

Analysing the Impact of Data Quality and Processing Techniques on the Accuracy of Virtual Reconstruction - A Case Study of a Deactivated Grain Milling Factory

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Dissertation presented to the School of Technology and Management of the Polytechnic Institute of Bragança to obtain a master's degree in industrial engineering in the scope of the double diploma with the Evangelical University of Goiás.

Dedication

For my family

Mother, father, sister, and grandparents

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I would like to express my sincere gratitude to all the individuals who contributed to the success of this research work during my master's degree. Your contributions have been invaluable and essential to the completion of this project.

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Abstract

This research work focuses on the digitalization of an ancient grain grinding machine using a 3D scanner. The preservation of cultural heritage, specifically in the field of industrial archaeology, is the main objective of this study. By employing advanced 3D scanning technology, the machine was captured in high resolution to create a virtual reconstruction.

The process involved utilizing a state-of-the-art 3D scanner to capture the intricate details and dimensions of the antique machine. The resulting three-dimensional model serves as a digital documentation of the artifact, enabling its preservation and analysis for future generations.

The study encompasses various aspects through the generated 3D model, detailed investigations into the machine's mechanisms, components, and historical context are possible, shedding light on its functional and historical significance.

Moreover, the digital restoration techniques applied in this research contribute to the preservation of the artifact's visual appearance, allowing for a virtual representation of its original state. This helps in visualizing the machine's original form and aids in understanding its intricate workings.

The findings of this study have broader implications for the field of cultural heritage preservation. The digitization of historical artifacts using 3D scanning technology provides an innovative approach for documenting, studying, and disseminating knowledge about such artifacts. Additionally, it facilitates remote access and virtual exhibitions, ensuring the wider dissemination of cultural heritage to a global audience.

This research work not only showcases the successful application of 3D scanning in preserving and studying an ancient grain grinding machine but also highlights the potential for further exploration and analysis of other industrial artifacts. The integration of advanced technologies and heritage preservation contributes to the understanding and appreciation of our industrial past, fostering a deeper connection with our cultural heritage.

Keywords: 3D Scanning, Cultural Heritage, 3D Scanner, Antique Grain Grinding Machine, Heritage Preservation, Industrial Archaeology, Virtual Reconstruction, Three-Dimensional Modeling, 3D Visualization, Digital Documentation, Historical Heritage, Artifact Digitization, Surface Analysis, Authenticity and Integrity, Data Interpretation, Virtual Representation.

Resumo

Este trabalho de pesquisa foca na digitalização de uma antiga máquina de moer grãos utilizando um scanner 3D. A preservação do patrimônio cultural, especificamente no campo da arqueologia industrial, é o principal objetivo deste estudo. Ao utilizar tecnologia avançada de escaneamento 3D, a máquina foi capturada em alta resolução para criar uma reconstrução virtual.

O processo envolveu a utilização de um scanner 3D de ponta para capturar os detalhes e dimensões intrincados da máquina antiga. O modelo tridimensional resultante serve como documentação digital do artefato, permitindo sua preservação e análise para as gerações futuras.

O estudo abrange vários aspectos através do modelo 3D gerado, investigações detalhadas sobre os mecanismos, componentes e contexto histórico da máquina são possíveis, lançando luz sobre sua importância funcional e histórica.

Além disso, as técnicas de restauração digital aplicadas nesta pesquisa contribuem para a preservação da aparência visual do artefato, permitindo uma representação virtual de seu estado original. Isso ajuda na visualização da forma original da máquina e auxilia na compreensão de seu funcionamento intrincado.

As descobertas deste estudo têm implicações mais amplas para o campo da preservação do patrimônio cultural. A digitalização de artefatos históricos utilizando tecnologia de escaneamento 3D oferece uma abordagem inovadora para documentar, estudar e disseminar conhecimento sobre esses artefatos. Além disso, facilita o acesso remoto e exposições virtuais, garantindo a ampla disseminação do patrimônio cultural para um público global.

Este trabalho de pesquisa não apenas demonstra a aplicação bem-sucedida de escaneamento 3D na preservação e estudo de uma antiga máquina de moer grãos, mas também destaca o potencial para exploração e análise adicionais de outros artefatos industriais. A integração de tecnologias avançadas e preservação do patrimônio contribui para a compreensão e apreciação do nosso passado industrial, promovendo uma conexão mais profunda com nosso patrimônio cultural.

Palavras-chave: Escaneamento 3D, Patrimônio Cultural, Scanner 3D, Máquina de Moer Grãos Antiga, Preservação do Patrimônio, Arqueologia Industrial, Reconstrução Virtual, Modelagem Tridimensional, Visualização 3D, Documentação Digital, Patrimônio Histórico, Digitalização de Artefatos, Análise de Superfície, Autenticidade e Integridade, Interpretação de Dados, Representação Virtual.

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Chapter 1

Laser scanning, a technology that utilizes laser strips and omnidirectional measurements to capture buildings, landscapes, and objects, is widely employed for 3D scanning purposes. It involves launching lasers to mark multiple points and record their horizontal and vertical information, as well as their angles. These points are then used to calculate the coordinates relative to the scanner, enabling the creation of 3D images through a triangulation mechanism (Edl, Mizerák, & Trojan, 2018).

The field of 3D modelling, which involves converting real-world objects into virtual representations, holds significant importance. This technology has direct implications for various industries, leading to cost savings. By scanning an industrial warehouse along with its machinery, it becomes possible to optimize the production line. This optimization can take the form of implementing a new production line, accommodating a different product, or re-planning the existing product to enhance production efficiency (Gregor, Budzel, Štefánek, & Plinta, 2008). The ability to conduct various tests in a virtual environment without disrupting the entire production line brings immense benefits to industries. They can make necessary changes while minimizing losses in production time since the scanning and planning processes can be carried out without interrupting machine operations.

Furthermore, the preservation of cultural heritage artifacts has become an urgent concern. These valuable objects, monuments, and even buildings are vulnerable to the risks of time, accidents, and catastrophes. Consequently, the practice of 3D scanning these artifacts has gained popularity (De Stefano, et al., 2016). This technology provides a means to create accurate and detailed virtual replicas of cultural heritage items, allowing for their preservation, study, and dissemination without subjecting the originals to potential harm.

In light of these considerations, this thesis aims to explore the application of laser scanning technology in the context of cultural heritage preservation. By utilizing advanced scanning techniques and data processing methods, the research will focus on creating highly accurate 3D models of cultural artifacts and architectural structures. The resulting virtual representations will serve as valuable resources for documentation, analysis, and restoration purposes. Additionally, the thesis will investigate the integration of these 3D models into virtual reality environments, opening up new possibilities for immersive cultural experiences and educational applications.

Through this research, we seek to contribute to the fields of laser scanning, 3D modelling, and cultural heritage preservation. By harnessing the power of technology, we strive to safeguard our collective heritage and promote its accessibility, ensuring that future generations can appreciate and learn from these irreplaceable cultural treasures. a virtual replica, to ensure that cultural heritages are more safely preserved and protected.

1.1 Framework

The research opportunity came up through the suggestion of the theme by the supervising teachers and with the availability of the laser equipment in the laboratory of the Polytechnic Institute of Bragança together with the interest of both the supervising teachers and the student for the approached subject.

1.2 Goals

The primary objective of this research is to undertake the digitalization of a historical machine that has been in operation for over five decades. With its significant contribution to the industry, the machine's operations ceased last year, leaving its future undetermined, whether it will be showcased in a museum or merely stored away. In order to ensure the long-term preservation of this invaluable historical artifact, the decision has been made to proceed with its digitization. Thus, the overarching aim of this study is to employ advanced digitization techniques to capture the intricate details of the machine accurately and generate a faithful and precise digital representation. By accomplishing this objective, the intention is to safeguard the machine's legacy and facilitate its accessibility for scholarly examination, documentation, and potential future utilization in academic and cultural domains.

1.2.1 General Goals

The general objectives of this study are to digitize the object, process the point cloud data, and determine the feasibility of printing.

1.2.2 Specific Goals

The specific objectives are to obtain a virtual model that can be utilized both in virtual

reality for preservation purposes and for printing to enable visualization and accessibility.

1.3 Dissertation structure

The present work is divided into 5 chapters.

Chapter 1: Introduction. In this chapter, the thesis begins by providing a comprehensive introduction to the research topic. The aim is to set the context and explain the significance of the study. The chapter outlines the research problem, highlighting the gap in existing knowledge or the need for further investigation. Additionally, it establishes the specific research objectives and questions that the study aims to address. By presenting an overview of the dissertation structure and organization, the chapter provides readers with a roadmap to follow the progression of the research study.

Chapter 2: State of Art. This chapter serves as a literature review, where the thesis critically analyses the existing body of knowledge related to the research topic. The goal is to review and synthesize relevant scholarly articles, books, and other sources to establish the current state of knowledge in the field. The chapter highlights key theories, concepts, and methodologies used in previous studies and identifies any gaps or limitations in the existing literature. By presenting a comprehensive overview of the state of the art, the thesis sets the foundation for its own research and demonstrates the contribution of its work.

Chapter 3: Materials and Methods. In this chapter, the thesis describes the materials, equipment, and methods used in the research study. The aim is to provide a detailed account of the experimental or data collection procedures, including any specialized tools, software, or technologies utilized. The rationale behind the chosen methods is explained, and their suitability for the research objectives is justified. Additionally, any limitations or constraints encountered during the research process are discussed to provide transparency and context for the results obtained.

Chapter 4: Results. This chapter presents and analyses the findings of the research study. It provides a detailed account of the data collected, observations made, or experiments conducted. The results are typically presented in a systematic and logical manner, often supported by tables, figures, or graphs to aid in data visualization. The thesis interprets and discusses the results, drawing connections to the research objectives and addressing any research questions or hypotheses. The chapter may also include any statistical analyses or qualitative interpretations necessary to support the conclusions drawn from the results.

Chapter 5: Conclusion and Future Works. In this final chapter, the thesis summarizes the key findings and contributions of the research study. It begins with a restatement of the research objectives and a brief overview of the main results obtained. The thesis then interprets and discusses the

implications of the findings, considering their significance in relation to the broader field of study. The chapter concludes with a reflection on the limitations of the research and any recommendations for future research directions or areas of further investigation. The thesis may also highlight any practical applications or potential impact of the research findings and propose avenues for future work to build upon the current study.

Chapter 2

The technology of scanning through 3D scanner was dated in 1960, with the purpose of recreating surfaces of places and objects. At first the technology of the time did not leave room for the goal to be achieved easily, not only computers, but also lights and cameras were not developed enough to ensure a good quality of scans. The first more capable models appeared in mid-1994, but they used technology based on laser point, not laser strip, could not detect colours and finally did not have all 6 degrees of freedom needed. Two years later, these difficulties had been overcome, then creating 3D scanners that were faster, could capture colours and scan complex (Edl, Mizerák, & Trojan, 2018).

