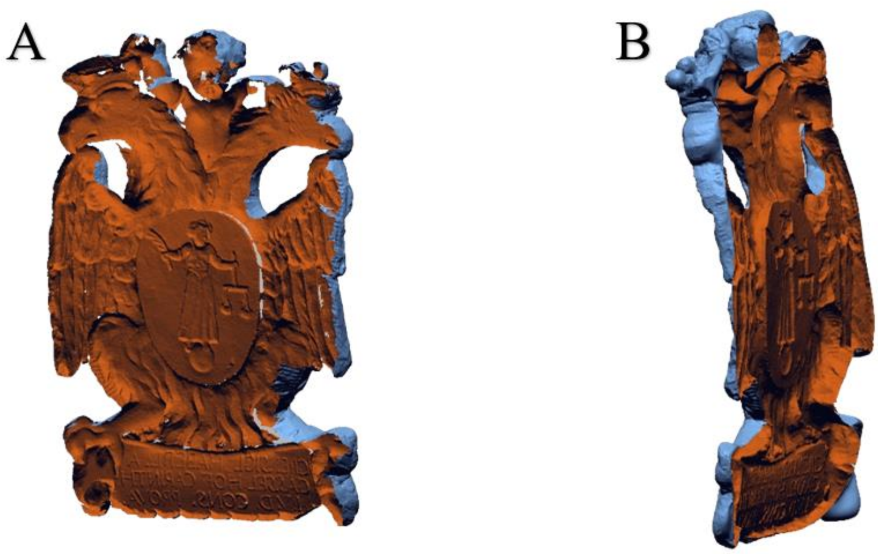

Figure 45 - A: Mesh model; B: Cured mesh model

Figure 46 represents the cured mesh where the Healing Wizard and hole-filling techniques were applied. This process resulted in a smooth and complete mesh, effectively addressing any imperfections and gaps in the original scan, thereby enhancing the overall integrity and accuracy of the model.

Figure 46 - - Final defect and hole free mesh

The next step, after obtaining the watertight mesh model, involves two key tasks. Firstly, it is essential to reconstruct any missing borders of the coat of arms. This step is crucial to ensure that the model accurately represents the original artifact in its entirety. Secondly, the back of the coat of arms must be reconstructed. This portion could not be captured during the initial scanning with the EinScan Pro HD, as the coats of arms are affixed to the walls of Palazzo Bo, preventing access to their rear surfaces. To reconstruct the back of the object it is necessary to align manually the object to the reference coordinates system, this step is critical as it establishes a consistent reference framework for all subsequent modifications. Accurate alignment ensures that the reconstructed sections integrate seamlessly with the existing scanned data. see *Figure 47*.

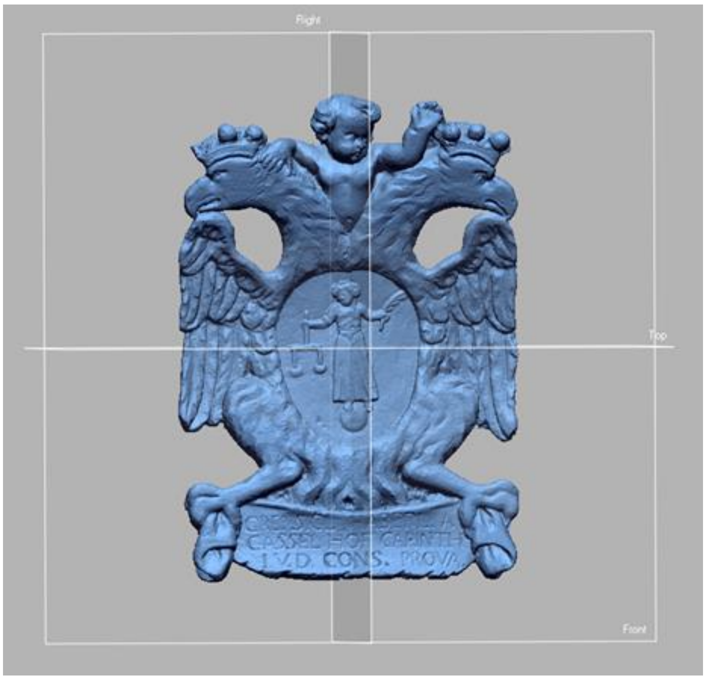

Figure 47 - Aligned mesh to the reference coordinates system

Figure 48 shows the offset of the Front plane. The offset value determines how far the Front plane will be moved away from its original position. This distance is crucial as it must be sufficient to avoid intersecting any of the mesh triangles.

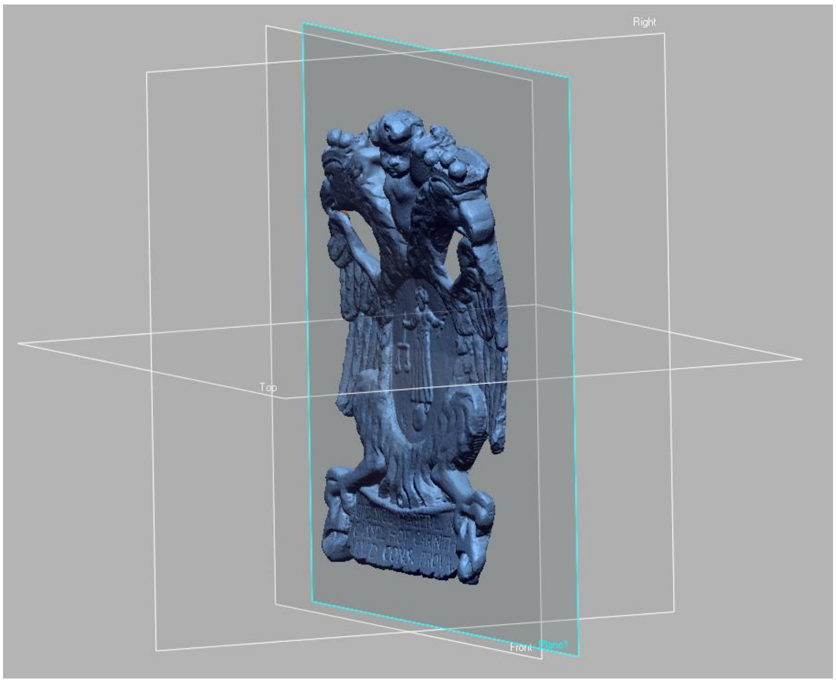

Figure 48 - Offset of the Front plane

Figure 49 shows the final reconstructed coat of arms.

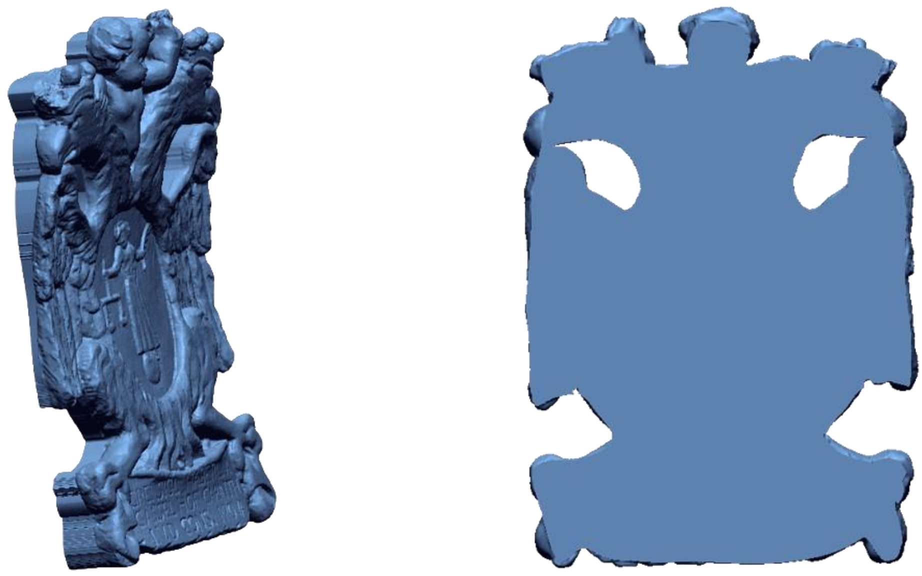

Figure 49 - Reconstructed coat of arms

Figure 50 presents the three additional coats of arms, captured using the EinScan Pro HD and reconstructed using the same methodology described earlier, utilising Geomagic Design X. Notably, there is a discernible difference in the reconstructed back thickness between *Figure 50 B* and *Figure 50 A & C*.

