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Digitization of Ancient Artefacts and Fabrication of Sustainable 3D-Printed Replicas for Intended Use by Visitors with Disabilities: The Case of Piraeus Archaeological Museum

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Abstract: The digitization of ancient artifacts and the fabrication of sustainable 3D-printed replicas present a promising solution for enhancing the accessibility to cultural heritage sites for visitors with disabilities. This article focuses on the case study of the Piraeus Archaeological Museum. The study investigates the process of digitizing a selection of ancient artifacts from the museum's collection and utilizing 3D printing technology to produce tactile replicas from recycled Polylactic Acid (PLA) material that provide a multisensory experience for individuals with disabilities like vision impairment. The research examines the technical challenges and considerations faced by the authors' team during the 3D scanning process of the artifacts, the manufacturing of raw material from 3D printing waste, as well as the optimization of 3D printing parameters to ensure the creation of high-quality 3D-printed replicas. Furthermore, the article points out the positive future impact that the 3D-printed replicas will have on the engagement and comprehension of vision-impaired visitors, highlighting the potential of this approach in promoting inclusivity and fostering a connection with cultural heritage.

Keywords: digitization; cultural heritage preservation; 3D scanning; 3D printing; museum; recycled PLA; FDM recycling; disabilities; social inclusion; special needs

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1. Introduction

The process of digitizing cultural heritage is of paramount importance in the preservation and dissemination of our extensive and varied human history. The utilization of digital technology to represent cultural artifacts, documents, artworks, and monuments serves to guarantee their enduring existence and ease of access for forthcoming generations. Through the process of digitization, these valuable artifacts are protected from the potential physical decay, loss, or devastation caused by natural calamities, conflicts, or neglect [1–5]. In addition, digital preservation facilitates extensive distribution, surpassing geographical limitations and granting individuals from diverse locations the opportunity to engage with and value cultural heritage that might otherwise be unattainable to them [6,7].

The process of digitization additionally enables and enhances the pursuit of research, education, and scholarship. Digital archives and databases offer researchers a convenient means of accessing a vast amount of information, thereby facilitating comprehensive studies and analysis. Virtual tours, interactive exhibits, and online resources have proven to be advantageous for students and learners as they provide an immersive experience and facilitate the exploration of cultural heritage [8]. The process of digitizing cultural heritage serves to democratize access to knowledge and comprehension of our shared historical legacy, thereby preventing its exclusive confinement to a select few individuals. This inclusive approach promotes the development of cultural appreciation, identity, and interconnectedness among diverse populations [9–11].

In addition, the process of digitization presents intriguing prospects for novel methodologies in the preservation and exploration of cultural heritage. The utilization of virtual reality (VR) and augmented reality (AR) technologies facilitates the creation of immersive experiences, thereby granting individuals the opportunity to engage with ancient sites, traverse historical periods, and interact with artifacts in manners that were previously inconceivable [12]. Digital restoration techniques have the capability to rejuvenate artifacts that have been damaged or undergone deterioration, effectively reinstating them to their initial state of magnificence. The process of digitization additionally facilitates the development of digital replicas, which in turn allows for a wider public accessibility to delicate or confidential artifacts, all the while maintaining the genuineness and soundness of the original items [13,14].

The process of digitizing cultural heritage has considerable importance for individuals with disabilities, as it affords them equitable opportunities to access and actively participate in our collective historical legacy. Digital platforms and resources possess the capacity to be purposefully crafted and modified in order to cater to a diverse range of disabilities, including but not limited to visual impairments, hearing impairments, and mobility limitations. Disabled individuals have the opportunity to engage with digitized artifacts, documents, and artworks using assistive technologies such as screen readers, captions, or tactile interfaces. This enables them to develop a more profound comprehension and connection to cultural heritage that may have been unattainable in conventional physical environments. The promotion of inclusivity enables individuals with disabilities to engage in cultural activities, thereby cultivating a sense of membership and guaranteeing the recognition and appreciation of their viewpoints and contributions [15–18].

The utilization of 3D scanning technology enables the generation of digital representations of tangible entities or surroundings. With the utilization of specialized scanners, such as those employing laser, structured light, or photogrammetry techniques, the process of 3D scanning is able to accurately capture the shape, texture, and geometric intricacies of tangible objects found in the physical world. The aforementioned procedure facilitates the generation of intricate digital models that can be utilized for a multitude of objectives, including but not limited to reverse engineering, quality assurance, virtual reality, and digital preservation [19–23].