2.1 Applications areas

Nowadays there are several applications for 3D laser scanning technologies. In the branch of archaeology several studies already make the use of scanners indispensable because, this technology is able to characterize the surface of bones more efficiently than the methods that were being used, thus bringing the possibility that scientists redo several comparative studies in different fields getting better and more accurate results, as the case of Andean issues and the studies carried out in the megalithic necropolis of Panoria, in Granada, Spain (C. Kuzminsky, A. Tung, Hubbe, & Villaseñor-Marchal, 2016; J.A. Benavides López, et al., 2016). Another popular function is that of a microscope with a pseudo infinite capacity to capture details. There are also studies of the feeding behaviour and diet of mammals that are now extinct, by analysing the dental micro-coating of fossils found (Carro, 2022).

Another field of application of the technology is the forensic study, where a wide range of scanners can be used, depending on the needs of the location, there are several types of 3d scanners can be both aerial and terrestrial, technology that has been used to analyse large-scale disasters such as earthquakes and tsunamis (Olsen & Kayen, 2012). It is also becoming popular the use of low cost 3d scanners implemented in drones, this practice is more used in outdoor locations and that are very large, such as quarries, forests, and car accident sites. With the great advance of technology in this area, the differences found in the point clouds between a terrestrial scanner and those used in drones are minimal, allowing this technology to be implemented in third world countries, where the budget available to police forces is often outdated (Rodrigues Cunha, Thiago Arrabal, Mourão

Dantas, & Rodrigues Bassanelli, 2022). A study conducted by the Wisconsin Institute for Discovery, University of Wisconsin, came to the conclusion that by using laser technology at crime scenes, the saving of various resources such as time and manpower, in the long term makes for a positive financial return for police forces that use it, and with the trend of technological growth, or in other words, an increase in the capacity and efficiency of the equipment and a reduction in the market price, this return will become increasingly positive as the years go by (Tredinnick, Smith, & Ponto, 2019).

The use of 3d scanners in construction is already very popular, to perform the construction of tunnels, a process that requires modelling, mesh creation and application of boundary conditions in CAD is used, these are the prerequisites for a finite element analysis (Schillinger & Ruess, 2015). However, there are many flaws in the process of modelling and mesh generation, so it is already possible to use the 3D point cloud technology to create the mesh and the finite element analysis in a precise way to reduce these flaws (Cui, et al., 2023). Another application in this area is the maintenance of tunnels, there is a difficulty in relation to maintenance and safety verification, because the tunnels usually have circular cylindrical models, or elliptical cylinders and follow a standard where the construction parameters are estimated by surface adjustment. This means that an approximation model of global optimization is normally used, and the differences between an approximation model and the theoretical model may indicate various deformations. There are also external factors which make these models not totally accurate, however, with the use of point clouds, this process has become safer and more accurate. (Yi, et al., 2019). A method that is also used for various studies on stone monuments to quantify the loss of material and consequently the remaining life of the structure (Fehér & Török, 2022; Delgado Rodrigues, 2015).

As shown, the laser scanner has several features and many areas of application, being used for the most varied tasks, reverse engineering, is also one of them, the most interesting. Where the 3D scanner dispenses the need for any kind of drawing or previous database. The data are collected by the scanner, which comes as a point cloud to then be reconstructed in software, where the various scans taken are united through the points present in the point clouds, to then be modelled in some CAD program, there are some difficulties for the equipment in relation to certain surfaces, shiny or holes, but this can easily be solved with some manual work in the mesh (A. Elizondo & F. Reinert, 2019). Studies conducted in order to more effectively and economically perform life monitoring, fatigue state and failure prevention on a wind turbine blade using 3D Scanning Laser Doppler Vibrometer technology (S.J. Rothberg, et al., 2017), show that there is a high level of accuracy between the calculated and measured shapes, both for stress and displacement, and also the structural part of the blade, although there are some aspects that can be improved, this technology

provides a lot of useful information and references for wind blade designers. The above-mentioned technology provides an optical vibration measurement in order to obtain and analyse the stress distribution on the surface of the structure, thus avoiding a high-cost preparation using strain gauges, another advantage is the fact that it is performed quickly, thus allowing several high-resolution scans to be made with minimal noise. However, this technology is limited to dynamic strain measurement, and the initial cost of obtaining the equipment can also be considered a disadvantage (Yuanchang Chen & D. Todd Griffith, 2023). There are also studies in the area that aim to use the scanners used for reverse engineering in the quality control part, but the process is still not efficient enough for small components, that some manual measurements can be made easily as shown in (Robin H. Helle & Hirpa G. Lemu, 2021).

For the purposes of preserving cultural heritage, it has become increasingly common to use technologies using scanners and saving in a virtual environment, either for accessibility purposes, for people who cannot travel to places that are often remote and/or difficult to access, or for monuments and major artifacts that are exposed to imminent decay or even at risk of being damaged and destroyed by disasters and accidents. This practice also aims to enable remote access for visitors who for some reason are unable to access the sites (Pavlidis, Koutsoudis, Arnaoutoglou, Tsioukas, & Chamzas, 2007). However, there are still certain difficulties in this field of study, several errors can occur during this process, although the laser scanning can produce very accurate information, there are still limitations and errors that can occur, since the change of natural light of the environment and temperature, if the programming is not correct and get a low number of scanning steps, low resolution. All factors must be considered when scanning an object considering its complexity (Yasutaka & Hernández, 2015). Currently it is estimated that soon these errors will be reduced dramatically, it is already possible to find several studies on methods that aim to reduce these errors and the correction through algorithms presented (Vasic, Quattrini, Pierdicca, Frontoni, & Vasic, 2022).

2.2 Scanner's Types

Scanners have become an essential tool in various fields, enabling the digitization of physical documents, images, and objects for storage, analysis, and sharing. With advancements in technology, a wide range of scanners has been developed to cater to specific needs and applications. While it is not possible to provide an exhaustive list, this section aims to present a brief overview of some existing scanner solutions,

Flatbed scanners are one of the most commonly used types, consisting of a flat, glass surface

on which the document or object is placed for scanning. A movable scanning head moves across the surface, capturing the image or document with the help of an array of sensors. These scanners are widely used for scanning documents, photographs, and flat objects. (Tuno, Mulahusić, Topoljak, & Đideliija, 2022). Also, portable scanners offer the convenience of on-the-go scanning. These devices are compact and lightweight, allowing users to easily carry them and scan documents or images wherever they are. Portable scanners have gained popularity due to their flexibility and versatility in various environments, such as business meetings, conferences, or fieldwork. They provide a practical solution for professionals who require immediate access to scanned documents without the need for bulky equipment or access to a dedicated scanning station. Additionally, advancements in portable scanner technology have led to improved image quality and faster scanning speeds, making them an attractive option for individuals seeking efficient and reliable scanning on the move.

Non-line-of-sight imaging based on Archimedean spiral scanning is an innovative technique that allows the reconstruction of hidden objects or scenes that are not directly visible to the imaging system. By utilizing indirect reflections and scattering of light, this approach captures information about occluded objects and enables the reconstruction of detailed 3D shapes and appearances. The Archimedean spiral scanning method involves projecting laser pulses onto a visible surface adjacent to the hidden object, which then bounce off onto the hidden object or scene and reach a detector. Advanced algorithms analyse the reflected light to reconstruct the geometry and appearance of the occluded objects. This scanning technique has shown promising results in various applications, such as surveillance, autonomous vehicles, robotics, and augmented reality. Ongoing research aims to refine the Archimedean spiral scanning technique, improve its accuracy and efficiency, and address challenges such as limited resolution and real-time implementation. Non-line-of-sight imaging based on Archimedean spiral scanning holds great potential for practical applications in object detection, scene understanding, and remote sensing, and it is an area of active research and development (Zhang, et al., 2023).

The focus of this work will delve deeper into scanners that utilize point cloud technology, examining their capabilities and applications in detail. While this section provided a brief overview of some existing scanner solutions, it is important to acknowledge that the field of scanning is continuously evolving, with new technologies and advancements being introduced regularly. In the subsequent sections, we will explore the intricacies of point cloud scanners, their advantages, and their potential for revolutionizing various industries such as architecture, engineering, and cultural heritage preservation. By examining the current state of the art and recent research findings, we aim to provide a comprehensive understanding of point cloud scanning and its implications for the

future of scanning technology.

2.3 Point Cloud

Three-dimensional (3D) scanning techniques using point clouds have revolutionized the field of digital representation and analysis of real-world objects. Point cloud-based scanning enables the capture and reconstruction of accurate and detailed geometric information of objects, facilitating applications such as virtual reality, reverse engineering, and cultural heritage preservation.

Commonly a set of 3D coordinates sampling a surface, or an object is called point cloud. Laser's scanners are very common acquisition for cultural heritage, it has a very high precision with millimetres accuracy and has a great field of view, rotating up to 360 degrees. Also, Structure from Motion (SFM) overlaps the exact points from different locations scans in most of cases, but this is not completely guaranteed (Santagati, Inzerillo, & Di Paola, 2013). If the material that is been scanned is very shiny, or has corrosion, lacks texture among other defects, the efficiency of SFM greatly decreases. So, if it's a very complex scene we might need to take many scans so they can match, if not by the software we need to do manually in a lot of cases. Which is not only time consuming but has the problem that in most of the cases we can't use physical markers, because they can cause damages to the cultural heritage site (Jie, et al., 2019). So, the process of cleaning all the noise and matching the different scans can become very complex (K.Y., H.C.L. , Santos, & Rocha, 2023).



Figure 1: Noise in point cloud (K.Y., H.C.L. , Santos, & Rocha, 2023)

The scanners that use a laser beam are based on the triangulation principle. This technique works in a similar way to photogrammetry, as it uses several images to perform the triangulation between the camera, the laser and the object as can be seen in Figure 2 (Poredoš, Primož, Povsic, Klemen, Novak, Boštjan, & Jezeršek, Matija, 2015). The three-dimensional relations between the captured light and the object's surface can be estimated through computer vision and image processing artifices (Hirano, 2020).

