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3D Imaging and Additive Manufacturing for Original Artifact Preservation Purposes: A Case Study from the Archaeological Museum of Alexandroupolis

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Featured Application: 3D scanning of ancient artifacts and subsequent 3D printing of their scaled replicas for cultural heritage preservation purposes.

Abstract: This study explores the use of advanced 3D imaging and printing technologies to digitally document and physically replicate cultural artifacts from the Archaeological Museum of Alexandroupolis. By employing structured light scanning and additive manufacturing techniques, detailed digital models and precise physical replicas of two significant artifacts were created—a humanoid ceramic vessel and a glass cup. A handheld 3D scanner was utilized for capturing intricate surface details, with post-processing methods to refine and colorize the digital models. Regarding 3D printing, both Fused Deposition Modeling (FDM) and Stereolithography (SLA) were employed, tailored to the artifacts' unique requirements for resolution and material properties. This dual approach supports heritage preservation by generating tangible educational resources and providing alternative exhibits to safeguard original artifacts. Our results demonstrate that integrating 3D scanning and printing effectively enhances the accessibility, durability, and educational utility of cultural heritage assets, offering a sustainable model for artifact preservation and study.

Keywords: 3D scanning; 3D printing; cultural heritage preservation; SLA 3D printer; FFF 3D printer; museum; Alexandroupolis; Greece

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1. Introduction

The preservation of cultural heritage is one of the most significant challenges in modern society. As archaeological and cultural artifacts naturally deteriorate over time, the need for innovative, noninvasive preservation methods becomes increasingly urgent [1–3]. This study explores the application of advanced 3D imaging and 3D printing technologies for documenting and replicating high-value cultural artifacts. The primary goal of this experimental approach is to develop an efficient workflow that enables both high-resolution digital documentation and precise physical reproduction of selected objects from museums and archaeological sites, utilized for various purposes.

Cultural management in the modern era demands innovative strategies to ensure the preservation, accessibility, and meaningful dissemination of a region's heritage [2].

In Greece, a nation endowed with a rich historical legacy, it is imperative that cultural professionals, museum curators, and policymakers develop interdisciplinary approaches to safeguard artifacts for both current and future generations [3]. By leveraging advanced technologies such as 3D scanning and additive manufacturing, cultural managers can produce highly accurate digital archives of significant objects, ensuring that their aesthetic and historical value remains intact despite environmental, logistical, or conservation challenges [4].

Equally important is the communication of Greek heritage in an accessible and engaging manner. Museum visitors, researchers, and educational institutions benefit from tangible learning experiences that bridge the gap between past civilizations and contemporary audiences. Accurately replicated, scaled 3D-printed models can transform distant or delicate objects into interactive teaching tools. These replicas enhance understanding and appreciation of cultural objects by allowing hands-on exploration and serve as catalysts for critical discourse about historical context, craftsmanship, and cultural significance. As a result, the communication of Greek heritage expands beyond traditional exhibitions to more participatory, learner-centered formats, promoting inclusive narratives and intercultural dialogue [2].

This synthesis of cultural management and communication strategies redefines how institutions approach preservation and public engagement. By incorporating technology-driven solutions, Greek cultural organizations can transcend geographical and physical barriers, providing digital platforms and traveling collections that bring heritage into classrooms, community centers, and research facilities worldwide. These practices support cultural sustainability: they protect authentic artifacts, nurture international scholarly collaboration, and present the richness of Greek cultural identity in ways that resonate with diverse audiences. In doing so, they ensure that Greece's legacy persists and evolves in meaningful, adaptive ways, reinforcing the role of cultural heritage as a dynamic resource rather than a static relic of the past [3].

In this context, 3D scanning is a technology that captures the precise shape, surface details, and dimensions of physical objects by generating a highly accurate digital model. Using a variety of methods—such as structured light scanning or laser scanning—3D scanners project patterns or laser beams onto an object, then capture the reflected data with sensors or cameras. These data are processed to create a digital 3D model that represents the object in high detail [4]. In cultural heritage preservation, 3D scanning plays an invaluable role by enabling noninvasive documentation of artifacts, monuments, and sites [5,6]. This is especially important for delicate or immovable items, where physical contact can lead to deterioration. Through high-resolution scans, museums, conservators, and researchers can create digital replicas that provide a permanent, unalterable record of the item's current state. These models can be studied in depth, analyzed, and compared over time to assess wear or damage, contributing to long term preservation planning. Additionally, 3D scanning facilitates access and education by producing digital copies of artifacts, which can be shared globally for academic research or public exhibitions. These models can also be used for virtual tours, online museums, and interactive learning experiences, broadening access to cultural heritage beyond physical limitations. In some cases, scanned data are used to produce accurate physical replicas through 3D printing, which can serve as substitutes in exhibitions or educational contexts, protecting the original artifacts from potential risks [7–10]. Ultimately, 3D scanning is becoming an essential tool in heritage preservation, offering a sustainable means to document, analyze, and share cultural assets with minimal impact on the original items.