One of the notable benefits of 3D scanning lies in its capacity to capture intricate and complex details that may present difficulties when attempting to replicate them using conventional measurement techniques. This feature renders it particularly valuable in disciplines such as industrial design, architecture, and forensics, where accurate dimensional information is of utmost importance. The utilization of 3D scanning technology also enables the establishment of digital archives and virtual museums, thereby contributing to the preservation of cultural heritage through the process of digitizing artifacts and archaeological sites. The use of this technology allows researchers, historians, and curators to effectively record, analyze, and disseminate significant artifacts and sites, thereby increasing their accessibility to a broader audience. Moreover, this approach serves to safeguard these valuable resources from potential harm or disappearance.

The advent of 3D printing has brought about a significant transformation in the manufacturing industry, leading to a revolution in the overall landscape of production processes [24]. The significance of this technology lies in its capacity to translate abstract concepts and designs into tangible manifestations with high accuracy and efficiency. Through the utilization of additive manufacturing techniques, 3D printers have the capability to fabricate objects in a sequential layer-by-layer manner. This process enables the production of intricate and complex structures that would pose significant difficulties or even be unattainable using conventional manufacturing methods. The versatility of this technology presents numerous opportunities in diverse industries such as aerospace, automotive, healthcare, and consumer goods [25–31].

One of the primary benefits associated with 3D printing lies in its inherent ability to facilitate customization and personalization. This technology enables individuals and businesses to customize designs in order to meet specific needs or preferences. The utilization of 3D printing technology allows for the production of individualized objects, such as personalized medical implants, customized fashion accessories, and unique architectural prototypes, at a comparatively affordable price. The degree of flexibility exhibited not only facilitates the generation of novel ideas but also improves the satisfaction of customers by providing products that precisely meet their specific needs. Furthermore, the utilization of 3D printing technology contributes to the advancement of sustainability efforts through the reduction of material waste and carbon emissions. This is primarily achieved by the inherent characteristic of 3D printing to require fewer resources in comparison to conventional manufacturing processes [32–35].

The alignment between the concept of the circular economy and the principles of 3D printing renders the latter a catalyst for sustainable manufacturing. The utilization of 3D printing technology presents distinct prospects for enhancing material efficiency, minimizing waste generation, and establishing closed-loop systems. The utilization of recycled or upcycled materials as feedstock for printing in a circular economy framework is facilitated by 3D printing, thereby reducing the reliance on virgin resources. The utilization of recycled plastics or other materials leads to a substantial reduction in the environmental impact of production, as it effectively decreases both energy consumption and waste generation. Furthermore, the utilization of 3D printing technology enables the production of goods as needed, thereby diminishing the requirement for extensive manufacturing processes and the consequent expenses related to transportation and storage. This, in turn, contributes to the establishment of a more streamlined and environmentally conscious system [36–39].

Furthermore, the application of the circular economy framework in the context of 3D printing encompasses the notion of prolonging the lifespan of products and effectively managing their disposal at the end of their useful life. Instead of completely discarding or replacing entire products, the utilization of 3D printing enables the facilitation of repairing and replacing specific parts or components. This approach facilitates the transition from a linear model characterized by the "take-make-dispose" paradigm to a circular model, wherein products are intentionally designed to possess longevity and facilitate ease of repair. The implementation of localized production and repair through 3D printing technology results in a reduction in waste, an extension of product lifespan, and an optimization of resource efficiency. In general, the application of circular economy principles to the field of 3D printing offers a promising opportunity for sustainable manufacturing. This approach aims to reduce waste, preserve resources, and fundamentally transform the processes of production and consumption [40,41].

In this study, a digitization process is presented regarding two statues preserved in the Archaeological Museum of Piraeus. The first one is known as the "Apollo of Piraeus" and is the only surviving bronze kouros and possibly the oldest known cast statue. It is presented separately from the rest of the bronze statues from the 1959 excavation. The god is identified by the bow, which is completed in the left hand, and in the right hand he held the (likely) golden flask. The goldsmith Apollo is also betrayed by the count, who, like the teenager, was covered with a thin sheet of gold. However, on a deeper level, the identification with god can now be founded on the ethos of the form. Our admiration in front of the statue is accompanied by the feeling of a high moral, a moral search, which—beyond the visible—directs the mind to a divine reality. Figure 1 depicts restoration operations on the aforementioned statue.

The second statue is known as the statuette of "Artemis Kindyas". The column-like statue of this eastern goddess is emphasized by the pose of the arms wrapped up in the belted himation. It was made in a hellenistic island workshop, probably around 1st cent. B.C. Figure 2 depicts the aforementioned statue being preserved in the Archaeological Museum of Piraeus.