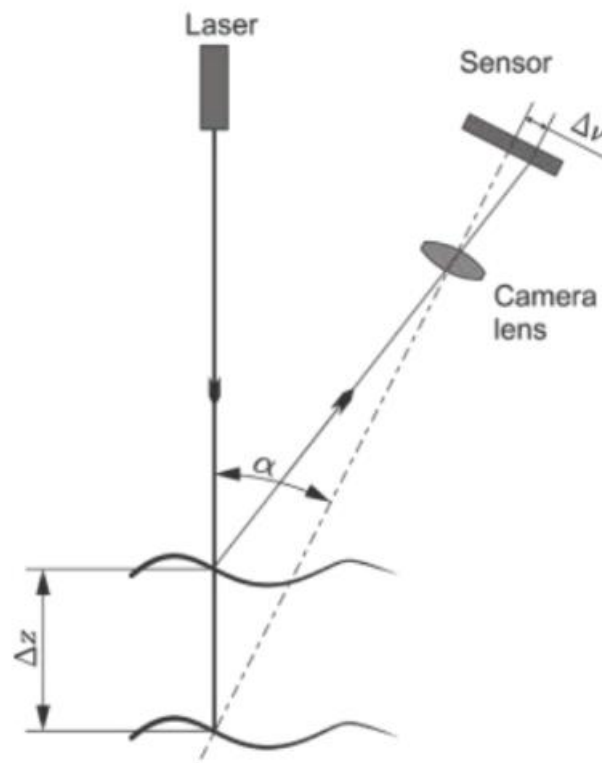


Figure 2: Triangulation principle

In recent years non-contact measuring techniques have attracted much interest from industries, as they are very versatile, can measure any part regardless of the material and do not cause any damage to what is being measured. However there are also limitations, the point cloud picks up interferences and noise, varying according to the surface of the material and the environment in which it is located, which can cause interference in the accuracy of the measurements of the equipment (Chengxing Wu & Baijin Chen, 2023; Haonan Pei, Puyu Zhang, Sizhe Du, & Ming Luo, 2023). The laser scanning technique use the triangulation method and obtain a 3D point cloud data, by using the laser ranging and imaging these point cloud data can be easily obtained in the special scenarios, with irregular surfaces, low lighting illumination, complex spaces, and objects (Manlin Xiao, Zheng Qi, & Huajie Shi, 2018).

The unsorted point cloud registration is essential in this cases of study, there are many methods to do the data registration, in (Cheng, et al., 2018) a comprehensive review is presented

from multiple angles and LiDAR (Multiscale Light Detection and Ranging) data registered at in the field of photogrammetry and remote sensing. Registering unclassified terrestrial laser scanners (TLS) point clouds is essential for many tasks in computer vision, photogrammetry, and remote sensing network. There is a study that extensively examine this TLS point cloud coarse registration in pairs, fine registration in pairs advantages of registration and multi-view registration and identification of weaknesses of the methods used (Zhen Dong, et al., 2020). Capturing a complex point cloud make the task more challenging than looks, isn't a simple fitting, depending on how many scans from different angles the data can be noisy, clutter or incomplete, even if you have enough scans the noise will still be there and the quality of the points may depend on the device or the algorithm used for the reconstruction (Filippo Bergamasco, Mara Pistellato, Andrea Albarelli, & Andrea Torsello, 2020).

2.4 3D Printing

In recent years, 3D printing, also known as additive manufacturing, has garnered significant attention, and witnessed remarkable advancements in both materials and processes. This section provides an overview of the state-of-the-art in 3D printing technology, highlighting key developments and their applications.

To date, there is a wide range of materials available for FDM 3D printing projects, offering a vast selection for users to choose from. These materials are categorized based on their purpose of use and often vary in cost per kilogram among different families.

Starting with the consumer category, these materials are specifically designed to be user-friendly and accessible to a wide range of individuals. They are commonly used in DIY 3D printing projects and offer ease of handling and printing for enthusiasts at home.

Moving on to the prosumer category, the materials require a higher level of skill and experience to work with. They are chosen by users who have a greater understanding of 3D printing and seek to meet more specific and demanding design needs. Prosumer materials offer improved quality and precision in prints, catering to those who are looking for enhanced control over their printing process.

In the industrial sector, the materials used in FDM 3D printing are of the highest quality and performance standards. These materials are extensively utilized in industries such as automotive and aerospace, where stringent requirements for strength, durability, and performance must be met. Industrial-grade materials exhibit superior mechanical properties, heat resistance, and

overall reliability, making them ideal for applications that demand exceptional performance.

When selecting materials for a 3D printing project, it is important to consider these distinctions and align them with the specific requirements of the project. Factors such as the complexity of the design, desired end-use characteristics, and budgetary considerations should be considered to make an informed choice regarding the most suitable material for the job Figure 3.

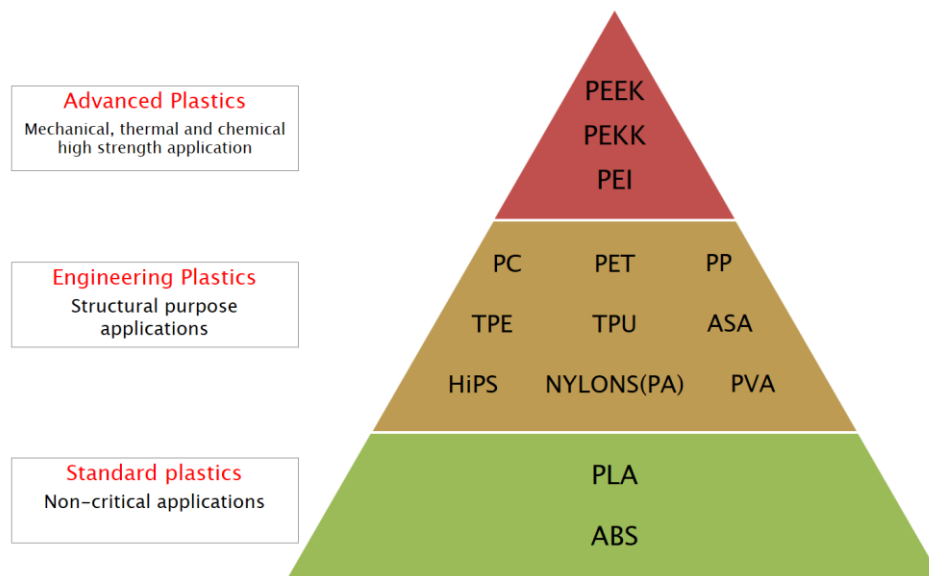


Figure 3: Materials applications

One of the critical factors driving the progress of 3D printing is the continuous development of new materials suitable for additive manufacturing. Researchers have been exploring a wide range of materials, including polymers, metals, ceramics, and composites, to enhance the capabilities and functionalities of 3D-printed objects.

Polymers, such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), have been widely used in 3D printing (Figure 4) due to their ease of use and affordability (Karaş, J. Smith, A. Fairclough, & Mumtaz, 2022). However, recent research has focused on improving their mechanical properties, thermal stability, and chemical resistance through various approaches, such as the incorporation of reinforcing fillers or the development of novel polymer blends.



Figure 4: Polymer 3d printer “Ultimaker S5” (Ultimaker, 2023)

In the field of metal 3D printing (Figure 5), significant progress has been made in overcoming challenges related to material properties, printability, and post-processing. For instance, researchers have developed new metal alloys specifically designed for additive manufacturing, such as titanium-aluminium-vanadium (Ti-6Al-4V), which offers excellent strength-to-weight ratio and corrosion resistance (Vafadar, Guzzomi, Rassau, & Hayward, 2021). Moreover, advancements in metal powder production techniques have enabled the utilization of a broader range of metal materials, including aluminium, copper, and nickel-based alloys (Costanzo, et al., 2022).



Figure 5: Metal 3D printer “Flex 350” (Systems, 2023)

3D printing processes have also evolved considerably, enabling the production of complex geometries and functional structures with high precision and efficiency. Several techniques, including vat photopolymerization, material extrusion, binder jetting, and powder bed fusion, have been refined to achieve superior print quality and resolution (Naol Dessalegn & Hirpa G., 2023).

Vat photopolymerization, utilizing photopolymer resins cured by light, has seen advancements in both hardware and materials (Figure 6). The introduction of digital light processing and continuous liquid interface production technologies has significantly reduced printing times and improved surface finishes (Zhang, et al., 2021). Researchers have also explored the incorporation of nanoparticles and functional additives into photopolymer resins to enhance their mechanical, electrical, and optical properties (Ikram, Al Rashid, & Koç, 2022).



Figure 6: Photopolymerization, 3D printer “Objet Eden 260V” (Stratasys, 2023)

Material extrusion, commonly known as fused deposition modelling, has benefited from advances in extrusion systems and nozzle design. Researchers have explored the use of multi-material and multi-nozzle systems to enable the fabrication of objects with varying properties and colours in a single print (Castillo, Monroy, & Ahmad, 2022). Furthermore, improvements in filament materials, such as the development of carbon fiber-reinforced thermoplastics, have led to enhanced mechanical strength and stiffness in FDM-printed parts (Giani, Mazzocchetti, Benelli, Picchioni, & Giorgini, 2022).

Binder jetting, a technique that selectively deposits a binder onto powder materials, has gained attention in the field of ceramics and composites. Recent studies have focused on optimizing

the binder formulation and post-processing techniques to enhance the mechanical strength and surface finish of printed parts (J.P. , et al., 2022). Researchers have also investigated the incorporation of nanoparticles and fibers into the powder materials to enhance the properties of printed ceramic and composite parts (Li , Durandet, Huang, Sun, & Ruan, 2022)

The state-of-the-art in 3D printing showcases significant advancements in both materials and processes, leading to enhanced capabilities and expanded applications. Ongoing research and development efforts continue to push the boundaries of 3D printing technology, paving the way for novel applications in fields such as aerospace, healthcare, and manufacturing.

Chapter 3

3.1 Used Equipment

The present master's research adopted a methodology with the purpose of developing a three-dimensional virtual representation of a grain milling space that houses ancient and historical machines, aiming at the preservation of historical heritage. To achieve this goal, the advanced scanner FARO S150 Figure 7 and Figure 8, widely recognized for its high precision in scanning, was utilized the relevant information's are available in Table 1 and Table 2



Figure 7: Faro Focus S 150 Laser (Faro Focus S 150 Laser Scanner, 2023)

Table 1: Technical information about the laser scanner (Faro, 2023)

Parameters	Values
Ranging Error(mm)	±1
Angular Accuracy	19 arcsec for vertical/horizontal angles
3D Point Accuracy	2 @10m 3.5 @25m
Field of View	300°vertical ⁶ / 360° horizontal
Beam Divergence	0.3mrad (1/e)
Beam Di	2.12mm (1/e)



Figure 8 : FARO® Laser Scanner Tripod

Table 2: Technical information about the scanner tripod

Parameters	Values
Material	Carbon fiber
Fully folded for transport	29" (730mm)
0 tubes extended (Minimum Height)	27" (679mm)
3 tubes extended (Maximum Height)	76" (1936mm)

In this research on 3D digitization using point clouds in a milling machine, it was crucial to have a highly advanced and up-to-date notebook. The use of a powerful and high-performance device was essential to handle the complex computational demands required for processing the acquired data.

The choice of an expensive notebook was justified by the need to handle large volumes of data and execute complex point cloud processing algorithms. These tasks require robust processing capabilities, generous RAM, and an advanced graphics card capable of handling the parallel processing required by 3D reconstruction algorithms.

Additionally, the processor speed is a critical factor in ensuring efficiency and agility in task execution. A latest processor with multiple cores and a high clock frequency is necessary to reduce processing time and enable real-time analysis of the data captured by the milling machine.

Storage capacity is another important aspect of the notebook. Given that 3D digitization can

generate substantial amounts of data, a high-capacity hard drive or a fast and spacious SSD is required to efficiently store the data and ensure no space limitations during the data capture and processing stages.