On the other hand, 3D printing, also known as additive manufacturing, is a process that creates physical objects by layering material based on a digital 3D model. Common 3D printing techniques include Fused Deposition Modeling (FDM), which uses thermoplastic filaments, and Stereolithography (SLA), which uses a photopolymer resin cured with UV light to achieve higher precision [11,12]. In cultural heritage preservation, 3D printing serves as a valuable tool by enabling the creation of exact replicas of artifacts, structures, and even large-scale archaeological findings. These replicas are invaluable in settings where the originals are too fragile, rare, or sensitive to handle, display, or transport [10]. By using digital 3D scans of the artifacts, conservators can produce accurate models that replicate the original piece's geometry, texture, and even, in some cases, color. These 3D-printed replicas serve multiple purposes: they are used in exhibitions as stand-ins to safeguard the originals, allowing the public to interact closely with the replica without risking damage to priceless items [13]. In educational settings, they provide hands-on experiences that deepen understanding and appreciation of historical artifacts. Three-dimensional printing is also used in restoration efforts, where missing parts of an artifact can be digitally reconstructed and printed, making it possible to restore items without permanently altering the original material. This approach preserves authenticity while making objects more complete and visually understandable [14]. Through these initiatives, 3D printing extends the reach and impact of cultural heritage preservation, allowing heritage institutions to balance access and preservation, while opening up new ways for people to engage with history.

This study incorporates advanced 3D scanning methodologies to digitally preserve and document two significant artifacts from the Archaeological Museum of Alexan droupolis: a humanoid ceramic vessel (code: AMAL 2131) and a glass vessel (code: AMAL 2113). These artifacts are invaluable due to their detailed craftsmanship and the cultural symbolism they hold, reflecting the artistic traditions of one of the most important Neolithic settlements in the Balkans. Specifically, the site near the village of Makri, located south of Alexandroupolis, is a noteworthy Neolithic settlement that dates back to around 6200 BCE and continued for at least a millennium. Archaeological finds from the region, particularly ceramic artifacts, reveal continuous habitation from the Neolithic to the historic periods, characterized by a variety of objects like tools, vessels, figurines, clay tables, loom weights, and other artifacts that delineate daily life in the settlement.

The humanoid vessel, spherical in shape and crafted from high-quality clay, exemplifies the Neolithic ceramic traditions of Southern Balkans, standing out in the Greek region for its size, preservation, and intricate artistic style. This artifact is estimated to date back to the second half of the 6th millennium BCE, a testament to the region's cultural and artistic developments. Excavations at the site have also uncovered traces of a classical and Hellenistic city that likely served as a trading post, possibly associated with the Peraia of Samothrace. The site includes deposits used for discarding broken or unwanted items, which have yielded extensive insights into the local material culture. The site's usage appears to have persisted sporadically until the end of the 1st century BCE, with renewed activity during the early Christian centuries. Finds from these deposits, such as amphorae with stamped handles, loom weights, and other diverse artifacts from the 5th to 4th centuries BCE, add depth to the understanding of the historical continuity in this area. Figure 1 depicts the two aforementioned artifacts.

The methodology involves a two-phase process: 3D scanning of artifacts followed by 3D printing of their scaled replicas. In the scanning phase, structured light scanning technology captures the complex geometries and intricate surface features of culturally significant objects, such as sculptures, decorative items, and ceramics. The accuracy of the digital model depends on several factors, including lighting conditions, surface reflectivity, and the object's size, which require careful selection of equipment and scanning techniques.

The raw data are then processed to generate a high-fidelity digital model suitable for subsequent 3D printing applications.



Figure 1. Humanoid vessel (code: AMAL 2131) and glass vessel (code: AMAL 2113).