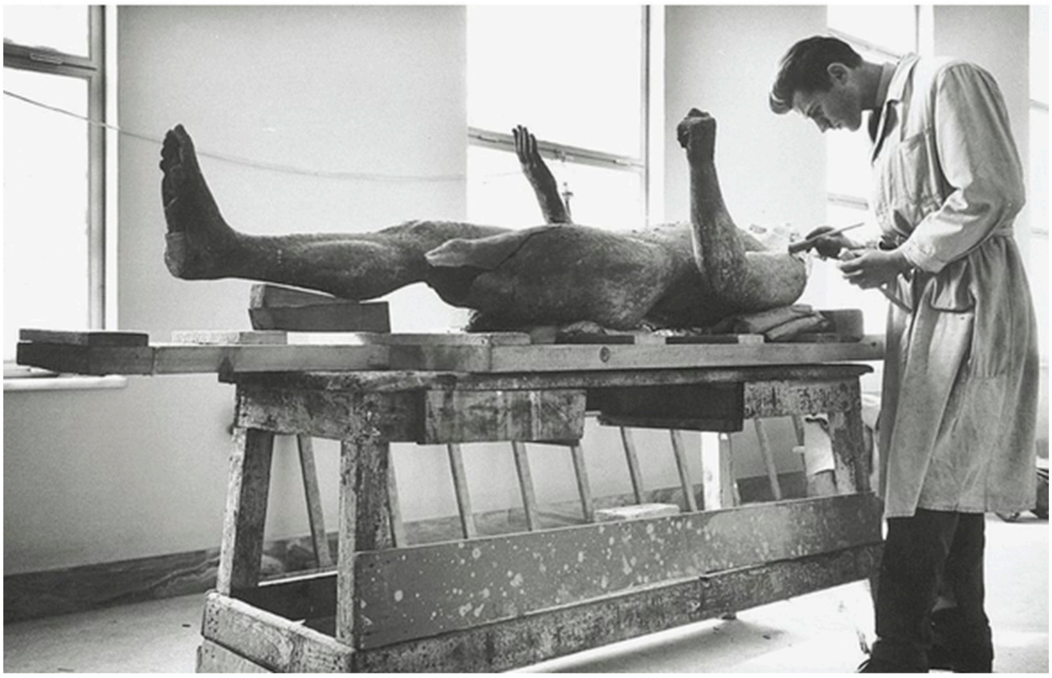

Figure 1. Christos Hatziliou maintains the bronze Apollo of Piraeus. National Archaeological Museum, February 1960 [42].

Figure 2. Marble statuette of Artemis Kindyas.

Both statues were found by chance in July 1959 due to drainage works at the intersection of Vasileos Georgiou I and Filonos streets, behind the Tinaneos garden in Piraeus, as shown in Figure 3. The excavation work was directed by the director of the Archaeological

Service, Ioannis Papadimitriou and the curator of Antiquities, Efthymis Mastrokostas. The statues had been stored in some area of the ancient port and were subsequently buried in order to be protected during the siege and destruction of Piraeus, in 86 BC, by the Roman general Lefkius Cornelius Sulla. After their discovery, they were sent to the National Archaeological Museum for preservation until February 1983, when they were returned to the Archaeological Museum of Piraeus [42].

Figure 3. Image from the excavation site where the statues were found [42].

The primary focus of this article centers around the case study conducted on the Piraeus Archaeological Museum. The procedure of digitizing a subset of historical artifacts from the museum's assortment and employing 3D printing technology to fabricate tangible replicas using recycled PLA material from 3D printing waste in the context of circular economy, thereby offering a multisensory encounter for individuals with visual impairments, is presented. This study investigates the technical complexities and factors associated with acquiring precise digital renditions of artifacts, producing raw materials from waste generated by 3D printing waste, and optimizing 3D printing parameters to guarantee the production of replicas of the desired quality. Moreover, the article examines the introduction of 3D-printed replicas on the engagement and comprehension of individuals with visual impairments. It emphasizes the potential of this method in promoting inclusivity and establishing a connection with cultural heritage. The results underscore the significance of integrating accessibility measures within cultural institutions and offer valuable insights into the potential advancements of digitization and 3D printing in augmenting the museum experience for individuals with visual impairments.