Furthermore, it is essential for the notebook to have a high-resolution and quality display, enabling precise and detailed visualization of the generated 3D models. The screen resolution and colour fidelity are important for accurate analysis of the obtained results.

In summary, the use of a highly advanced and up-to-date notebook, despite its considerable cost, is indispensable to enable the work of 3D digitization using point clouds in a milling machine. The processing power, memory, storage capacity, and screen quality are crucial factors in ensuring efficiency and accuracy in the conducted analyses Figure 9 and Table 3.



Figure 9: Dell Precision 7670

Table 3: Device specifications

DESKTOP-AH9EPHK Precision 7670	
ⓘ Especificações do dispositivo	
Nome do dispositivo	DESKTOP-AH9EPHK
Processador	12th Gen Intel(R) Core(TM) i7-12850HX 2.10 GHz
RAM instalada	64,0 GB (63,7 GB utilizável)
ID do Dispositivo	027AA28F-91F5-47A9-8606-59430B40CD66
ID do Produto	00355-62955-41305-AAOEM
Tipo de sistema	Sistema operativo de 64 bits, processador baseado em x64
Caneta e toque	Suporte para toque com 10 pontos de toque

The graphics card is undeniably one of the most crucial factors when it comes to efficient

processing in similar projects. For projects of this nature, it is highly recommended to utilize a graphics card equivalent to or like the Nvidia RTX A2000. This particular graphics card boasts impressive characteristics, including 8 GB of dedicated memory. This substantial amount of memory makes a significant difference, as it can drastically reduce processing time from several hours to just a matter of minutes, even though the process may still not be considered exceptionally fast. While modern computers with lower-performance graphics cards may be considered recent, they may not possess the necessary capabilities to handle the complexity of data processing required for such projects. Thus, an upgrade to a more powerful graphics card, such as the Nvidia RTX A2000, becomes essential to ensure efficient and timely data treatment. For further details regarding the specifications of the Nvidia RTX A2000, please refer to Table 4 provide by Nvidia.

Table 4: examples of graphics card characteristics for graphics data processing (Nvidia, 2023)

Especificações	
Memória da GPU	
NVIDIA RTX A2000	6 GB GDDR6
NVIDIA RTX A2000 12GB	12 GB GDDR6
Interface de memória	192-bit
Largura de banda de memória	288 GB/s
Código de correção de erros [ECC]	Sim
Núcleos CUDA baseados na arquitetura NVIDIA Ampere	3.328
Núcleos Tensor de terceira geração da NVIDIA	104
Núcleos RT NVIDIA de segunda geração	26
Desempenho de precisão única	8,0 TFLOPS²
Desempenho do núcleo RT	15,6 TFLOPS²
Desempenho Tensor	63,9 TFLOPS³
Interface do sistema	PCI Express 4.0 x16
Consumo de energia	Potência total da placa: 70 W
Solução térmica	Ativa
Formato	2.7" H x 6.6" L, slot duplo
Conectores para visor	4x mDP 1.4a com mecanismo de travamento
Máximo de visores simultâneos	4x 4096 x 2160 @ 120 Hz, 4x 5120 x 2880 @ 60 Hz 2x 7680 x 4320 @ 60 Hz
Mecanismos de codificação/decodificação	1x codificador, 1x decodificador (+ decodificador AV1)
Pronto para VR	Sim
APIs de gráficos	DirectX 12.07*, Shader Model 5.17*, OpenGL 4.68⁵, Vulkan 1.2⁵
APIs de computação	CUDA, DirectCompute, OpenCL™

The process of scanning the environment was conducted meticulously, aiming to capture the maximum number of points possible from the desired machine. In order to achieve an exhaustive level of detail, scans were performed from different positions, angles, and heights. This comprehensive

approach allowed for a comprehensive and accurate three-dimensional representation of the desired machine.

Each scanning position was carefully planned and executed, taking into consideration the specific characteristics of the machine and the surrounding environment. From each scanning point, a point cloud was generated, containing detailed information about the geometry and textures of the machine's surface. By combining these point clouds from different positions, a unified point cloud representing the machine in its entirety was created.

The variation in scanning positions, angles, and heights enabled the exploration of different perspectives of the machine, capturing details that might be obscured in a single scan. This multifaceted approach ensured that no important aspect of the machine was overlooked during the scanning process.

By consolidating these points into a single point cloud, a highly detailed three-dimensional mesh of the desired machine was constructed. This mesh faithfully preserved the characteristics and nuances of the machine, providing a visually impressive level of detail.

However, it is important to highlight that this process required extensive data collection and meticulous post-processing work. Scanning from multiple positions, angles, and heights resulted in a large volume of points that needed to be processed and unified into a coherent mesh. This process demanded significant computational resources and advanced data processing techniques.

3.2 Point Cloud-Based scans and Image-Based

3D scanners play a crucial role in capturing the geometry and appearance of real-world objects for various applications, including reverse engineering, cultural heritage preservation, and virtual reality. This section aims to compare two common approaches in 3D scanning: point cloud-based scanners and image-based scanners. We will examine their principles, advantages, and limitations.

Point cloud-based scanners utilize laser-based technologies, such as structured light or time-of-flight, to capture the 3D coordinates of points on the object's surface. These points are then used to reconstruct the object's geometry in the form of a point cloud (Mian, Bennamoun, & Owens, 2013). We are going to compare the most popular types of laser scanners that utilize point cloud data, namely terrestrial laser scanners, mobile mapping systems, metrology scanners, and aerial scanners. An example of point cloud of the ancient library at Wuhan University Figure 10 which were captured using the RIEGL VZ-400 laser scanner system and 5D Mark II camera (Zhen Dong, et al., 2020).

Terrestrial laser scanners are widely used for high-precision 3D scanning applications. These scanners are stationary devices that emit laser beams in a sweeping motion, capturing multiple points on an object's surface. They offer excellent accuracy and detail, making them ideal for applications such as architecture, civil engineering, and cultural heritage documentation (Li, Xiong, Zhang, Wang, & Huang, 2020). Notable brands in this category include FARO Focus and Leica ScanStation. The differences between TLS systems (in terms of cost and functionality) mostly comes down in Table 5 to accuracy and range.

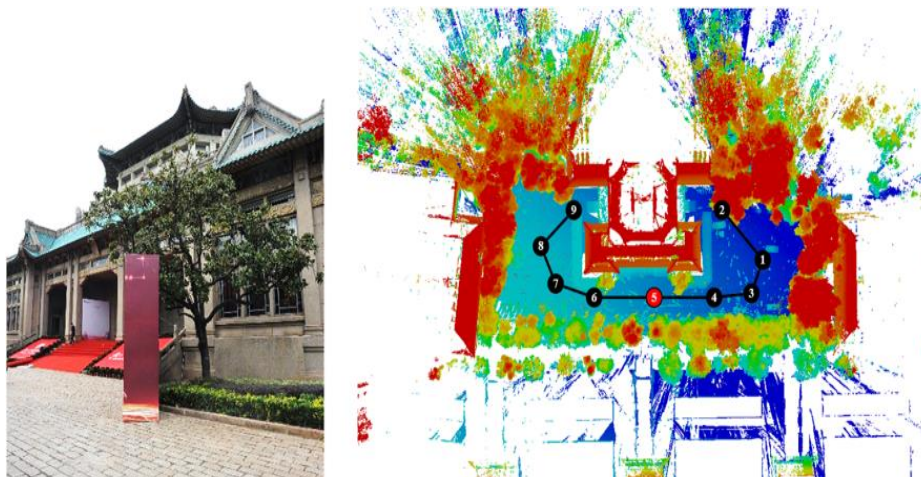


Figure 10: Ancient library at Wuhan University

Table 5: comparison between the most popular scans on the market

Short-range terrestrial laser scan	Price point	Accuracy	Instrument Range
	17 to 35 thousand euros	+/- 5mm - 10mm	<30m
	Examples: Faro Focus 70, Leica BLK360		
Medium-range terrestrial laser scan	Price point	Accuracy	Instrument Range
	45 to 70 thousand euros	+/- 2mm - 10mm	100m to 400m
	Examples: Faro Focus 150/350; Leica P30/40/RTC360; Z+F Imager 5016		
Long-range terrestrial laser scan	Price point	Accuracy	Instrument Range
	98 to 175 thousand euros	+/- 5mm - 15mm	1km to 6km
	Examples: Riegl VZ-2000i, VZ-4000, VZ-6000; Maptek XR3, LR3; Leica P50		

Mobile mapping systems combine laser scanning technology with navigation sensors, such as GPS and inertial measurement units (IMUs), to capture 3D data while in motion. These systems are commonly mounted on vehicles and can rapidly scan large areas, making them suitable for applications like road infrastructure mapping and urban planning (Li, Xiong, Zhang, Wang, & Huang, 2020). Popular brands offering mobile mapping systems are found in Table 6

Table 6 : comparison between mobile mapping systems

Vehicle scanners	Price point	Accuracy	Instrument Range
	290 to 580 thousand euros	+/- 20mm - 40mm	120m - 360m
	Examples: Riegl VMX-2HA, Trimble MX-9, Pegasus II		
Trolley scanners	Price point	Accuracy	Instrument Range
	58 to 116 thousand euros	+/- 2mm - 10mm	30m to 36m
	Examples: Leica ProScan, Faro Focus Swift, NavVis M6		
Wearable scanners	Price point	Accuracy	Instrument Range
	23 to 70 thousand euros	+/- 6mm - 30mm	25m to 100m
	Examples: Leica BLK2GO, NavVis VLX, GeoSLAM Zeb Horizon		

Also, metrology scanners are designed specifically for high-precision measurement and inspection tasks. These scanners employ laser-based technologies to capture point cloud data with exceptional accuracy and resolution. They are extensively utilized in industries such as automotive, aerospace, and manufacturing for dimensional analysis and quality control purposes (Javaid, et al., 2022) . Prominent brands in this category are in Table 7.

And lastly aerial scanners, also known as airborne or drone-based scanners, capture 3D data from an elevated perspective using laser scanning technology mounted on aircraft or unmanned aerial vehicles (UAVs). These scanners cover large areas efficiently and enable the creation of detailed digital terrain models, topographic maps, and 3D city models (Li, Xiong, Zhang, Wang, & Huang, 2020). Table 8 show a few examples and characteristics.