This variation in back thickness is attributed to the distinct hanging positions of each coat of arms. For instance, the coat of arms depicted in *Figure 50 C* is positioned completely parallel to the wall, resulting in a relatively uniform and thin back thickness. Conversely, the coats of arms in *Figure 50 A & B* are more inclined, leading to a thicker back in comparison. This discrepancy highlights the influence of the object's orientation during scanning on the reconstructed geometry, underscoring the importance of accounting for such factors in the reconstruction process to achieve accurate and faithful representations of the artefacts.

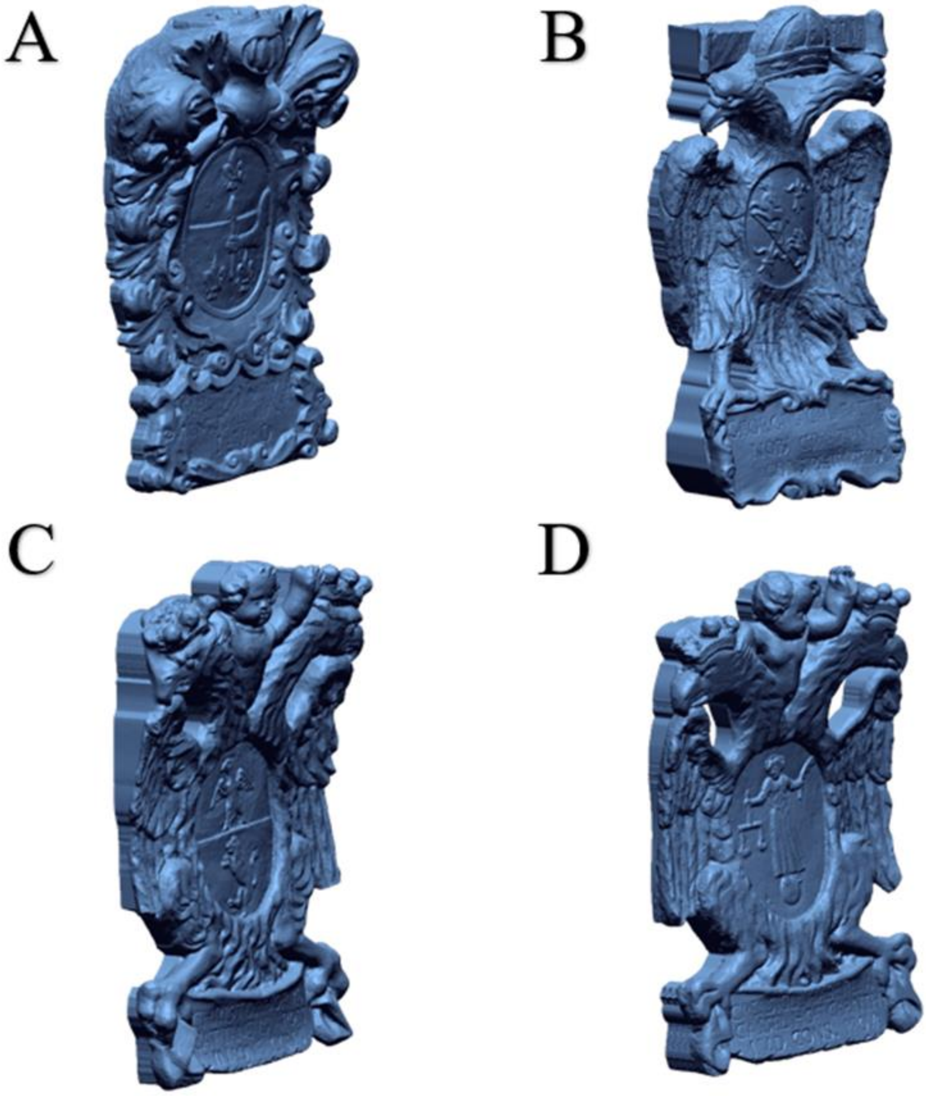

Figure 50 - Fully reconstructed coats of arms with the EinScan Pro HD. A: Stemma 1; B: Stemma 2; C: Stemma 3; D: Stemma 4

Figure 51 shows the fully reconstructed coats of arms scanned with the Revopoint POP 3 using the same process described above for the coats of arms acquired with the EinScan Pro HD.

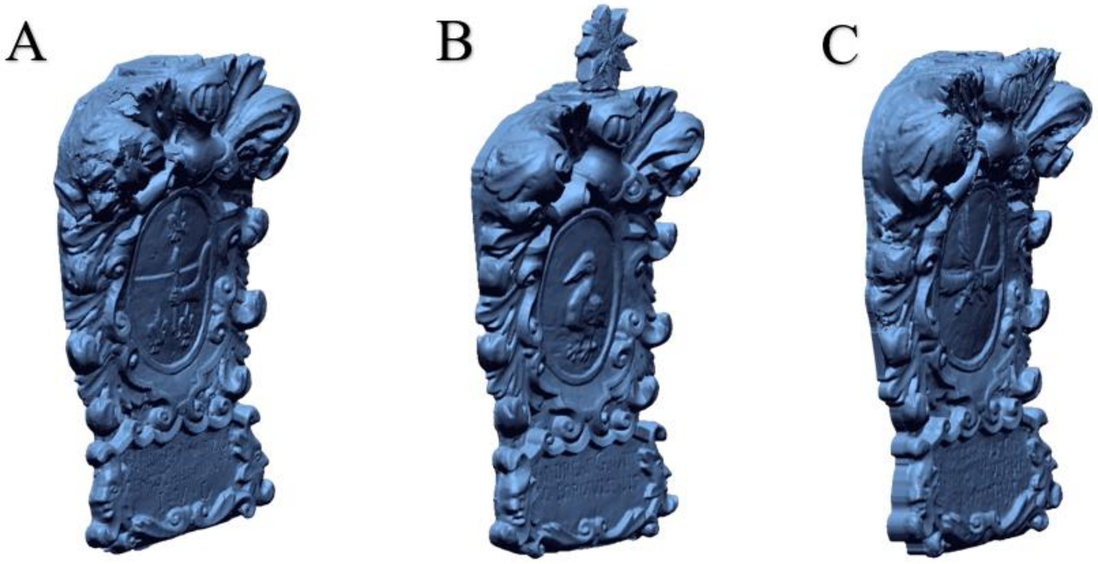

Figure 51 - Fully reconstructed coats of arms scanned with the Revopoint POP 3. A: Stemma A; B: Stemma B; C: Stemma C

Post Processing results

In this section, the results obtained from the acquisition process and post-processing of the acquired data will be presented.

Figure 52 A exhibits a coat of arms scanned utilising the Handheld Rapid Scan, whereas *Figure 52 B* depicts a coat of arms captured using the Handheld HD Scan. As the two scanned objects differ, it is currently impractical to analyse the disparities between the two scanning modes. However, conducting additional acquisitions of the same object would allow for a more accurate assessment of the differences in scan quality, resolution, detail, and other relevant factors between the two modes.

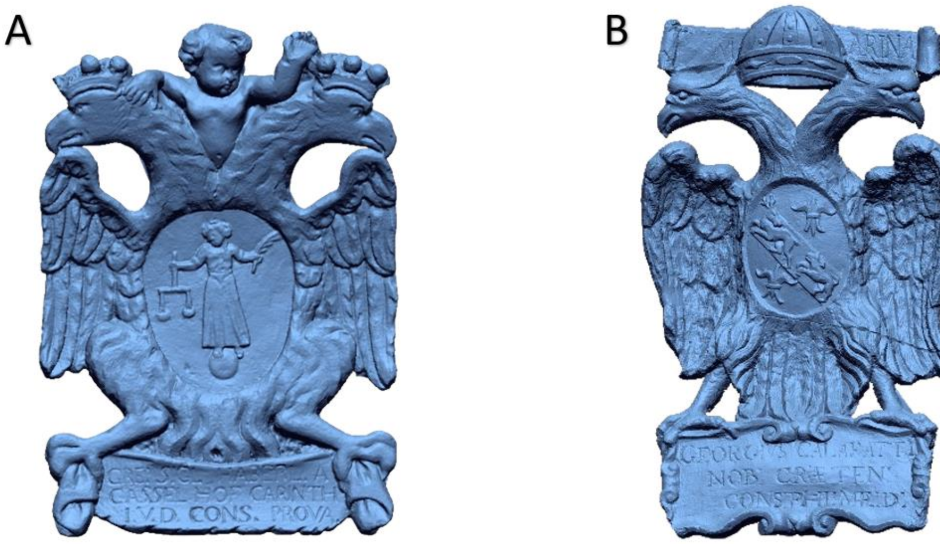

Figure 52 - – A, Stemma 3: Handheld Rapid Scan acquisition; B: Handheld HD Scan acquisition

To better understand the differences between the Handheld Rapid Scan and the Handheld HD Scan, we can compare several key metrics related to the data they produce. Specifically, by examining the number of points in the point cloud of the acquired data and the number of triangles in the final meshes, we can gain insights into the precision and detail each scanning method provides.