2. Materials and Methods

In this article, the use of 3D scanning, 3D printing, and material recycling equipment is being presented in order to successfully fabricate scaled replicas of the two aforementioned statues. More specifically, an Artec™ Eva™ 3D scanner (Senningerberg, Luxembourg) was used, which facilitates the high-resolution, three-dimensional scanning of objects, particularly statues, with exceptional precision and accuracy [43,44]. Designed for professional applications in the field of digital preservation and analysis, the scanner employs structured light scanning technology to capture the intricate details of the object's surface. The Artec 3D Eva scanner features a lightweight design, enhancing its portability and ease of use during the scanning process. It exhibits an elevated scanning speed, enabling efficient and time-effective data acquisition. Additionally, the scanner is equipped with advanced tracking algorithms and real-time fusion capabilities, ensuring the seamless integration of individual scans into a cohesive 3D model. This scanner stands out for its ability to capture both geometry and texture, offering a comprehensive representation of the scanned object. Its high-resolution imaging capabilities and reliable performance make it suitable for professionals in the fields of archaeology, cultural heritage preservation, art restoration, and various industrial applications. Artec Studio 3D 14 software was used in the post-processing stages of the 3D Scanning procedure in processes like mesh cleaning/preparation and scan alignments. Figure 4 depicts the aforementioned 3D scanner that was being used in this case.

Figure 4. Artec™ L-1748 (Senningerberg, Luxembourg) Eva™ 3D scanner used for digitizing statue replicas.

The employed 3D printing equipment, the Raise3D™ Pro2™ Plus 3D printer [45], exhibits a diverse array of features and capabilities tailored for professional applications. The printer's construction prioritizes meticulous precision and operational efficiency, utilizing Fused Filament Fabrication (FFF) technology to fabricate intricate three-dimensional objects through a layer-by-layer approach. The Pro2 Plus model distinguishes itself with a notable build volume, enabling the production of large-scale statues and complex structures. Additionally, its dual extrusion system facilitates the simultaneous printing of multiple materials or colors, contributing to the creation of visually captivating and functionally versatile objects. Enhanced stability and print quality are ensured through the robust and enclosed build chamber, which mitigates the influence of external factors on the printing process. Advanced functionalities such as automatic bed leveling, filament detection, and power failure resumption further enhance the printer's user-friendliness and seamless printing experience. The Pro2 Plus model's high-resolution printing capability enables the accurate replication of fine details, resulting in visually remarkable representations of scanned objects. In summary, the Raise3D Pro2 Plus 3D printer emerges as a dependable and adaptable tool, empowering professionals in realizing intricate and complex designs within the additive manufacturing domain. Figure 5 depicts the aforementioned 3D printer that was being used in this case.

Figure 5. Raise3D™ Pro2™ Plus 3D printer used to fabricate the scaled statue replicas.

In the process of producing recycle raw material to fabricate the statue replicas, the 3DEvo™ SHR3Dit™ and 3DEvo™ Composer™ equipment were employed to recycle Polylactic Acid (PLA) filament derived from failed 3D prints and removed support structures [46]. The 3D Evo SHR3Dit serves as a filament recycling system designed specifically to process waste 3D-printed materials. It utilizes a series of shredding, cutting, and pelletizing steps to transform discarded PLA prints and supports into usable plastic granulates. The 3D Evo Composer, on the other hand, functions as a filament maker; the pellets and granulates are fed into the extruder to melt and reform into filament form, ensuring the consistent production of high-quality filament from the recycled PLA material. Figure 6 depicts the aforementioned material shredding equipment that was used in this case.

Figure 6. 3D Evo SHR3Dit material shredding equipment that was used in this case.

The recycling procedure involves a meticulous separation process to ensure the utilization of only white-colored PLA for a clean and uniform outcome. Failed prints and support structures are carefully sorted, and any non-white PLA components are eliminated from the recycling process. The remaining white PLA waste is then processed through the 3D Evo SHR3D, where it undergoes the shredding, cutting, and pelletization stages. Once converted into small granulates, the recycled PLA material is mixed with virgin PLA material at a ratio of 70% recycled material and 30% virgin material. This blending approach combines the sustainability benefits of recycling with the desirable properties of virgin PLA, such as consistency and reliability, resulting in a filament with optimal printing characteristics. Figure 7 depicts the aforementioned material shredding equipment that was used.

Figure 7. 3D Evo Composer filament maker equipment that was used in this case.

The integration of the 3D Evo SHR3D and 3D Evo Composer showcases an effective and sustainable approach to reducing waste in 3D printing. By employing advanced recycling machinery, the process enables the reuse of discarded PLA materials, thereby minimizing environmental impact and promoting a circular economy within the additive manufacturing industry.

3. Results

The scanning process took place at the exhibition area of the Piraeus Archaeological Museum, utilizing the Artec Eva 3D scanner's portability. This feature enabled the scanner to be easily transported and positioned for the capture of the intricate details of the statues. Both exhibits, the god Artemis statue and the Apollo of Piraeus statue, presented surfaces with textures suitable for scanning using a structured light 3D scanner. The statue of Artemis, crafted from marble, offered a generally non-reflective texture that allowed the 3D scanner to acquire a substantial amount of accurate geometric data. The scanner's structured light technology effectively captured the fine contours and features of the marble statue, ensuring a comprehensive representation of its form. Figures 8 and 9 depict the actual 3D scanning operations performed in the Archaeological Museum of Piraeus by members of the authors' team on the 27 June 2023.