Table 7 : metrology scans comparison

Arm Scanners	Price point	Accuracy	Instrument Range
	> 100 thousand euros	0.004mm	Max 2m - 3m
	Examples: Faro Quantum Scan Arms, Faro Super 6DoF TrackArm		
Structured light scanners	Price point	Accuracy	Instrument Range
	11 to 31 thousand euros	+/- 0.02mm - 0.11mm	0.1m to 10m
	Examples: Faro Freestyle 2, Artec Eva, Creaform HandyScan 3D		

Table 8 : Aerial scans comparison

Aerial (long-range)	Price point	Accuracy	Instrument Range
	> 1 million euros	+/- 0.5m to 10m	Kilometers
	Examples: Riegl VQ-1560 II, Leica CityMapper 2		
Aerial (short-range)	Price point	Accuracy	Instrument Range
	52 to 116 thousand euros	+/-30mm	Kilometers
	Examples: Emesent Hovermap, mdLiDAR1000-aaS		

Advantages of point cloud-based scans:

- **Accuracy and Detail:** Point cloud-based scanners are known for their ability to capture fine details and intricate geometries with high accuracy. They are particularly suitable for capturing complex surfaces and irregular shapes (Mian, Bennamoun, & Owens, 2013).
- **Non-Dependence on Texture:** Point cloud-based scanners are not reliant on object texture or color. They can capture geometry regardless of surface characteristics,

making them suitable for scanning objects with homogeneous or featureless surfaces.

- **Independent of Lighting Conditions:** These scanners are less affected by variations in lighting conditions, allowing for consistent results in different environments.

Limitations of point cloud-based scans:

- **Limited Color Information:** Point cloud-based scanners typically do not capture color information directly. Additional techniques, such as color mapping or texture projection, are required to overlay color onto the reconstructed model.
- **Sensitivity to Reflective Surfaces:** Shiny or reflective surfaces can pose challenges for point cloud-based scanners as the laser may reflect and produce erroneous measurements.
- **Data Post-Processing:** Point cloud data requires processing and alignment to generate a complete and accurate 3D model, which can be time-consuming.

Image-based scanners rely on photogrammetry techniques to reconstruct 3D models using a series of images captured from different viewpoints. These images are analysed to extract depth and surface information, enabling the reconstruction of the object's geometry (Gargallo, Ballesta, & Lerma, 2015; Pizarro, Colomina, & Foresti, 2019).

Advantages of image-based scans:

- **Color and Texture Information:** Image-based scanners inherently capture color and texture information along with the geometry, producing visually realistic 3D models.
- **Ease of Use:** Image-based scanning can be performed using consumer-grade cameras or smartphones, making it accessible and convenient for a wide range of applications.
- **Rapid Scanning:** Image-based scanners can capture 3D data quickly by capturing multiple images from different viewpoints simultaneously (Zhang, Hu, & Feng, 2020).

Limitations of image-based scans:

- **Texture Dependency:** Image-based scanners rely on texture and visual features for accurate reconstruction. Lack of texture or repetitive patterns on the object's surface

can affect the quality of the resulting model.

- **Lighting Conditions:** Changes in lighting conditions during image acquisition can introduce inconsistencies in the reconstructed model.
- **Occlusion Challenges:** Objects with complex geometries or occluded surfaces may pose challenges for image-based scanners, resulting in incomplete reconstructions.

The differences, consider the scanning of a statue using a point cloud-based scanner (Mian, Bennamoun, & Owens, 2013) and an image-based scanner (Gargallo, Ballesta, & Lerma, 2015). The point cloud-based scanner captures precise geometric details of the statue's intricate carvings, while the image-based scanner produces a visually appealing 3D model with realistic colors and textures.

Both point cloud-based scanners and image-based scanners have their strengths and limitations in 3D scanning applications. Point cloud-based scanners excel in capturing accurate geometric details, while image-based scanners offer visually realistic models with color and texture information. The choice between the two approaches depends on the specific requirements of the application, such as accuracy, visual fidelity, and the nature of the object being scanned.

3.3 Data acquisition

The data collection process consisted of multiple visits to the old milling room Figure 11, which is already deactivated, located in Bragança, Portugal. During these visits, the scanner was strategically positioned in different areas of the space to capture as many details as possible. Ten scans were taken, that was a very time-consuming task, as multiple scans were taken at different angles, ranging from a minimum of 90 degrees to a maximum of 360 degrees at the center of the room in order to capture as much detail as possible. On average, these scans took about 40 minutes, with scans at lower angles taking up to 80 minutes.



Figure 11: Milling room

Prior to each scanning session, adjustments and calibrations were carried out on the scanner to ensure precise data readings. It is crucial to highlight that there is a limitation of the equipment, where the closest 0.6 meters are not captured. This limitation became a challenge as the environment in question had a very limited space between the machines, making it difficult to scan between them.

For data cleaning and processing, five software programs were used mainly: Faro Scene, SolidWorks, ReCap, ReCap Photo and Meshmixer.

The raw data collected were imported into the FARO SCENE software, where they underwent a treatment process. Initially, cleaning and refinement of the point cloud were performed to eliminate noise and unwanted artifacts. Additionally, a specific machine was selected to be the focus of the research. Subsequently, there was a need to export the mesh for further refinement in order to carry out its virtualization, as the file size was too extensive to be manipulated in SOLIDWORKS. Others software's also encountered difficulties in reading and opening the file, so the decision was made to export the SCENE software file to RECAP PHOTO and, subsequently, to MESHMIXER.

From the virtualization of the milling environment, all the ancient and historical machines present in the room were meticulously documented. Furthermore, relevant details about the environment were described and recorded with the intention of preserving the historical heritage. The data were properly organized and structured to facilitate their long-term preservation. below is the result of the montage made using Faro Scene and ReCap

Figure 12.



Figure 12: Virtual space

In relation to the machine highlighted in red on Figure 13, it is of utmost importance to emphasize its purposeful selection as the main object of the comprehensive scanning process. A meticulous evaluation of the overall map, which presents the spatial distribution of all scans performed, reveals a remarkable disparity, as there are only 9 visible points instead of the expected 10. This discrepancy stems from the occurrence of a defective scan, specifically identified as number 2 in the adjacent figure. Consequently, it became urgent to resolve this problem immediately in order to maintain the integrity and comprehensiveness of the acquired data.



Figure 13: Overview map (red square, machine selected for study, blue points, places where the machine was positioned for the scans)

An attached report provides detailed information on the results of the Color-Coding analysis. The analysis revealed the following metrics: point error ranging from less than 8 mm to 20 mm, overlap ranging from over 25.0% to less than 10.0%, and an overview of the scan point statistics Figure 14. The maximum point error was measured at 5.0 mm, with an average point error of 1.8 mm. The minimum overlap observed was 20.9%. This comprehensive report offers valuable insights into the accuracy and quality of the scanning process, aiding in the assessment and interpretation of the reconstructed environment.

Número de varreduras	10
Período de gravação	25/01/2023 16:31:47 - 30/05/2023 17:58:21
Modificado	06/06/2023 12:15:39
Localização	Adicione uma localização.
Caminho	C:\Users\jroch\OneDrive\Ambiente de Trabalho\Sala moagem Antonio\Originals\Teste k\

Processamento

10 Varreduras

Todas as varreduras neste projeto foram processadas.

Varreduras do processo

Registro

2 Grupos 1.8 mm

Todos os clusters estão registrados.

Mostrar relatório

Nuvem de Pontos de Projeto

Não foi criada uma Nuvem de pontos de projeto.

Criar

Figure 14: Project in Faro Scene

3.4 Grain Milling Machines

Grain milling is an essential step in food production, playing a fundamental role in obtaining flours, cereals, animal feed, and other derivative products. The quality of the milling process has a significant impact on the texture, particle size distribution, yield, and efficiency of the final product. Therefore, it is crucial to use suitable grain milling machines that can meet the demands of the food industry.

Over the years, significant technological advances have been made in the field of grain milling machines, driven by scientific research and the development of new technologies. An important aspect is the development of high-efficiency grinders, aiming to reduce energy consumption and increase production capacity. Studies such as (Zhang, Zhang, & Chen, 2019) have presented a new type of impact grinder with a high-speed and high-power rotor, resulting in higher grinding efficiency.

Another crucial aspect is the precise control of the particle size distribution of the final product. Obtaining specific particle sizes is of utmost importance in various food industries. In this regard, studies have focused on the development of advanced control systems to ensure the desired particle size distribution. (Li, Gao, & Chen, 2020) developed mathematical models based on artificial intelligence algorithms to predict and control particle size distribution during the grinding process.

However, there are challenges and limitations that need to be addressed in the field of grain milling machines. A common challenge is the wear of machine components, especially when dealing with hard grains. Research has been conducted to find more durable coating materials that can increase the lifespan of components and reduce maintenance costs (Chen, Xu, & Wu, 2018) analysed different coating materials for grinding machine components, aiming to find solutions for this challenge.

Furthermore, contamination and food safety are ongoing concerns in the food industry. During the milling process, there is a risk of grain contamination by undesirable microorganisms. Therefore, studies have focused on the development of effective cleaning and sanitation systems for milling machines to reduce the presence of these microorganisms in the final products. (Silva, Fonseca, & Gomes, 2021) evaluated the effectiveness of different cleaning and sanitation systems for milling machines, contributing to ensuring food safety.

In summary, technological advancements in grain milling machines have been driven by scientific research and the development of new technologies. References such as (Zhang, Zhang, & Chen, 2019), (Li, Gao, & Chen, 2020), (Chen, Xu, & Wu, 2018), and (Silva, Fonseca, & Gomes,

2021) provide a solid foundation for understanding these advancements and the challenges faced in the field. The ongoing pursuit of innovative solutions and improvement in milling machines will contribute to the production of high-quality food and meeting the demands of the food industry.

In addition to the technological advancements in grain milling machines, it is important to recognize and preserve the ancient technologies that have contributed to the development of these innovations. The history of grain milling is rich and dates back thousands of years, with traditional techniques that have been passed down through generations.

Ancient milling technologies, such as stone mills, have played a fundamental role in grain processing throughout history. These traditional techniques provide a deep understanding of the basic principles of milling and the interaction between grains and milling surfaces.

Preserving and valuing these ancient technologies is crucial for several reasons. Firstly, they are part of the cultural and historical heritage of many communities, representing ancestral traditions and knowledge. Additionally, these techniques can offer valuable insights for improving and optimizing modern milling machines.

Understanding the traditional milling processes and their limitations can inspire the development of innovative approaches that combine the best of ancient practices with new technologies. By integrating the knowledge gained from ancient practices with modern advancements, it is possible to achieve more efficient, precise, and sustainable milling.

Furthermore, the preservation of ancient milling technologies contributes to diversity and resilience in the food sector. By valuing traditional practices, we can maintain a wide range of milling methods adapted to the specific needs of different cultures, regions, and types of grains.

Therefore, it is essential to recognize and preserve ancient milling technologies, incorporating them into research and future innovations. By combining technological advancements with the accumulated knowledge of centuries, we can propel the grain milling industry towards a future with efficient, sustainable, and culturally significant solutions.

3.5 Limitations

The study faced several limitations. of the equipment used, such as its inability to operate in extreme weather conditions, including temperatures below 0 degrees Celsius. Furthermore, the need for power for site lighting, coupled with the lack of electricity supply on rainy days, was another factor that posed considerable difficulties. Given that the structure to be mapped was quite old, the shortage of power during rainy periods became an additional concern. The consequence of these limitations resulted in the postponement of the start of scanning operations to the warmest

part of the day during winter. The difficulties encountered during the site scanning visits underscore the importance of carefully assessing the equipment limitations before commencing work. Additionally, the presence of extreme weather conditions and the lack of electrical power in old structures represent significant challenges, requiring prior planning and alternative strategies to ensure the success of scanning activities. In the specific case of this study, carrying out the work only during the warmest part of the day allowed for minimizing the negative effects of sub-zero temperatures.