The point cloud represents the raw data captured by the scanner, consisting of numerous points in 3D space that outline the surface of the scanned object. A higher number of points in the point cloud typically indicates greater detail and resolution in the captured data.

On the other hand, a higher number of points requires more computational power and time for post-processing, as well as a longer acquisition time.

The final mesh, derived from the point cloud, is composed of triangles that form a continuous surface representation of the scanned object. The number of triangles in the final mesh is a crucial factor in determining the smoothness and accuracy of the 3D model. A higher triangle count generally leads to a more refined and precise mesh, accurately reflecting the intricacies of the original object.

By comparing these metrics for the Handheld Rapid Scan and the Handheld HD Scan, we can assess which method provides higher resolution and better detail, as well as understand the trade-offs between scanning speed and data quality. *Table 1* shows these comparisons, offering a clear view of the performance characteristics of each scanning method.

Table 1 - Number of points and triangles of the Coats of Arms acquired with the Einscan Pro HD (source: Geomagic Design X)

Coat of Arms (Einscan)	Points Cloud (points)	Mesh (triangles)
Stemma 1	941,649	1,463,119
Stemma 2	6,284,169	8,666,750
Stemma 3	955,344	1,489,891
Stemma 4	946,244	1,556,750

Stemma 1, Stemma 3, and Stemma 4 were all acquired using the Handheld Rapid Scan mode, whereas Stemma 2 was scanned using the Handheld HD Scan mode. The differences in the data captured by these two modes are quite significant and highlight the varying levels of detail and resolution provided by each scanning method.

Stemma 2, which was scanned with the Handheld HD Scan mode, is composed of 6,284,169 points. This high number of points indicates a very detailed and high-resolution capture of the scanned object. In comparison, Stemma 1, Stemma 3, and Stemma 4, all scanned with the Handheld Rapid Scan mode, each contain approximately 950,000 points. This lower point count suggests that while the Rapid Scan mode is faster and captures less detail than the HD Scan mode.

In terms of the final mesh, the number of triangles also reflects the difference in detail and resolution between the two scanning modes. The mesh of Stemma 2 consists of 8,666,750 triangles, resulting in a highly detailed and accurate 3D model. On the other hand, the meshes of Stemma 1, Stemma 3, and Stemma 4 each have around 1,500,000 triangles. Although this is still a significant number, it indicates that the Rapid Scan mode produces a less detailed mesh compared to the HD Scan mode.

In fact, after trying the Handheld HD Scan mode we noticed that the points cloud post processing of the Exscan PRO Software was extremely time consuming (> 30 minutes). We consequently decided to adopt the Handheld Rapid Scan mode for the remaining two coats of arms which can be observed in *Figure 53*.

Figure 53 - Coats of Arms acquired with the Handheld Rapid Scan mode.

Other three coats of arms were acquired with the Revopoint POP 3 (see *Figure 54*).

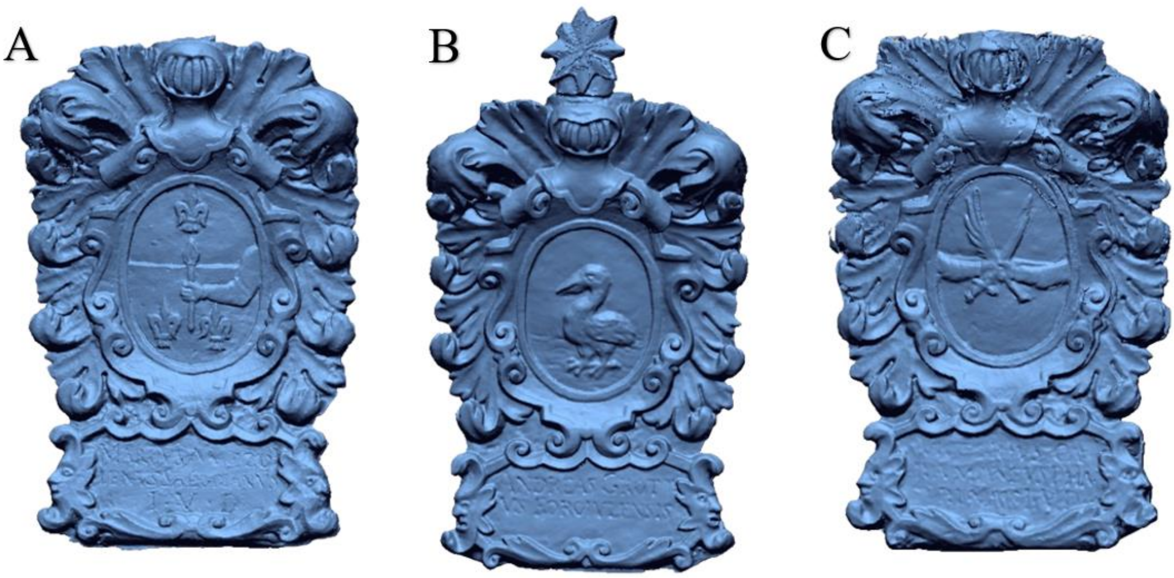

Figure 54 - Revopoint POP 3 acquisition. A: Stemma; B: Stemma B; C: Stemma C

A primary challenge encountered when using the Revopoint POP 3 was the manual acquisition process, which required the operator to maintain a high level of stillness throughout the object acquisition; this requirement directly impacted the acquisition time.

In *Figure 55*, some examples illustrate errors resulting from impromptu or rapid movements made by the operator during the acquisition process. These errors manifest as duplicated surfaces and a loss of fine details within the scanned objects.

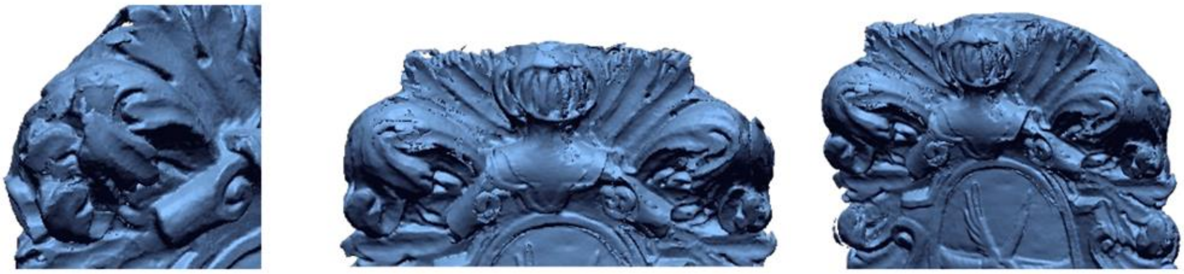

Figure 55 - Examples of errors made with the Revopoint POP 3

Despite the inherent challenges of the manual acquisition, the Revopoint POP 3 managed to yield satisfactory results, largely attributed to the sophisticated capabilities of its accompanying software, Revoscan 5. This software played an important role in refining the acquired data, significantly enhancing the overall quality of the scanned objects. *Figure 53* showcases the stark disparity between the initial RAW data (*Figure 56 A*) and the meticulously processed output achieved through the Revoscan 5 software (*Figure 56 B*). This transformation underscores the software's effectiveness in optimizing scans, thereby elevating the level of detail, accuracy, and overall fidelity of the captured imagery.

Figure 56 - A: Raw Data acquired with the Revopoint POP 3; B: Refined Data by Revoscan 5 software.

Table 2 highlights the number of points in the point clouds and the number of triangles in the meshes generated by the Revopoint POP 3. When comparing these values with those in *Table 1*, which presents the corresponding data for the EinScan Pro HD, a significant difference becomes apparent.