Figure 8. Actual 3D scanning operations of the Artemis statue performed in the Archaeological Museum of Piraeus by members of the authors' team.

In contrast, the Apollo of Piraeus statue, made of copper, posed a unique challenge due to the metal's inherent reflective properties. However, the scanning process was still feasible due to the material's oxidation over the years. The copper surface had transformed into a non-reflective green state, which was easily scannable using the structured light technology. This serendipitous transformation allowed the scanner to accurately capture the intricate details and surface characteristics of the Apollo statue, providing a comprehensive digital representation.

Moreover, the large scale of the statues presented an additional obstacle during the scanning process. To ensure the accurate scanning of all parts of the statues' bodies without overlooking any surface areas, a ladder and an extension cable were utilized. These tools facilitated the positioning of the scanner at different angles and distances, enabling a comprehensive coverage of the statues' surfaces. Additionally, due to the statues' significant size and the high level of detail captured, the collected data had to be saved in multiple project files. This approach was necessary to manage the vast amount of data and ensure efficient processing, as the complexity of the statues' features exceeded the computational capacity of a single project file.

Figure 9. Actual 3D scanning operations of the Apollo of Piraeus statue performed in the Archaeological Museum of Piraeus by members of the authors' team.

The post-processing procedure involving the collected data is often the most challenging phase in the digitization process. It involves several crucial steps to convert the individual scan files into a high-detail, prinTable 3D model. Firstly, the scan data must be meticulously cleaned to remove any unwanted noise or artifacts. This process requires the designer's careful attention, as they need to delete small sections at a time with precise movements to preserve the integrity of the statue. Various tools from Artec Studio 3D 14 software are employed during this cleaning stage to ensure a thorough removal of unwanted elements. Figure 10 shows the acquired data from the 3D scanning process at the post-processing stage.

Secondly, the individual scan data must be accurately aligned to maintain the statue's geometry without any overlapping surfaces. To achieve this, certain preparatory steps are taken during the scanning procedure. For instance, when scanning parts of the statue's body that are detached, such as the hands, additional reference points are placed in the scanned area. These reference points aid in the alignment process and are subsequently deleted. Figure 11 depicts the acquired data from the 3D scanning process at the alignment phase, post processing procedure.

Once the individual scan data are cleaned and properly aligned, the registration procedure takes place, where the scans are fused together to create a workable mesh file. Subsequently, post-processing steps are conducted on the mesh object. Initially, a "small object filter" is applied to eliminate small mesh objects that may have resulted from unwanted noise in the data. Additionally, certain areas of the body that were not captured accurately, such as the spaces below the armpits or between the fingers, may contain holes in the mesh. To address this, the designer can bridge and fill these areas using surrounding geometry data as a reference, ensuring the overall accuracy of the features.

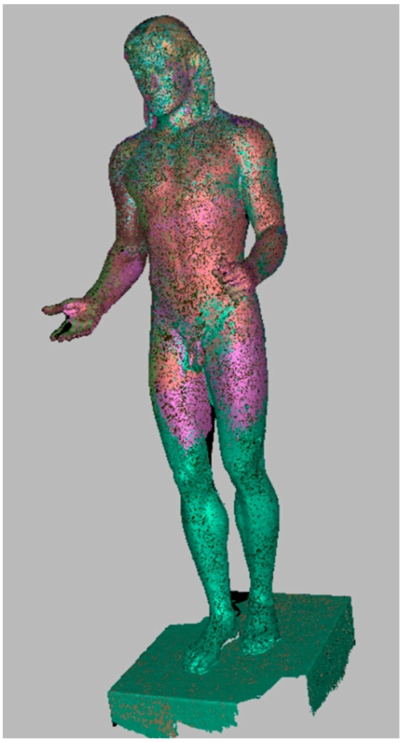

Figure 10. Acquired data from the 3D scanning process at the post-processing stage.