In addition to the limitations related to equipment and weather conditions described also by (H.C.L., K.Y. , Santos, & Rocha, 2023), an additional factor that hindered the site scanning visits was the need to obtain prior authorization from the owner of the old milling grain factory. Access to the structure was subject to restrictions, preventing the research team from freely conducting their work according to their own schedule. Obtaining permission to access the grain factory involved negotiation processes and prior scheduling, resulting in significant delays in carrying out the scanning activities. This additional restriction added complexity to the study logistics and limited the research team's flexibility regarding available times and days to perform the work. It is important to emphasize that the need to obtain prior authorization from the owner of the old grain factory not only added an additional layer of logistical challenges but also directly impacted the efficiency and effectiveness of the site scanning visits. Complying with these prerequisites for access was essential to ensure the integrity of the study but also represented another barrier to overcome during the process.

Another factor that contributed to the difficulties encountered during the site scanning visits was the closing time of the old grinding factory. Access to the site was conditioned to the operating hours established by the owner, resulting in frequent interruptions in the studies. Due to the time restrictions, the research team was required to plan reduced activities divided into multiple visits before completing the entire planned scope. These interruptions not only limited the available time for scanning but could also compromise the continuity and consistency of the collected data.

Furthermore, the closing time of the old grinding factory did not always coincide with the warmest part of the day when weather conditions were most favourable for operating the scanning equipment. This lack of synchronization between access hours and ideal environmental conditions resulted in an even narrower time window for carrying out the scanning activities.

These interruptions and time limitations caused by the closing time of the old grinding factory constituted yet another challenge faced during the study, requiring careful time management, and maximizing efficiency during the available periods.

In addition to the difficulties encountered during the site scanning visits, another significant

challenge was found in the data processing stage. The availability and capacity of the software and hardware resources used for this purpose were severely limited, leading to delays and additional complications in the process.

Initially, the software required for data processing was unavailable at the research site, awaiting delivery from the responsible company. When it was finally obtained, a new problem arose: the requirement for considerable computational power for its proper execution. Although it was installed on several computers in the institute's laboratory, it was found that these machines had limited capacity, making it unfeasible to carry out the data processing work.

The inability to install the software on personal computers due to contractual and licensing restrictions also proved to be a significant limitation. Only one machine within the institute's laboratory proved capable of handling the processing demands required for the treatment of the data in question.

However, there were multiple people working simultaneously with the same software on different projects, leading to a resource contention and additional delays in data processing. The need to share a single machine to perform these tasks resulted in long waiting periods, hindering the efficient and timely completion of data processing for the collected data during the scanning visits.

The limitations in data processing represented an additional challenge in the research development. The initial unavailability of the required software, followed by power incompatibility with the available computers, and the need to share a single high-performance machine among multiple individuals, led to significant delays and difficulties in the data processing process.

For future research, it is essential to ensure the early availability of the necessary software and appropriate hardware resources for data processing. Additionally, considering the efficient allocation of computational resources through planning and coordination among ongoing projects is crucial to avoid unnecessary delays and optimize the effectiveness of data processing in similar studies.

Chapter 4

The results obtained after three days of work at the deactivated grain milling factory have been analysed and documented for this work. During this period, seven scans of the environment were collected using the renowned FARO® SCENE 3D Point Cloud Software, well-known for its reliability in accurately reconstructing virtual environments. It is important to emphasize that this process is notably time-consuming, given the complexity of the captured information.

After obtaining these scans, the data cleaning stage was initiated to eliminate any unwanted noise. The data filtering tool, specifically the clipping box function, was used to remove unnecessary data. In this regard, the auxiliary software Autodesk ReCap was employed due to its superior visualization capabilities of the reconstructed environment. Repeated iterations of the cleaning and filtering process were performed until the machine with the highest accessibility and best conditions in the point cloud was selected.

Once this selection was made, the mesh corresponding to that machine was created and exported to the SolidWorks software for additional refinement. However, due to the considerable file size, two other software programs, ReCap Photo and Meshmixer, were necessary. Through the combined use of these tools, it was possible to optimize the mesh, ensuring that no relevant information for the study object was lost.

After completing the optimization stage, the correction of identified defects was initiated. In particular, the reflective surfaces of the machine needed to be remodeled according to the capabilities offered by the available software. Additionally, a region of the machine containing a grid exhibited severe loss of detail, making proper treatment impossible in that specific area.

The application of data processing techniques in conjunction with the functionalities of the mentioned software enabled the attainment of high-quality results despite the challenges faced during the process. However, it is important to note that there are still limitations to overcome, especially regarding the correction of defects on reflective surfaces and the region affected by the loss of detail as can be seen in Figure 15.

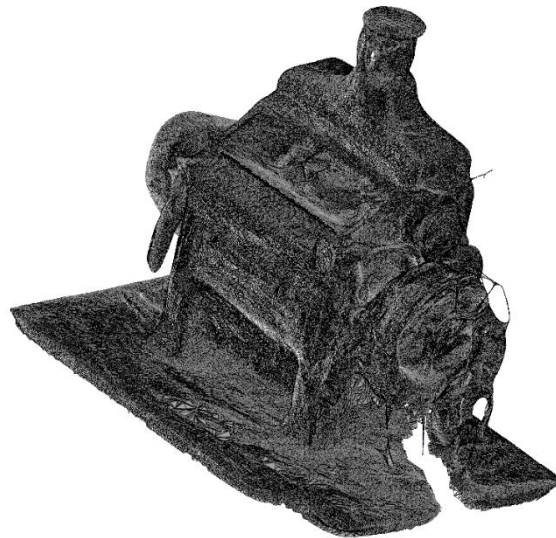


Figure 15: First scans mesh (SolidWorks)

In light of the challenges encountered, particularly with regards to the area containing the grid, it was deemed necessary to conduct an additional visit to the deactivated grain milling factory. This decision was motivated by the objective of addressing the severe loss of detail observed in that specific region. As a result, three new scans were successfully acquired, contributing to an improved quality of the grid reconstruction, as depicted in the Figure 16.

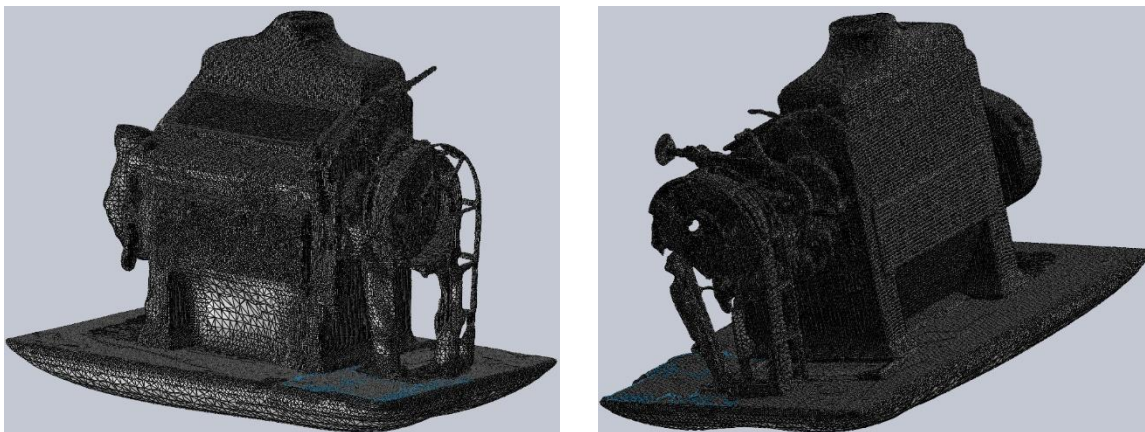


Figure 16: second scans mesh (SolidWorks)

These additional scans were performed using the same FARO® SCENE 3D Point Cloud Software previously utilized, ensuring consistency in the data collection methodology. Each scan involved meticulous attention to detail and adherence to established protocols to ensure accurate representation of the environment.

Upon obtaining the new scans, the subsequent steps of data cleaning, filtering, and mesh creation were repeated. The software tools, including Autodesk ReCap, SolidWorks, ReCap Photo,

and Meshmixer, were employed in a similar manner as previously described to refine the data and optimize the mesh. The goal remained to eliminate unwanted noise, enhance the representation of the grid, and maintain the fidelity of the reconstructed environment.

The results of this supplementary visit and the subsequent processing of data demonstrated a considerable improvement in the quality of the grid. Notable advancements were achieved in capturing the intricate details, contours, and features that were previously compromised. The refined mesh, derived from the augmented dataset, provided a more accurate and comprehensive representation of the deactivated grain milling factory, specifically with respect to the grid area.

This enhancement is evidenced in the figure displayed above, which clearly illustrates the increased level of detail and precision achieved through the incorporation of the additional scans. The improved quality of the grid reconstruction serves to enhance the overall fidelity and reliability of the virtual representation, contributing significantly to the objectives of this research endeavour.

By addressing the limitations identified in the initial dataset, a more comprehensive understanding of the grid area was achieved, thereby enabling more accurate analyses and interpretations.

It is important to note that while this additional visit and the subsequent improvements significantly enhance the quality of the grid reconstruction, certain challenges may persist due to the nature of the reflective surfaces and the intricacies involved in capturing their features accurately. However, through the meticulous application of advanced software tools and the implementation of refined methodologies, it is expected that these challenges can be further mitigated, leading to a more comprehensive and precise representation of the deactivated grain milling factory.