Table 2 - Points and triangles of the Coats of Arms acquired with the Revopoint POP 3 (source: Geomagic Design X

Coat of Arms (POP 3)	Points Cloud (points)	Mesh (triangles)
Stemma A	558,870	1,080,209
Stemma B	614,255	1,896,255
Stemma C	647,394	1,959,020

The points acquired with the EinScan Pro HD in Handheld Rapid Scan mode are nearly double those captured with the Revopoint POP 3. This disparity clearly demonstrates that the EinScan Pro HD is capable of capturing much finer details than the Revopoint POP 3. In fact, the higher number of points in the point cloud translates to a more detailed and accurate representation of the scanned object. In practical terms, this means that the EinScan Pro HD can capture intricate features and subtle textures that the Revopoint POP 3 might miss.

We can also compare Stemma A, acquired with the Revopoint POP 3, and Stemma 1, acquired with the EinScan Pro HD (*see Figure 57*).

Figure 57 - A: Stemma 1 scanned with the Einscan Pro HD; B: Stemma A scanned with the Revopoint POP 3

Figure 57 presents a detailed comparison between Stemma 1, acquired with the EinScan Pro HD, and Stemma A, acquired with the Revopoint POP 3. Both of these coats of arms were scanned with texture, which enhances the analysis by providing additional visual information.

One of the most noticeable differences is the colour of the texture. Despite both scans being conducted under identical lighting conditions, the textures differ significantly. This suggests that the EinScan Pro HD and the Revopoint POP 3 handle colour data differently, with the EinScan Pro HD likely providing more accurate colour representation.

Another significant difference is the presence of acquisition errors in Stemma A, scanned with the Revopoint POP 3. The errors are quite evident in the higher part of the coat of arms which appears almost doubled in that area. This issue arises because manual scanning with the Revopoint POP 3 is challenging in fact the operator must maintain a very steady hand to avoid such errors. The difficulty in keeping the device stable during manual scanning leads to overlapping or duplicated points in the data, resulting in the distorted appearance of the scanned object.

At the same time Stemma 1, acquired with the EinScan Pro HD, shows more precise and detailed features. This is particularly evident in the lower part of both the coats of arms, where the inscribed text is much clearer in Stemma 1 than in Stemma A. This higher level of detail captured by the EinScan Pro HD is indicative of its superior scanning capabilities, which include better point cloud density and more accurate texture mapping. These features make the EinScan Pro HD more suitable for applications requiring high precision and detail, such as heritage preservation. Furthermore, the differences in the scanning quality between the two devices highlight the importance of choosing the right equipment for specific tasks. While the Revopoint POP 3 may be sufficient for simpler, less detail-oriented projects, the EinScan Pro HD proves to be the better option for tasks that demand a high level of accuracy and detail. This comparison underscores the importance of understanding the strengths and limitations of each 3D scanning device to achieve the best possible results in various applications.

4.2.3 Preparing the model for 3D printing

In order to print the 3D models of the coats of arms it was decided to adopt two different additive manufacturing technologies:

- fused deposition modelling (FDM), a material extrusion technology;
- stereolithography (SLA), a vat photopolimerisation technology.

In FDM (Fused Deposition Modelling), a thermoplastic polymer filament is fed into an extruder, which contains a heater to melt the filament. The filament is drawn inward using a pinch feed mechanism and then extruded as a molten bead of material through a circular nozzle. The movable FDM head proceeds to deposit the extruded material layer by layer onto a substrate via the nozzle (S. R. Subramaniam et al. 2019).

To achieve a 3D print of desirable dimensions, the FDM (Fused Deposition Modeling) technology was chosen, employing the Creality CR-10 Smart Pro 3D (18F, JinXiuHongDu Building, Meilong Blvd., Longhua Dist., Shenzhen, China) printer. This printer is distinguished by its generous print size of 300x300x400mm, offering a printing precision of ±0.1mm, and supporting nozzle diameters of 0.4mm or 0.6mm. For this project, Ultimaker Cura® (Ultimaker

B.V., Utrecht, Netherlands) was selected as the slicing software to prepare the model for printing.

The initial step involves importing the 3D model into the Cura software. A scaling factor of 0.4 is then applied to adjust the size accordingly. Subsequently, the model needs to be oriented and positioned onto the build plate to ensure optimal printing (*see Figure 58*).

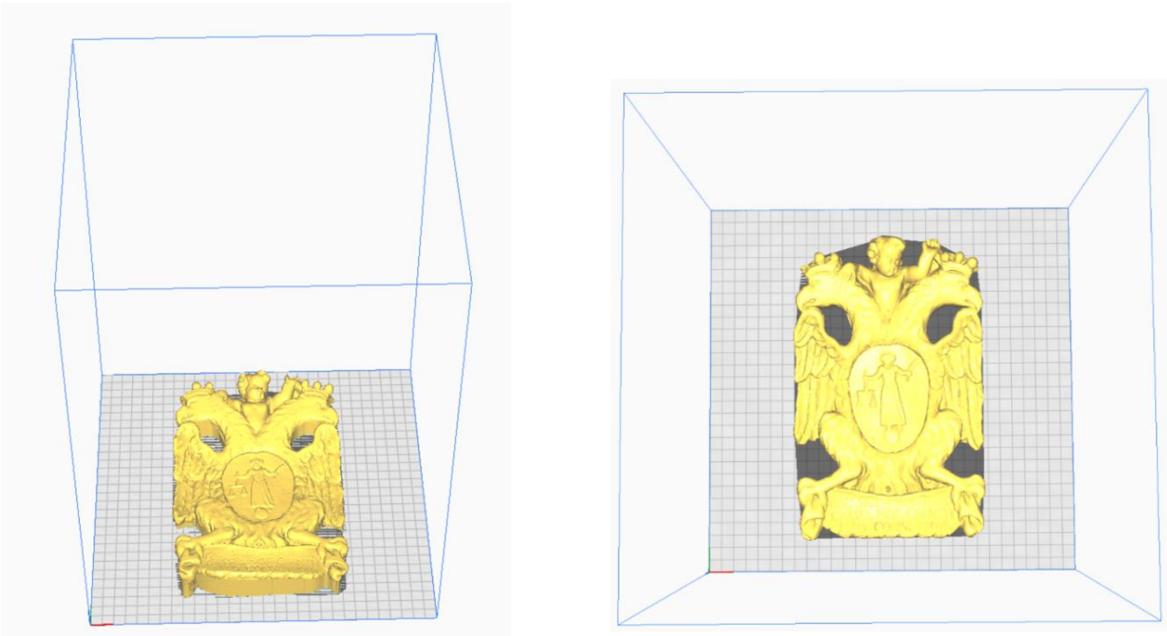

Figure 58 - 3D model positioned onto the built plate of the 3D printer

After having oriented the model on the built plate it is necessary to understand if it has overhangs or areas that require support during printing, if so, it is needed to add support structures using the support generation tool in Cura and to adjust the support settings as necessary to optimize support placement and density (*see Figure 59*).

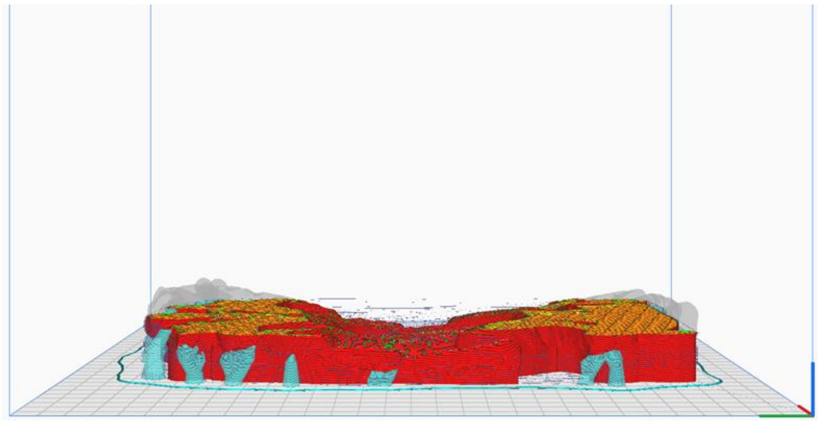

Figure 59 - Printing supports

The next step is to choose the appropriate print settings based on the printer, filament and desired print quality. The filament chosen for this project is PLA (pure Polylactic Acid). PLA stands as the predominant raw material in extrusion-based 3D printing, particularly in fused deposition modelling (FDM) approaches. Its popularity stems from its biodegradability and environmentally friendly nature. However, PLA does have limitations, including mechanical weakness and a certain rate of water solubility, which restricts its application in certain areas (E. H. Tümer et al. 2021). Given this information the parameters chosen include a layer height of 0.2mm and an infill density of 15%.