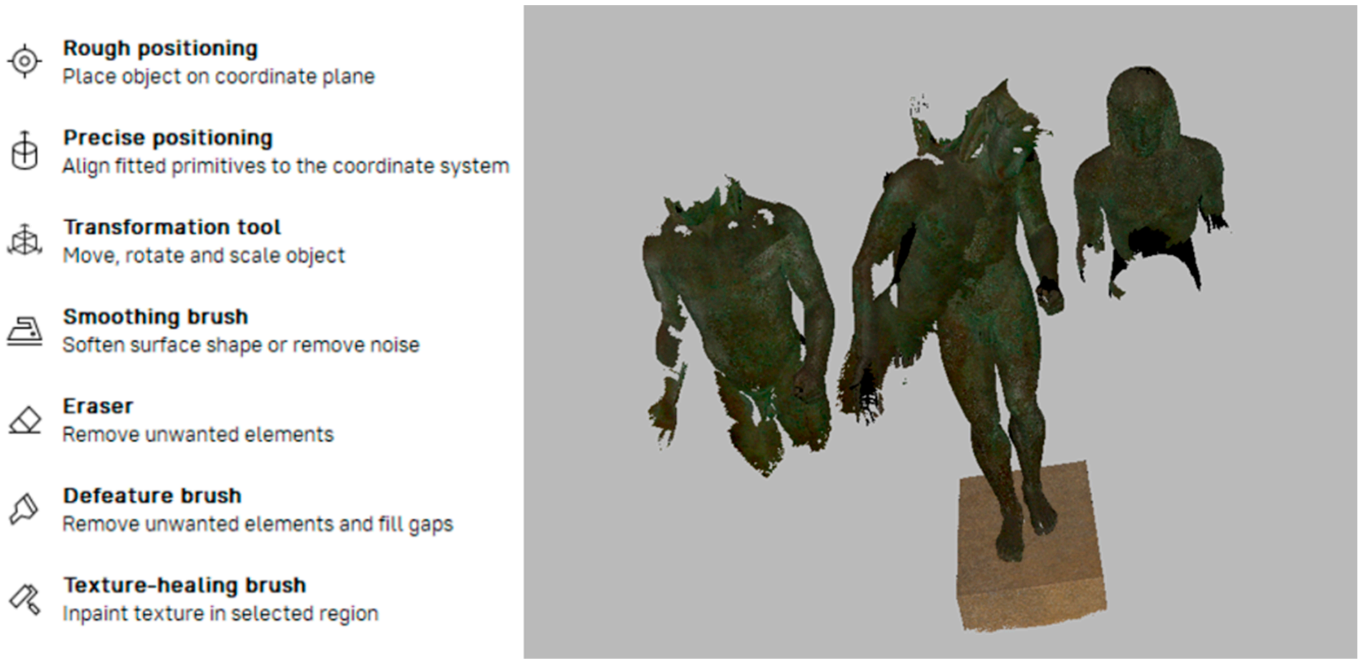

Figure 11. Acquired data from the 3D scanning process at the alignment phase, post processing procedure.

During the continuation of the process, the designer focuses on smoothing surfaces that exhibit noise or imperfections resulting from the scanning process. This step requires utmost care to avoid removing important details from the statue's geometry. Once these post-processing steps are completed, the 3D mesh file becomes a solid representation of the statue and is ready for 3D printing. However, an optional step involves applying texture and color to the 3D model. Although the texture is not utilized during the printing process, it is crucial for the creation of an accurate digital twin of the object. Following this optional step, the 3D mesh file can be saved in formats such as obj, 3mf, or stl, and then sent to slicing software for further preparation. Both obj and 3mf file formats retain color information, whereas the stl format is commonly used in the 3D printing industry but does not include color information. Figure 12 depicts the final 3D model obtained after the end of the post-processing stage.

Figure 12. Final 3D model obtained after the end of the post-processing stage.

The slicing settings play a critical role in the 3D printing process, ensuring optimal printing parameters for the Apollo of Piraeus statue and the statue of Artemis. For both statues, a 20% infill setting was chosen, which determines the internal density of the printed object. This infill percentage strikes a balance between structural integrity and material conservation. Additionally, a layer height of 0.2 mm was selected, determining the vertical resolution of each printed layer. This choice strikes a balance between print quality and printing speed, producing smooth surfaces while maintaining reasonable print times.

To ensure efficient and accurate printing, a printing speed of 60 mm/s was set. This speed determines how quickly the printer's extruder moves along the X and Y axes during the printing process. The chosen speed enables a balance between printing time and print quality, ensuring reliable and time-effective results. Moreover, a Z-hop setting was implemented to assist with these tall objects. This feature enables the printer's nozzle to lift slightly when moving across the printed object's surface, reducing the chances of collision and preventing any unwanted dragging of the material.

Regarding temperature settings, the bed temperature was set to 60 °C, ensuring the proper adhesion of the PLA material to the print bed. This temperature promotes a stable printing environment and prevents the warping or detachment of the printed object during the process. Furthermore, the extruder temperature was set to 210 °C, which is suitable for recycled PLA material. This temperature allows for the efficient melting and extrusion of the recycled PLA, enabling successful layer bonding and consistent print quality throughout the printing process.