In summary, the decision to conduct an additional visit and acquire three new scans was motivated by the need to address the limitations observed in the initial dataset, particularly in the area containing the grid. The improved quality of the grid reconstruction, as illustrated in the figure above, demonstrates the positive impact of these efforts. This endeavour exemplifies the commitment to ensuring the accuracy and reliability of the virtual representation, contributing to the advancement of knowledge in the study of the deactivated grain milling factory. The result after

the new scans can be seen in Figure 17

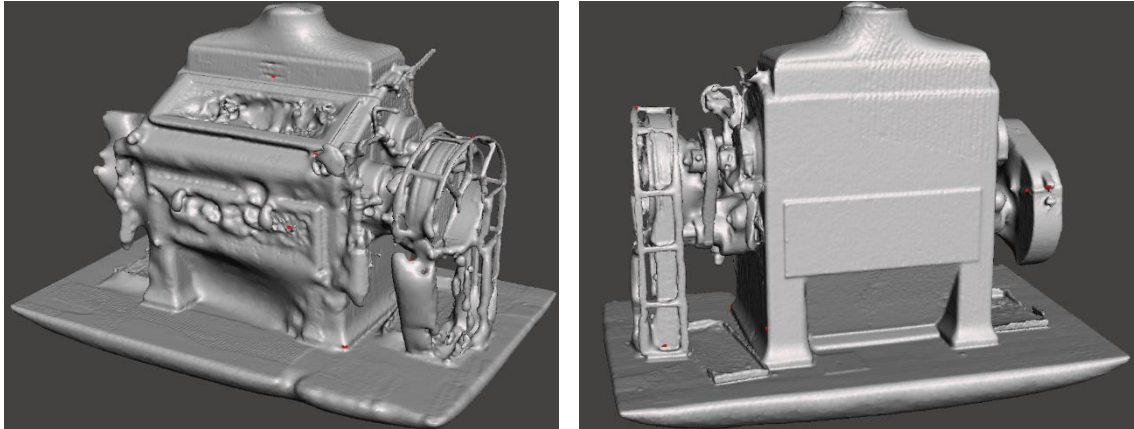


Figure 17: Results after refining the mesh (Meshmixer)

Following the improvement in the mesh quality, the correction of distorted surfaces was initiated, employing both SolidWorks and Meshmixer software tools. SolidWorks was utilized to redesign components such as glass and illuminated surfaces, aiming to achieve a higher fidelity with the actual machine. Meshmixer, on the other hand, was employed for adjustments and assembly of the mesh with the developed components. Throughout this process, the maximum care was taken to ensure a faithful representation of the real machine.

Despite the significant improvement achieved in the grid area, it became apparent that further refinement was necessary to attain an ideal reconstruction. Despite investing several hours of work, the grid region remained suboptimal. Consequently, a decision was made to redraw the entire grid in SolidWorks, striving to preserve the original captured features from the point cloud as closely as possible. The Figure 18 and Figure 19 depicts the progress made in this regard.

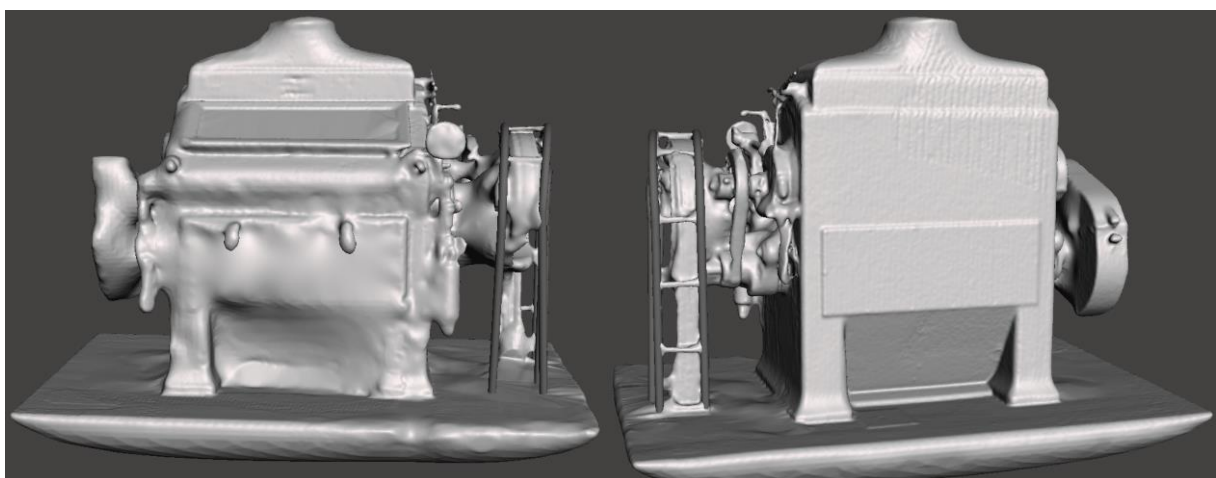


Figure 18: assembly with the grid

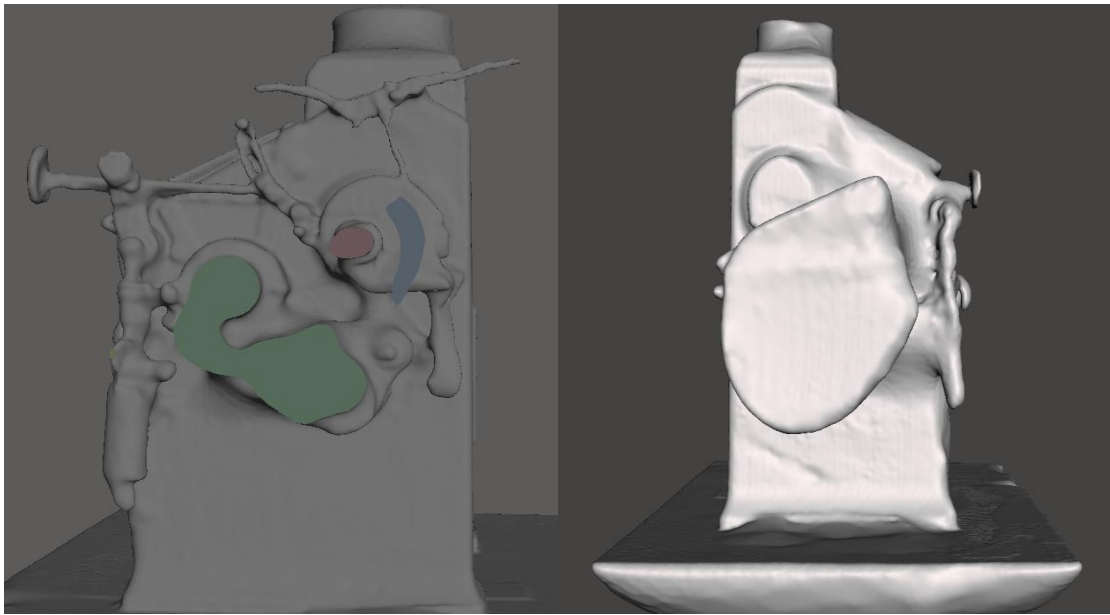


Figure 19: refinements results

This undertaking exemplifies the dedication and meticulousness applied in addressing the challenges encountered during the reconstruction process. By investing additional effort into accurately representing the grid, the aim was to enhance the overall authenticity and reliability of the virtual model.

However, it is important to acknowledge that even with the comprehensive efforts exerted, achieving an exact replica of the real machine remains a complex endeavour. The nature of the reflective surfaces and the intricate details of the grid present inherent difficulties in achieving a flawless reconstruction. Nevertheless, by leveraging the advanced capabilities of SolidWorks and diligently fine-tuning the design, a considerable level of fidelity was attained.

The image presented above illustrates the progress made in redrawing the grid. While the final result may not be ideal, it represents a significant improvement compared to the previous iterations. The diligent utilization of SolidWorks in conjunction with the insights obtained from the point cloud data allowed for a more precise and faithful representation of the grid.

In conclusion, the correction of distorted surfaces commenced after the enhancement of the mesh quality. Both SolidWorks and Meshmixer were utilized to address the distortions and refine the representation of various machine components, with a particular focus on glass and illuminated surfaces. Despite the significant progress achieved, the grid area proved to be particularly challenging, necessitating a complete redraw in SolidWorks. The image provided above showcases the efforts dedicated to achieving the closest possible resemblance to the original grid captured in the point cloud.

While the reconstruction of the grid may not be flawless, it demonstrates the commitment

to achieving the highest level of fidelity and accuracy in the virtual representation. These endeavours contribute to advancing the understanding of the deactivated grain milling factory, despite the complexities involved in accurately reproducing the intricate details of the real machine.

Chapter 5

5.1 Developed works

In conclusion, this research project focused on the digitalization of an ancient grain grinding machine using a 3D scanner. The aim was to preserve and analyse this historical artifact within the context of industrial archaeology. While the use of a 3D scanner provided valuable insights and documentation, it is important to acknowledge the challenges encountered during the process and evaluate the limitations of the method employed.

Throughout the project, several difficulties were encountered that impacted the effectiveness and accuracy of the digitalization process. One of the primary challenges was the limited capability of the 3D scanner to operate under extreme climatic conditions. The machine's inability to function in temperatures below 0 degrees Celsius restricted the scanning activities, particularly during the winter season when such conditions were common. Additionally, the requirement for a stable power supply for illumination posed challenges, as the old structure often experienced power outages during rainy days, further limiting the available scanning time.

Moreover, access to the ancient grinding machine was subject to the approval and availability set by the owner, which added another layer of complexity to the project. This restricted access hindered the research team's ability to conduct scanning sessions freely, leading to delays and constraints in data collection.

Furthermore, limitations in data processing and analysis were encountered due to the unavailability of the required software. The software necessary for data treatment was pending delivery from the company that sold the scan and, upon receipt, posed additional challenges regarding the computational power required to run it effectively. While attempts were made to install the software on various computers within the laboratory, it was discovered that the available machines lacked the necessary processing power, rendering them inadequate for the data treatment process. The software's inability to be installed on personal computers due to licensing agreements further constrained the options for data processing. Eventually, only one high-performance machine in the laboratory proved capable of handling the data treatment, but it was shared among multiple researchers working on different projects. This led to further delays in data processing, as a single machine was insufficient to accommodate the simultaneous demands of various research endeavours

Taking into account these challenges and limitations, it can be concluded that the method

employed in this research, utilizing a 3D scanner for the digitalization of the ancient grain grinding machine, is not the ideal or recommended approach for capturing detailed and precise data. While the 3D scanner served as a valuable tool for initial documentation and visualization, its limitations in capturing fine details and producing refined data became evident.

Alternative software solutions available in the market, which combine point cloud scanning with powerful software such as SolidWorks, offer a more comprehensive and accurate approach for capturing and analysing complex machinery. These software packages allow for more in-depth scanning, capturing finer details, and facilitating a more precise and refined data treatment process. While these software options may come with a higher cost, their capabilities and compatibility with advanced scanning technologies make them a more viable choice for comprehensive and detailed digitalization projects.

It is important to recognize that advancements in scanning technologies and software applications continue to evolve rapidly. Future research endeavours in the field of digitalization of historical machinery should consider exploring alternative scanning methods and software solutions that can better capture and analyse intricate details, ensuring a more comprehensive understanding of the artifact's structure and functionality.

While the digitalization of the ancient grain grinding machine using a 3D scanner provided valuable insights and initial documentation, it is imperative to acknowledge the limitations and challenges encountered. Moving forward, researchers should explore and invest in more advanced software solutions that can effectively combine point cloud scanning with powerful data treatment tools to ensure a more precise, refined, and comprehensive digitalization process of historical machinery.

Furthermore, it is important to highlight that one of the potential benefits of 3D scanning the ancient grain grinding machine would be the ability to 3D print the result. This physical reproduction would enable a tactile and accessible experience for individuals with visual impairments or those who are unable to visit the museum where the machine is exhibited.

However, due to the various difficulties encountered throughout the project, including the limitations of the scanning equipment, delays in data processing, and inconsistent access to the machine, unfortunately, it was not possible to carry out the 3D printing within the established timeline. The lack of adequate time to address all the setbacks and challenges faced prevented the completion of this additional step.