The last stage of this process is reviewing the slice preview to ensure that the model slices correctly and that tere are no errors or issues with the print layers (*see Figure 60*).

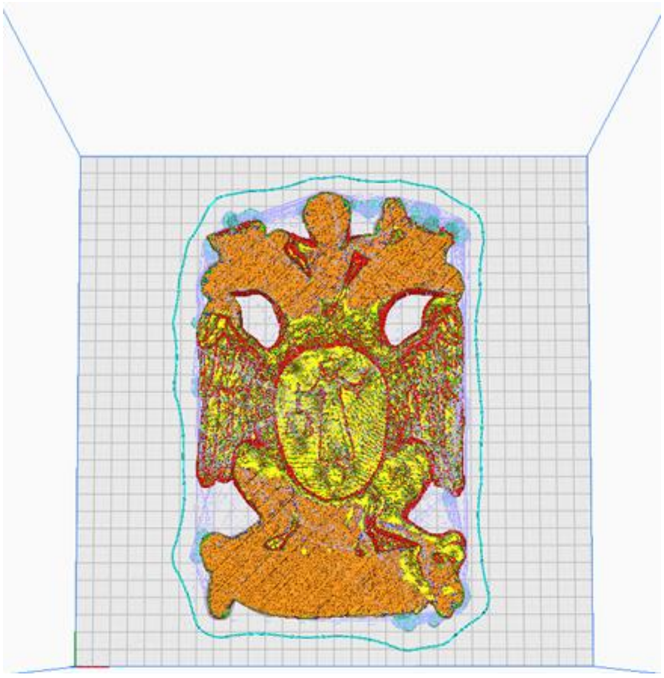

Figure 60 - Slicing of the model

Once the slicing is considered correct the printing can be launched, during this phase the printing time is shown, the total time reacquired for our project is 1 day 1 hour and 11 minutes (*see Figure 61*).

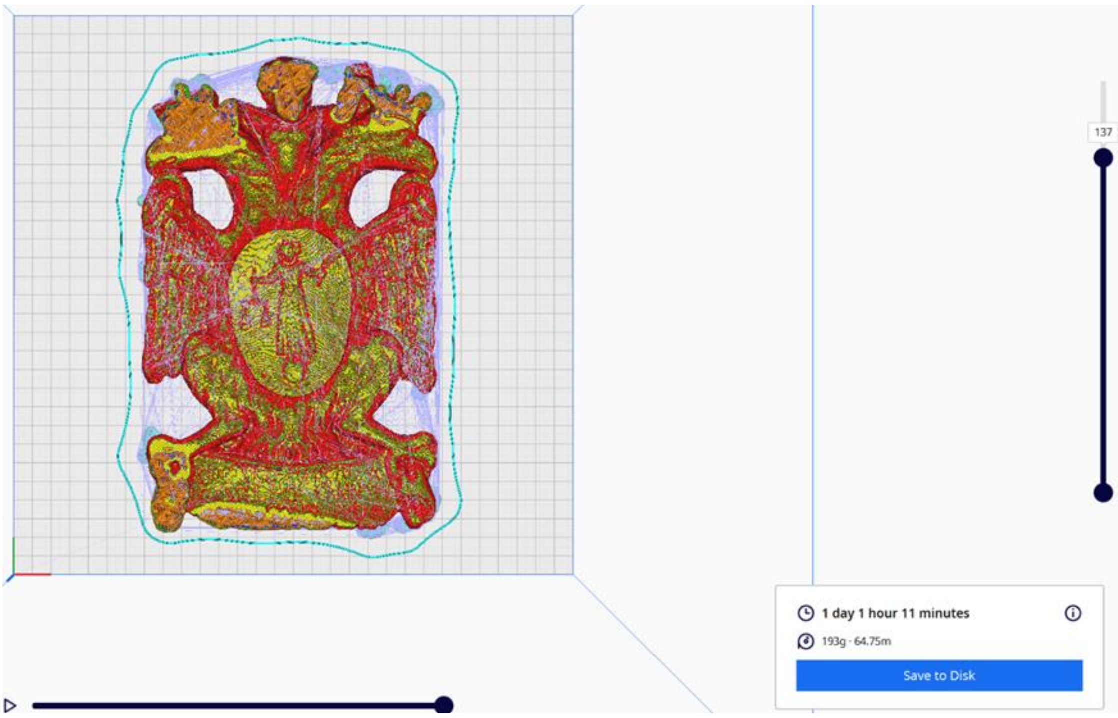

Figure 61 - Launching of the print

Following the printing of the full version of the coat of arms, it was determined that printing additional details would enhance readability. Specifically, the decision was made to print the middle part and the text underneath separately with a SLA 3D printer, the Formlabs Form 3 (Formlabs Inc., Somerville, Massachusetts, US).

SLA (stereolithography) operates as a vat polymerisation method, wherein layers of a liquid precursor contained in a vat are successively exposed to ultraviolet (UV) light, causing selective solidification. Within the resin, a photoinitiator (PI) molecule reacts to incoming light and, upon irradiation, triggers a localized chemical polymerisation reaction. This reaction results in curing solely in the areas exposed to UV light. Following the development of the initial layer in this manner, a fresh resin film is applied, irradiated, and cured. Consequently, the part grows incrementally, layer by layer, through this process (C. Schmidleithner et al. 2018).

The Formlabs Form 3 is characterised by a laser spot size of 85 microns, by a build volume of 145x145x185mm and a layer thickness of 25-300 microns. In order to prepare the model for printing the PreForm® (Formlabs Inc., Somerville, Massachusetts, US) software was used.

The first step requires importing the 3D model in the software and orienting and positioning it on the build platform in a way that minimizes the need for supports and ensures the best surface finish. Preform only allows the user to set one parameter, being it the layer height, chosen in our case of 0.1mm. PreForm automatically generates support structures for the model based on its geometry and orientation but users can customize support structures manually if needed (*see Figure 62*).

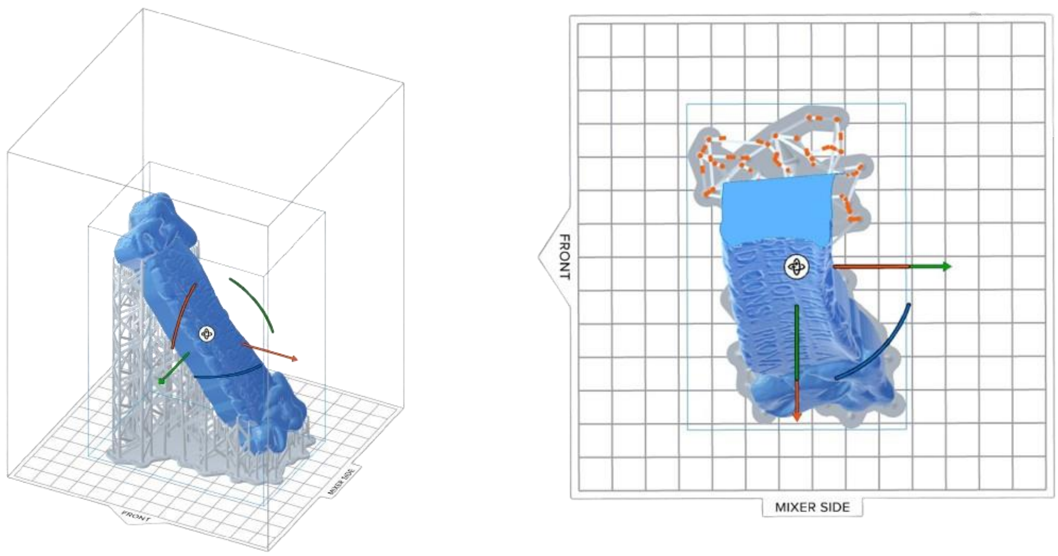

Figure 62 - Creation of support structures

Figure 63 displays the model, prepared for printing and characterized by the use of Grey v4 resin. This resin variant is well-suited for general-purpose prototyping and design, particularly for models demanding intricate details, similar to ours. Additionally, the figure indicates the estimated printing time required for this specific model.