Once the slicing settings were finalized, the next step involved exporting the prepared 3D model to G-code format. G-code contains the instructions that control the printer's movements, temperatures, and extrusion during the printing process. The G-code file generated from the slicing software contains all the necessary information, such as layer-by-layer instructions, infill patterns, and speed settings, to accurately reproduce the digital model as a physical object. This G-code file is then transferred to the 3D printer, which interprets and executes the instructions, layer by layer, thus fabricating the Apollo of Piraeus statue and the statue of Artemis in a precise manner. Figure 13 shows a screenshot of the slicing process, and Figures 14–16 show one of the statues' replicas upon the completion of the 3D printing process.

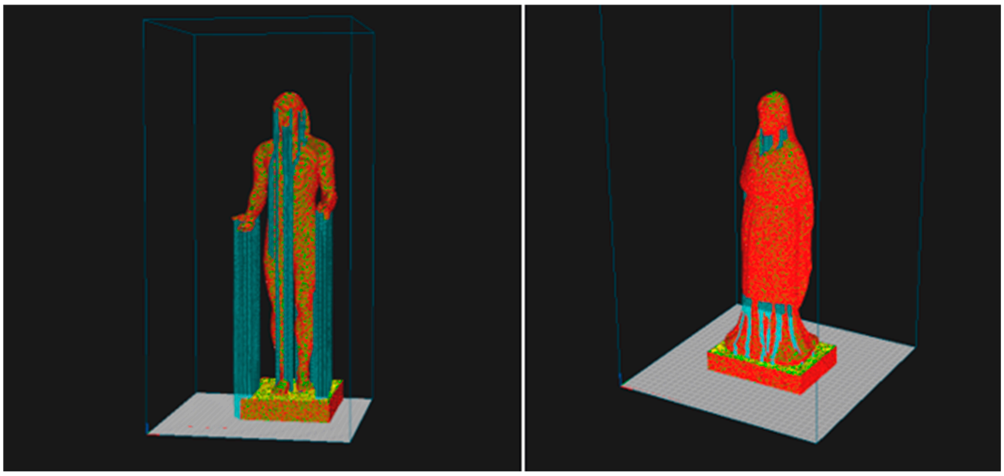

Figure 13. Final 3D model obtained after the end of the post-processing stage.

Figure 14. Apollo of Piraeus statue replica upon the completion of the 3D printing process.

Figure 15. Apollo of Piraeus statue replica upon the completion of the 3D printing process and support structures removal.

Figure 16. Artemis Kindyas statue replica upon the completion of the 3D printing process and support structures removal.

4. Discussion

Performing 3D scanning in a museum can present several challenges and potential problems. Firstly, the delicate nature of artifacts and artworks raises concerns about potential damage during the scanning process. The equipment and movement required for scanning could accidentally cause vibrations or collisions, endangering the integrity of the objects. Additionally, the presence of valuable and irreplaceable items raises security issues, as the scanning process may require the temporary removal of items from their controlled environments. Ensuring the safety and protection of these artifacts is paramount. Another challenge lies in capturing accurate and detailed scans. Museums often have objects with intricate textures, fine details, and reflective surfaces, making it difficult to achieve high-quality scans that capture the true essence of the object. Lighting conditions and reflections can further complicate the scanning process, leading to incomplete or distorted scans. Finally, time constraints can be a factor as well. Museums have limited access to artifacts due to exhibition schedules and visitor traffic, making it challenging to allocate sufficient time for comprehensive scanning processes. Overcoming these problems necessitates careful planning, expertise in scanning techniques, and close collaboration between museum staff and scanning specialists to ensure the preservation and accurate documentation of the museum's valuable collection.

Moreover, the process of 3D scanning, particularly in complex environments such as museums, often demands the utilization of high-performance computers. The specified system requirements include HD: Intel Core i7 or i9, 32 GB RAM, NVIDIA GPU with CUDA 6.0+ and at least 2 GB VRAM; and SD: Intel Core i5, i7 or i9, 12 GB RAM, GPU with 2 GB VRAM. Therefore, such computers need to possess robust processing power, advanced graphics capabilities, and ample storage capacity to handle the large amounts of data generated by scanning equipment. High-performance CPUs with multiple cores and high clock speeds are crucial for efficient data processing and the reconstruction of 3D models. Additionally, powerful GPUs (Graphics Processing Units) are essential for real-time rendering, enabling the accurate visualization and analysis of the scanned objects. Ample RAM is required to handle the vast datasets and ensure smooth data processing. Furthermore, the storage system should offer high-speed access to accommodate the large file sizes produced during the scanning process. Utilizing such high-performance computers ensures the timely and accurate processing of the acquired data, facilitating the creation of detailed and realistic 3D models of the museum artifacts.