This gap in the ability to 3D print the digitized model represents a missed opportunity to enhance the accessibility and dissemination of the cultural heritage represented by the ancient grain grinding machine. 3D printing would have allowed individuals with visual impairments or mobility

restrictions to have access to an accurate physical replica of the artifact, offering a unique sensory experience and the possibility to explore and understand its shape, texture, and structure.

Although 3D printing was not realized in this specific project, it is crucial to recognize the potential of this technology for future research and cultural heritage preservation initiatives. 3D printing of digitized models of ancient industrial machines can play a significant role in accessibility, education, and cultural outreach, enabling a broader audience to access and interact with historical heritage.

In summary, although the 3D printing of the digitized model of the ancient grain grinding machine was not realized due to the encountered difficulties and time constraints, it is crucial to acknowledge its potential to enhance accessibility and cultural dissemination. This technology continues to evolve, and with proper research and investment, its use in future heritage preservation projects can be explored, ensuring that individuals with disabilities or access restrictions can also enjoy and engage with the historical richness represented by ancient industrial machines.

5.2 Future works

In light of the findings and challenges identified in this research project, there are several areas of future work and research that can be pursued to enhance the digitalization of ancient machinery and address the limitations encountered. These potential directions for future studies aim to improve the overall process and outcomes of capturing and representing these historical artifacts.

One avenue for future work involves the integration of advanced scanning technologies. While this project utilized a 3D scanner, future research can explore the utilization of more sophisticated techniques such as laser scanning or structured light scanning. These technologies offer higher precision and can capture finer details of intricate machinery, resulting in more accurate digital models.

Another important area of future research is the development of specialized software. The limitations experienced in data processing and analysis highlight the need for software that can handle large and complex datasets resulting from the digitalization of ancient machinery. Such software should provide robust tools for data treatment, point cloud alignment, and mesh refinement to ensure accurate and refined models.

To enhance accessibility and engagement, future research can focus on the integration of multi-sensory experiences alongside the digital models. This can involve the development of interactive virtual reality or augmented reality applications that allow users to virtually explore and interact with the machinery, providing a more immersive and educational experience.

Inclusion and accessibility should be prioritized in future research endeavours. Collaboration with accessibility experts can ensure that the resulting digital models and replicas are designed and optimized to meet the specific needs of individuals with disabilities, enabling a more inclusive experience for all.

Comparative studies can be conducted to evaluate the effectiveness and limitations of different digitalization methods, such as photogrammetry, laser scanning, and structured light scanning, in capturing the intricate details of ancient machinery. These studies can provide insights into the most suitable techniques for different types of machinery and improve the overall accuracy and quality of digital models.

Furthermore, future research should not only focus on the digitalization of individual machines but also on the preservation and documentation of industrial heritage as a whole. This can involve the development of comprehensive databases and platforms that house digital replicas, historical information, and interactive content related to industrial artifacts. Such platforms can

serve as educational resources and contribute to the long-term preservation of industrial heritage.

By exploring these future directions, researchers can overcome the limitations encountered in this study and further advance the field of digitalization of ancient machinery. The ultimate goal is to improve accessibility, promote cultural heritage, and facilitate a deeper understanding of industrial history through accurate and immersive digital representations of these remarkable artifact

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Appendix

Relatório de registro

Projeto	DefaultProject
Grupo	Scans
Período de gravação	25/01/2023 16:31:47 - 30/05/2023 17:43:57
Localização	
Data do relatório	21/06/2023 14:36:50

Codificação por cores

Erro de ponto	< 8 mm	> 20 mm
Sobreposição	> 25.0 %	< 10.0 %

Visão geral

Estatísticas do ponto de varredura

Erro de ponto máximo	2.5 mm
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Média de erro de ponto	1.4 mm
------------------------	--------

Sobreposição mínima	32.8 %
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Erros da varredura

Estatísticas do ponto de varredura

Cluster/Varredura	Conexões	Máx. Erro de ponto [mm]	Média de erro de ponto [mm]	Mín. Sobreposição
FARO_Scan_067	5	2.0	1.4	34.0 %
FARO_Scan_068	5	1.5	1.2	32.8 %
FARO_Scan_069	4	2.5	1.8	36.0 %
FARO_Scan_072	3	1.5	1.3	32.8 %
FARO_Scan_073	5	2.5	1.3	44.8 %
FARO_Scan_150	4	1.4	1.1	40.6 %

Erros detalhados

Estadísticas do ponto de varredura

Cluster/Varredura 1	Cluster/Varredura 2	Erro de ponto [mm]	Sobreposição
FARO_Scan_067	FARO_Scan_073	1.1	49.3 %
FARO_Scan_067	FARO_Scan_072	1.4	34.0 %
FARO_Scan_068	FARO_Scan_067	1.4	42.2 %
FARO_Scan_068	FARO_Scan_073	0.9	52.5 %
FARO_Scan_068	FARO_Scan_072	1.5	32.8 %
FARO_Scan_069	FARO_Scan_067	2.0	36.0 %
FARO_Scan_069	FARO_Scan_068	1.4	58.6 %
FARO_Scan_069	FARO_Scan_073	2.5	48.4 %
FARO_Scan_072	FARO_Scan_073	0.9	44.8 %
FARO_Scan_150	FARO_Scan_067	1.3	42.1 %
FARO_Scan_150	FARO_Scan_068	0.8	55.3 %
FARO_Scan_150	FARO_Scan_069	1.4	40.6 %
FARO_Scan_150	FARO_Scan_073	0.9	61.3 %

Incompatibilidades de inclinômetro

Cluster/Varredura	Varredura	Incompatibilidade [deg]
FARO_Scan_150	FARO_Scan_150	0.0116
FARO_Scan_069	FARO_Scan_069	0.0147
FARO_Scan_068	FARO_Scan_068	0.0249
FARO_Scan_067	FARO_Scan_067	0.0218
FARO_Scan_072	FARO_Scan_072	0.0287
FARO_Scan_073	FARO_Scan_073	0.0205

Relatório de registro

Projeto	Teste k
Grupo	Scans
Período de gravação	25/01/2023 16:31:47 - 30/05/2023 17:58:21
Localização	
Data do relatório	12/06/2023 11:26:36

Codificação por cores

Erro de ponto	< 8 mm	> 20 mm
Sobreposição	> 25.0 %	< 10.0 %

Visão geral

Estatísticas do ponto de varredura

Erro de ponto máximo	5.0 mm
Média de erro de ponto	1.8 mm
Sobreposição mínima	20.9 %

Erros da varredura

Estatísticas do ponto de varredura

Cluster/Varredura	Conexões	Máx. Erro de ponto [mm]	Média de erro de ponto [mm]	Mín. Sobreposição
FARO_Scan_150	7	2.0	1.3	25.5 %
FARO_Scan_151	5	5.0	4.2	20.9 %
FARO_Scan_149	8	3.5	1.7	25.5 %
FARO_Scan_072	8	5.0	2.0	22.9 %
FARO_Scan_073	8	2.3	1.3	34.8 %
FARO_Scan_067	6	1.4	1.2	29.2 %
FARO_Scan_068	9	4.8	1.6	20.9 %
FARO_Scan_069	8	1.9	1.5	22.9 %
FARO_Scan_070	8	3.6	2.5	26.6 %
FARO_Scan_071	9	4.1	1.6	29.2 %

Erros detalhados

Estatísticas do ponto de varredura

Cluster/Varredura 1	Cluster/Varredura 2	Erro de ponto [mm]	Sobreposição
FARO_Scan_150	FARO_Scan_073	0.9	47.1 %
FARO_Scan_150	FARO_Scan_067	1.1	36.4 %
FARO_Scan_150	FARO_Scan_071	1.0	30.8 %
FARO_Scan_150	FARO_Scan_070	2.0	26.6 %
FARO_Scan_150	FARO_Scan_149	1.3	25.5 %
FARO_Scan_151	FARO_Scan_070	3.6	43.5 %
FARO_Scan_151	FARO_Scan_071	4.1	53.7 %
FARO_Scan_151	FARO_Scan_072	5.0	29.0 %
FARO_Scan_149	FARO_Scan_151	3.5	46.3 %
FARO_Scan_149	FARO_Scan_070	1.8	92.7 %
FARO_Scan_149	FARO_Scan_071	1.1	62.3 %
FARO_Scan_149	FARO_Scan_072	1.6	41.3 %
FARO_Scan_149	FARO_Scan_073	1.6	34.8 %
FARO_Scan_072	FARO_Scan_070	3.6	38.1 %
FARO_Scan_072	FARO_Scan_073	1.0	44.8 %
FARO_Scan_067	FARO_Scan_072	1.4	34.0 %
FARO_Scan_067	FARO_Scan_073	0.9	61.2 %
FARO_Scan_067	FARO_Scan_071	1.3	29.2 %
FARO_Scan_068	FARO_Scan_150	0.9	40.6 %
FARO_Scan_068	FARO_Scan_151	4.8	20.9 %
FARO_Scan_068	FARO_Scan_149	1.5	38.2 %
FARO_Scan_068	FARO_Scan_072	1.0	32.9 %
FARO_Scan_068	FARO_Scan_073	0.9	59.6 %
FARO_Scan_068	FARO_Scan_067	1.1	46.9 %
FARO_Scan_068	FARO_Scan_069	1.1	58.6 %
FARO_Scan_068	FARO_Scan_070	2.3	37.6 %
FARO_Scan_068	FARO_Scan_071	1.2	43.7 %
FARO_Scan_069	FARO_Scan_150	1.5	38.4 %
FARO_Scan_069	FARO_Scan_149	1.5	44.0 %
FARO_Scan_069	FARO_Scan_072	1.8	22.9 %
FARO_Scan_069	FARO_Scan_073	1.5	48.6 %
FARO_Scan_069	FARO_Scan_067	1.2	30.8 %
FARO_Scan_069	FARO_Scan_070	1.9	44.9 %
FARO_Scan_069	FARO_Scan_071	1.4	32.7 %
FARO_Scan_070	FARO_Scan_073	2.3	35.1 %
FARO_Scan_071	FARO_Scan_072	0.9	54.5 %
FARO_Scan_071	FARO_Scan_073	1.1	40.5 %
FARO_Scan_071	FARO_Scan_070	2.5	59.5 %

Incompatibilidades de inclinômetro

Cluster/Varredura	Varredura	Incompatibilidade [deg]
FARO_Scan_068	FARO_Scan_068	0.0076
FARO_Scan_069	FARO_Scan_069	0.0176
FARO_Scan_150	FARO_Scan_150	0.0197
FARO_Scan_149	FARO_Scan_149	0.0480
FARO_Scan_151	FARO_Scan_151	-
FARO_Scan_067	FARO_Scan_067	0.0292
FARO_Scan_071	FARO_Scan_071	0.0084
FARO_Scan_072	FARO_Scan_072	0.0163
FARO_Scan_070	FARO_Scan_070	-
FARO_Scan_073	FARO_Scan_073	0.0046