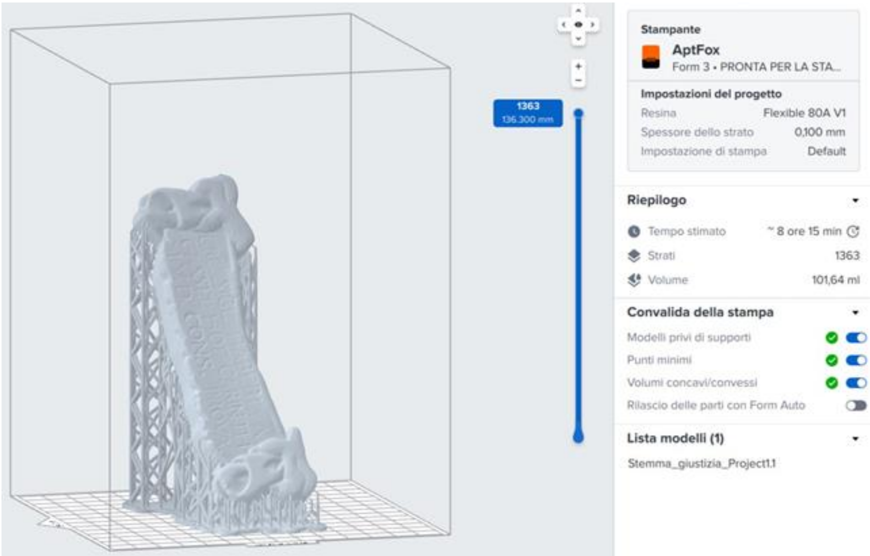

Figure 63 - Final model ready for printing

The same process was followed for the preparation of the printing of the 3D model of the middle part of the coat of arms (see *Figure 64*).

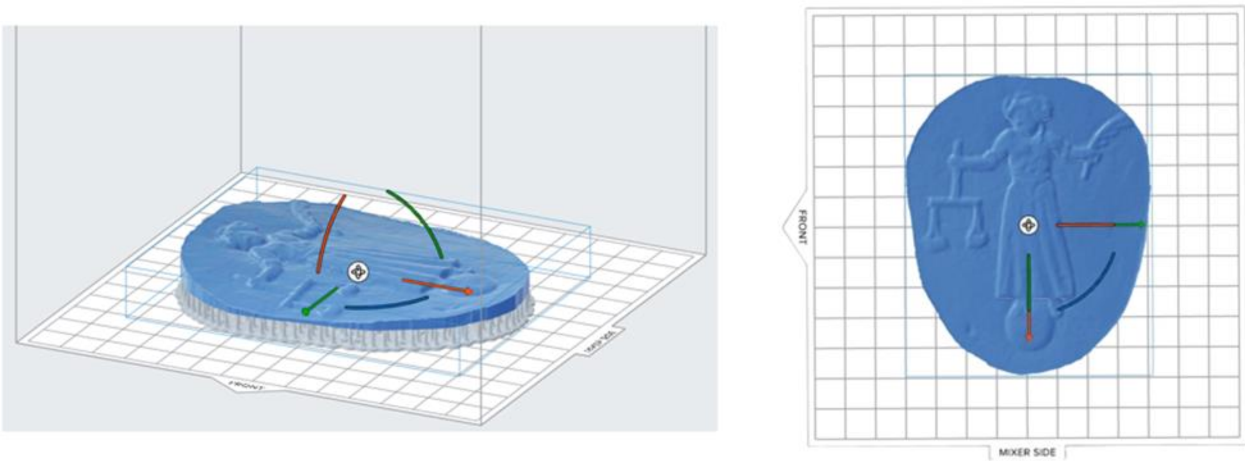

Figure 64 - Preparation for printing of the middle detail

4.3 3D printing

The total 3D model of the coat of arms was printed with the Creality CR-10 Smart Pro and white PLA, *Figure 65* shows the first layer which is critical for the adhesion of the following layers. The printing process starts with the outline shape of the model and the description of the supports.

Figure 65 - Beginning of the printing

Figure 66 shows the final printed coat of arms.

Figure 66 - Final printed model

Given the fact that the total version printed model presents some inaccuracies in the most detailed areas as shown in *Figure 67 A & B*, it was decided to proceed with the printing of these areas with the SLA technology.

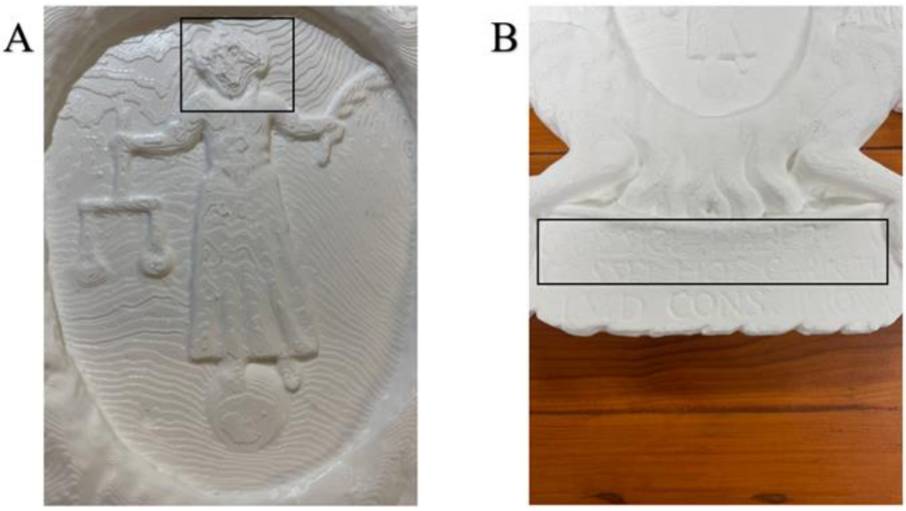

Figure 67 - Inaccuracies of the FDM print

In order to enhance detail clarity of the details (the central figure and the text beneath it) the Formlabs Form 3 printer was employed. Following completion of the printing process, the object must be detached from the build platform and immersed in a solvent to eliminate any residual uncured resin. Subsequently, to achieve full hardening, the model undergoes a final curing step under UV light.

Figure 68 showcases the post-processing pipeline required by the Formlabs Form 3 for the printed 3D model of the written text detail:

i. *Figure 68 A* represents the fresh finished printing;
ii. *Figure 68 B* shows the removal of the built plate from the 3D printer in order to allow the detachment of the model;
iii. *Figure 68 C* shows the Form Wash, a device which allows efficient cleaning of printed parts using isopropyl alcohol (IPA) or alternative solvents to remove uncured resin from the printed parts;
iv. *Figure 68 D* represents the Form Cure, an oven which provides controlled heating and UV light exposure to maximize material properties, like strength and performance for stereolithography prints.

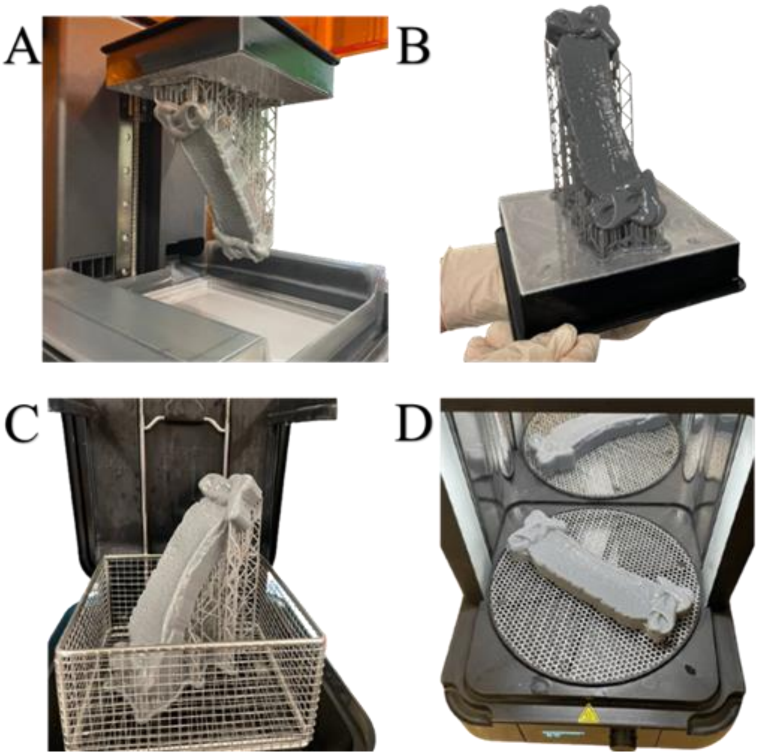

Figure 68 - Post-processing pipeline of the Formlabs Form 3

The identical post-processing procedure outlined earlier was also applied to refine the detail of the central figure, as depicted in *Figure 69*:

i. *Figure 69 A* shows the finished printed model and first mechanical cleaning needed to remove the excess of resin;

ii. *Figure 69 B* showcases the Form Wash, the cleaner which uses isopropyl alcohol (IPA) to better clean the printed parts;

iii. *Figure 69 C* represents the Form Cure, Supplies the essential light and heat required to effectively post-cure 3D printed components, enhancing them to their peak performance properties.