Despite the significant advancements in 3D scanning technology, certain challenges and limitations exist that are inherent to its utilization. Several issues are frequently encountered when working with 3D scanners, such as obtaining optimal levels of accuracy and resolution. This poses a significant challenge in the context of 3D scanners, particularly when confronted with intricate forms or minute intricacies. The ability of scanners to accurately capture minute details or complex surface textures may be limited, leading to a decrease in the level of precision and accuracy in the resulting scanned model.

In addition, the process of scanning reflective surfaces poses challenges for 3D scanners, particularly when dealing with materials that exhibit high reflectivity or transparency. These materials may introduce challenges in obtaining precise data as a result of light reflections or refractions, resulting in scans that are either incomplete or distorted. In our case, both statues were made out of non-reflective materials, thus facilitating the process of 3D scanning.

Furthermore, 3D scanning is characterized by its time-consuming nature and inherent complexity, necessitating a high level of expertise and patience. The appropriate configuration, arrangement, and calibration of the scanner are of utmost importance, and the process of scanning sizable or complex objects can be time-consuming. Furthermore, the process of post-processing and data alignment may be necessary in order to integrate multiple scans or rectify any errors, thereby contributing to the overall intricacy of the task. One limitation of scanners is their restricted range and field of view, which can hinder their ability to effectively scan larger objects or capture a wide area in a single scan. This constraint has the potential to impose restrictions on the efficacy of scanning various types of objects.

What is more, the cost of advanced 3D scanning equipment can be relatively high, thereby limiting its accessibility to individuals or small enterprises. The financial implications associated with acquiring high-quality scanners, as well as the accompanying software and hardware infrastructure, may pose a significant obstacle for individuals seeking to employ 3D scanning technology.

Another question is whether the aforementioned work aligns with the Sustainable Development Goals (SDGs), also known as the Global Goals, that were set by the United Nations in 2015 as a universal call in order to end poverty, protect the planet, and ensure that by 2030, all people have reached certain standards of peace and prosperity [47–49]. In this context, this work addresses SDG 4 (Quality Education) by promoting inclusive and accessible learning experiences for disabled individuals. Through 3D-printed replicas, it enables these visitors to engage with cultural heritage and history, fostering a sense of connection and understanding. Additionally, the article contributes to SDG 9 (Industry, Innovation, and Infrastructure), as it showcases the integration of cutting-edge technologies, such as digitization and 3D printing, to preserve ancient artifacts while promoting sustainability. Furthermore, the research directly aligns with SDG 11 (Sustainable Cities and Communities) by enriching the cultural offerings of the Piraeus Archaeological Museum, making it more accessible to diverse groups of people, including those with visual impairments. Overall, this article discusses how technology and innovation can bridge gaps in inclusivity and contribute to sustainable development in the field of cultural heritage and tourism.

Other literature works also present the important topic of the need for accessibility of art and archaeology museums, like the published work of Alonso Tak and Pazos-Lopez under the title "Socializing Art Museums. Rethinking the Publics' Experience" [50–53]. As future work, in accordance with all the aforementioned data presented in this manuscript, the authors' team's intention is to also conduct a small-scale survey regarding the impact of this initiative on the greater experience that such visitors will enjoy during their Museum visit. The procedure is yet to be planned, along with other relevant actions, in the context of social inclusivity.

5. Conclusions

In conclusion, the case of the aforementioned operations conducted at the Piraeus Archaeological Museum demonstrates the potential of digitization and 3D printing in improving the accessibility to cultural heritage sites for visitors with disabilities. By utilizing these technologies, the study successfully captured accurate digital representations of ancient artifacts and produced tactile replicas using sustainable, recycled PLA material. The investigation of technical challenges involved in the process, such as capturing accurate digital representations and optimizing 3D printing parameters, has provided valuable insights for future implementations. This article also highlighted the positive impact of these 3D-printed replicas on the engagement and comprehension of individuals with disabilities like vison impairment, underscoring the significance of inclusivity and connection with cultural heritage. The findings emphasized the importance of integrating accessibility measures within cultural institutions and shed light on the future prospects of digitization and 3D printing in enhancing the museum experience for individuals with visual impairments. Future work includes the continuation and expansion of the aforementioned operations in the Archaeological Museum of Piraeus, in terms of digitizing and fabricating statue and other artifact replicas in addition to other tactile aids for visitors with disabilities, bridging the accessibility gap and fostering a deeper appreciation of ancient artifacts for all visitors.

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