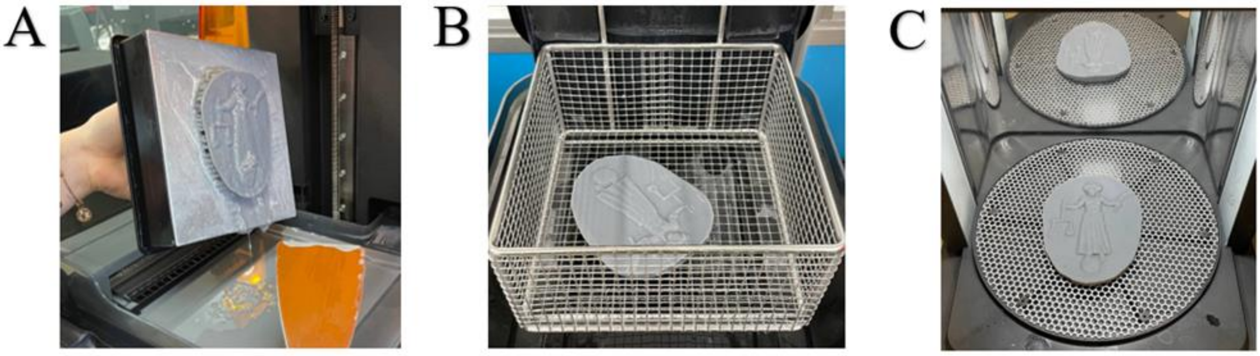

Figure 69 - Post- processing pipeline of the Formlabs Form 3

Chapter 5: Preliminary survey on the project feasibility

The following is a preliminary survey designed for two individuals with visual impairments who volunteered to provide initial feedback for this project. Their valuable insights will help inform and guide the development of the project, ensuring that it meets the needs and preferences of visually impaired individuals effectively. Through their participation, we aim to gather valuable feedback on various aspects of the project, including the comprehensibility and readability of the 3D reconstructions, the utility of different printing technologies, and the overall impact of the initiative on their visit experience. Their input will play a crucial role in refining and enhancing the project to create a more inclusive and accessible environment for all visitors, regardless of visual ability. We appreciate their willingness to participate and contribute to this important endeavour.

1.DEMOGRAPHIC INFORMATION:	
Age	
Gender	
Level of visual impairment	

2.COMPREHENSION OF THE OBJECT:
To what extent were you able to understand the structure and details of the coat of arms through its 3D representation? ☐ Very understandable ☐ Understandable ☐ Neutral ☐ Somewhat understandable ☐ Not very understandable

3.READABILITY OF THE COAT OF ARMS:
Please rate the readability of the reconstructed coat of arms based on your tactile experience. ☐ Very readable ☐ Readable ☐ Neutral ☐ Somewhat readable ☐ Not very readable

4.UTILITY OF THE INITIATIVE:
Do you find it useful to create 3D representations of coats of arms at Palazzo Bo for visually impaired individuals? Considering the guided tour, how much do you think knowing about and touching these representations can change the visit experience? ☐ Very useful ☐ Useful ☐ Neutral ☐ Somewhat useful ☐ Not useful

5.TACTILE PERCEPTION OF PRINTING LAYERS:
Were you able to distinctly perceive the different printing layers through touch? ☐ Yes, the printing layers are distinct and perceptible ☐ The printing layers are distinguishable but difficult to perceive ☐ Neutral ☐ The printing layers are indistinct and difficult to perceive ☐ No, I could not perceive the printing layers

6.INFLUENCE OF PRINTING LAYERS ON READABILITY:
To what extent did the printing layers affect your ability to read or understand the reconstructed coat of arms? ☐ Very influential, significantly hindered readability ☐ Moderately influential, slightly hindered readability ☐ Neutral, did not notice any distraction in readability ☐ Slightly influential, minimally affected readability ☐ Not influential, had no effect on readability

7.UTILITY OF PRINTING CENTRAL DETAILS AND SUBSEQUENT CARTOUCHE WITH OTHER PRINTING TECHNOLOGY:
Did you find it useful to print the central details of the coat of arms and the subsequent cartouche with SLA printing technology to facilitate the tactile perception of the coat of arms? ☐ Very useful ☐ Useful ☐ Neutral ☐ Somewhat useful ☐ Not useful

8.PERCEPTION OF DIFFERENCES BETWEEN FDM AND SLA PRINTING:	
Did you notice any differences in tactile perception between a coat of arms printed using FDM (Fused Deposition Modelling) and one printed using SLA (Stereolithography)? ☐ Yes, I noticed differences ☐ No, I did not notice any differences	
If you noticed differences, what are they?	

9.INFLUENCE OF PRINTING SIZE:
To what extent did the size of the printed coat of arms influence your perception and understanding? □ Very influential, size significantly influenced perception and understanding □ Moderately influential, size slightly influenced perception and understanding □ Neutral, size had no influence on perception and understanding □ Slightly influential, size minimally influenced perception and understanding □ Not influential, size had no effect on perception and understanding

10.PROJECT FEEDBACK AND SUGGESTIONS:	
Do you have any additional feedback to share regarding the project to create 3D reconstructions of coats of arms at Palazzo Bo for visually impaired individuals? Do you have any suggestions on how to improve the initiative?	

On Wednesday, June 5th, 2024, two individuals with visual impairments participated in our survey, offering preliminary feedback on the project. The survey took place in an office room at Palazzo Bo. Initially, participants were not provided with any information about the objects to assess the understandability of the 3D reproduced Coat of Arms. After noting the inherent difficulty in discerning the objects, additional information and details about the representations were provided to the participants. Initially, the entire 3D reproduction of the Coat of Arms was presented, followed by the presentation of the 3D printed details, aimed at determining their usefulness for enhancing readability. *Figure 70* shows the two participants touching the 3D reproduction of the Coats of Arms.

Below is a summary of their responses:

1.DEMOGRAPHIC INFORMATION:	□ 42, woman, totally blind since birth	□ 41, man, totally blind since birth
2.COMPREHENSION OF THE OBJECT:	□ Not very understandable at first; very understandable after some explanation	□ Not very understandable
3.READABILITY OF THE COAT OF ARMS:	□ Somewhat readable without a guide; very readable with a guide	□ Somewhat readable

4.UTILITY OF THE INITIATIVE:	Very useful	Very useful
5.TACTILE PERCEPTION OF PRINTING LAYERS:	Very influential, significantly hindered readability	No, I could not perceive the printing layers at first, but once I realized they were not part of the Coat of Arms, they became quite distinct
6.INFLUENCE OF PRINTING LAYERS ON READABILITY:	Not influential, had no effect on readability	Moderately influential, slightly hindered readability
7.UTILITY OF PRINTING CENTRAL DETAILS AND SUBSEQUENT CARTOUCHE WITH OTHER PRINTING TECHNOLOGY:	Very useful (centre part)	Very useful (centre part)
8.PERCEPTION OF DIFFERENCES BETWEEN FDM AND SLA PRINTING:	Yes, I noticed differences: the different feel to the touch of the materials	Yes, I noticed differences: the more abundance of printing layers on the FDM prints
9.INFLUENCE OF PRINTING SIZE:	Moderately influential, size slightly influenced perception and understanding	Moderately influential, size slightly influenced perception and understanding
10.PROJECT FEEDBACK AND SUGGESTIONS:	Necessity of explanation of what is being touched	The project holds immense value as it opens up new experiences for visually impaired individuals. Initially, it may be challenging to comprehend what we are touching, but with proper explanation, it transforms into an extraordinary experience

Figure 70 - The participants of the survey touching the 3D reproductions of the Coats of Arms

The survey conducted with visually impaired participants yielded valuable insights into the effectiveness and utility of the 3D reconstruction project for the Coats of Arms at Palazzo Bo. Overall, the feedback was largely positive, with participants expressing appreciation for the initiative's aim to enhance accessibility for individuals with visual impairments. The project was deemed very useful in providing tactile representations of the Coats of Arms, facilitating comprehension and engagement.

However, challenges were also identified, particularly regarding the initial comprehension of the objects and the influence of printing layers on readability. This highlights the importance of clear explanations and tactile differentiation during the tactile experience. Additionally, differences between FDM and SLA printing were noted, suggesting the need for further exploration and refinement of printing techniques to optimize tactile perception.

Despite these challenges, the project was recognized for its potential to significantly improve accessibility to cultural heritage for visually impaired individuals. The feedback underscores the importance of ongoing efforts to innovate and refine accessibility initiatives, ensuring that they effectively meet the needs of diverse audiences. Moving forward, continued collaboration with visually impaired individuals and further refinement of tactile representations will be essential for maximizing the impact and effectiveness of this project.

Conclusions

The reconstruction of the Coats of Arms of Palazzo Bo in 3D is intricately linked to the overarching goal of digitising cultural heritage for enhanced accessibility and engagement. Just as museums are digitising their collections to broaden access and facilitate educational experiences, the 3D reconstruction of these historical artefacts serves a similar purpose. By digitally recreating the coats of arms, individuals who may not have the opportunity to physically visit Palazzo Bo can still engage with and explore these significant symbols of heritage. This accessibility extends to diverse audiences, including those with visual impairments who can benefit from tactile representations or virtual experiences of the coats of arms. Furthermore, the availability of 3D reconstructions facilitates research, education, and preservation efforts related to these cultural artefacts, enriching our understanding and appreciation of history. In essence, the reconstruction of the coats of arms exemplifies the transformative potential of digital technologies in democratising access to cultural heritage and fostering broader societal connections.

Art museums have historically maintained strict controls over the distribution of high-quality images of artworks, aiming to safeguard them from misuse and maintain their integrity and authenticity. This cautious approach reflects a commitment to ensuring that artworks are viewed in appropriate and respectful contexts, protecting their value and meaning. Traditionally, museums have closely managed the reproduction and dissemination of their prized collections, often requiring formal requests and permissions for their use. However, the rise of digital technologies has brought about a paradigm shift, challenging the traditional model of image control. In today's digital age, controlling the flow and reuse of these images has become increasingly challenging. The widespread accessibility of digital platforms has democratized access to art images, allowing broader audiences to engage with museum collections. While this increased accessibility has its advantages, it also poses certain challenges and risks for museums. On the positive side, greater access to high-quality art images allows for broader dissemination of cultural heritage and facilitates educational and scholarly pursuits. It enables individuals worldwide to appreciate and study artworks remotely, transcending geographical and logistical barriers. Additionally, the digital sharing of art images can enhance public engagement with museum collections, fostering a sense of inclusivity and cultural exchange. However, this democratization of access also brings potential risks. The widespread availability of digital images raises concerns about copyright infringement, unauthorized commercial use, and misrepresentation of artworks. Museums must navigate the delicate balance between promoting access to their collections and protecting the rights and interests of artists, donors, and cultural institutions. Overall, while the digital revolution has revolutionized access to art images, museums must adapt their strategies to effectively manage and navigate the complexities of the digital landscape. Embracing innovative approaches to digital engagement while upholding principles of ethical stewardship and cultural preservation is essential for museums in the digital age (M. Sanderhoff, 2013).

The widespread availability of art images online presents both opportunities and challenges for museums. On one hand, it enables greater public engagement and education, allowing people who may not have access to museums in person to experience and learn about masterpieces. However, it also raises concerns about the potential misuse of these images. To adapt to these changes, some museums are re-evaluating their strategies and embracing digital dissemination. By providing open access to high-quality images, museums can enhance their role as cultural institutions in the digital age. This shift involves striking a balance between protecting their collections and promoting broader public engagement and innovative uses of art.

Institutions like the Smithsonian are prioritizing digitization initiatives to improve accessibility to their collections. This includes creating high-resolution images and 3D scans of significant artefacts, not only for preservation purposes but also to enable interactive and educational experiences online. This approach transforms the way audiences interact with museum collections, fostering greater accessibility and understanding (J. Stromberg, 2013).

By embracing digital technology, museums are undergoing a profound transformation, redefining themselves as dynamic hubs of culture and education in the 21st century. Through innovative digital initiatives, these institutions are extending their reach beyond physical walls, engaging audiences worldwide in immersive and interactive experiences. Digital platforms allow museums to showcase their collections in new and dynamic ways, fostering deeper connections with diverse audiences. Moreover, digital technologies enable museums to adapt to changing visitor expectations, offering personalized and accessible experiences that cater to a wide range of interests and abilities.

Museums are now acknowledging the necessity of establishing strong digital infrastructures such as upgrades to management systems and the facilitation of broad digital accessibility. While this transition poses significant challenges, particularly for smaller institutions, it is imperative for maintaining relevance in the contemporary digital landscape (J. Butler, 2017).

Value of the 3D reproduction of The Coats of Arms

In the evolving landscape of digitalisation, the creation of 3D reconstructions of the Coats of Arms holds significant economic value. These 3D reconstructions not only contribute to the preservation and dissemination of cultural heritage but also open up new opportunities for economic growth and sustainability. By digitising Coats of Arms in 3D, Palazzo Bo can attract a wider audience, including virtual visitors from around the world, thereby increasing their visibility and revenue streams. Additionally, 3D reconstructions offer commercial opportunities for licensing and merchandising, as well as collaborations with industries such as tourism, education, and entertainment. Furthermore, the development of expertise in 3D reconstruction technologies can lead to job creation and skill development in areas such as digital modelling, animation, and virtual reality. Overall, investing in the creation of 3D reconstructions of Coats of Arms not only enriches cultural heritage but it could also stimulate economic growth and innovation in the digital age.

At the same time creating a reduced 3D reconstruction of a wall of Coats of Arms of Palazzo Bo for the visually impaired can serve as an innovative economic strategy for diversifying income for several reasons:

i. Enhancing accessibility and inclusivity: by providing 3D models that the visually impaired can touch and feel, Palazzo Bo can make its collections more accessible. This inclusivity can attract a broader audience, including those with disabilities, who may have previously felt excluded from traditional exhibits.

ii. Educational value: schools and educational institutions can utilise these 3D models as teaching aids, providing a tactile learning experience that enhances the understanding of history and art for all students, not just those who are visually impaired.

iii. Economic diversification: developing and selling 3D printed replicas of the coats of arms can open up new revenue streams. These replicas can be sold as souvenirs in museum gift shops or through online platforms.

iv. Grants and Funding: projects that focus on accessibility and inclusivity are often eligible for special grants and funding from governmental bodies and non-profit organizations dedicated to supporting the arts and accessibility. This can bring in additional funding and resources.

v. Collaborations and Sponsorships: partnering with technology companies specialising in 3D printing and design can result in sponsorship deals or collaborative funding. These companies might be interested in showcasing their technology in a real-world application.

vi. Tourism and marketing: promoting Palazzo Bo as accessible to all can attract more tourists, including those with disabilities, as well as their families and support networks. This inclusivity can enhance the institution's reputation and draw in more visitors.

vii. Marketing and public relations: highlighting the institution’s commitment to accessibility can be a powerful marketing tool. Positive media coverage and word-of-mouth recommendations can significantly increase visitor numbers.

viii. Preservation of Heritage: 3D reconstructions help in preserving the details of historical artefacts digitally. This ensures that even if the physical objects deteriorate over time, their detailed replicas remain available for future generations.

ix. Digital archives: Creating digital archives of these 3D models can serve as a resource for researchers and historians worldwide, potentially leading to academic collaborations and increased visibility for the institution.

x. Implementation strategy: in order to use advanced 3D scanning technologies to create accurate models of the coats of arms it could be possible to partner with companies that specialise in 3D printing to produce high-quality tactile replicas.

xi. Interactive exhibits: integrate these 3D models into interactive exhibits where visually impaired visitors can explore the details through touch, accompanied by audio descriptions or Braille information.

xii. Community engagement: engage with the visually impaired community to understand their needs and preferences, ensuring the 3D models and exhibits are user-friendly and truly beneficial.

In conclusion, by implementing a 3D reconstruction project, institutions like Palazzo Bo can not only fulfil their social responsibility towards accessibility but also create new economic opportunities and enhance their cultural value in the community.

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