In the printing phase, the digital models are transformed into physical replicas using Fused Deposition Modeling (FDM) and Stereolithography (SLA) [15]. FDM is chosen for its accessibility and compatibility with thermoplastic materials, while SLA provides higher resolution, making it ideal for reproducing intricate details. The combination of FDM and SLA optimizes material strength and reproduction quality according to each artifact's specific requirements [16,17].

By integrating high-resolution digital imaging with sophisticated 3D printing techniques, this study bridges the digital and physical worlds, enabling the preservation of cultural assets in both formats. The replicas produced through this process serve various purposes, including educational tools, conservation research, and museum displays, enhancing accessibility and engagement with cultural heritage. This dual methodology underscores the role of technological innovations in advancing the study, preservation, and accessibility of cultural artifacts.

2. Materials and Methods

The materials and methods chapter, focusing on the 3D scanning process for this study, includes a description of the equipment used and the techniques applied to capture precise digital models of cultural heritage objects. Given the importance of recording fine details, the EinScan Pro 2x, a portable scanner from Shining 3D^{TM} (Hangzhou, China) was selected as the primary equipment. This scanner offers a dual-mode function, operating both as a handheld scanner and as a stationary scanner with a rotating platform. This dual functionality allowed flexibility in the scanning approach, which was adapted based on

the size and fragility of each object, thus minimizing handling risks and providing ease of usage due to its portability.

The EinScan Pro 2x scanner employs structured light scanning technology, which is well suited for capturing complex surface geometries with high accuracy. In structured light scanning, a series of light patterns is projected onto the object's surface, and the deformations of these patterns are analyzed to produce a detailed 3D map of the object. This method ensures high precision in capturing even the smallest surface variations, which are essential for the detailed analysis of cultural heritage artifacts. Additionally, the scanner is equipped with a high-resolution camera to capture color data of the object's surface, integrating geometric and color data to create realistic and informative digital replicas.

During preparation for scanning, each artifact was placed on a motorized rotating platform, enabling full 360-degree capture. The rotation speed and scanning angles were carefully controlled to ensure that every part of the artifact was captured through multiple passes from different perspectives. This approach minimizes the chance of missing any surface detail, particularly in areas that may be obscured or challenging to access with traditional scanning methods.

The post-processing phase was conducted using the EXScan Pro v3.7.4.0 software, the dedicated software provided with the 3D scanner from Shining 3DTM (Hangzhou, China). Initially, raw scan data underwent noise reduction and artifact removal to eliminate unwanted reflections and scanning inconsistencies. The individual scan files were then aligned using an automated and manual registration process, ensuring accurate merging of multiple scans into a unified model. Mesh refinement techniques were applied to fill small gaps and correct surface irregularities, followed by smoothing filters to enhance model fidelity. To assess the accuracy of the final models, deviation analysis within EXScan Pro was performed, comparing the reconstructed digital replicas to the raw scan data. This allowed the quantification of dimensional accuracy and ensured minimal deviation from the original artifacts. The choice of EXScan Pro was based on its seamless integration with the scanning hardware, its advanced algorithms for mesh optimization, and its ability to maintain high-resolution details, which are critical in cultural heritage preservation.

For the 3D printing phase in this study, the scanned data from the aforementioned artifacts were used to create 1:2 scale replicas. This scaling down facilitated diverse use while preserving the integrity of the original items. The replica of the glass vessel AMAL 2113 was printed using a Formlabs Form 2 SLA (Formlabs, Somerville, MA, USA) resin printer, chosen for its high accuracy and capacity to reproduce intricate details. The printing process employed high-quality white resin, along with adaptive layer height technology, which ensured a smooth, finely detailed finish. This detailed approach allowed the fine characteristics of the glass cup—such as its unique contours and subtle textures—to be accurately replicated in the final model. The resulting 3D-printed replica not only mirrors the appearance of the original artifact, but also serves as a valuable resource for researchers and educators interested in studying the artistry and craftsmanship of ancient glasswork.

In contrast, the replica of the ceramic anthropomorphic vessel AMAL 2131 was produced using a Creality CR20 FFF 3D printer (Creality, Shenzhen, China)with white PLA filament. This method provided a distinct yet effective representation of the vessel, capturing its robust form and signature textures. PLA was selected for its environmentally friendly properties and ease of use, allowing the museum to create a durable and visually appealing replica. Both 1:2 scale replicas serve as significant educational tools, enabling visitors to engage with and appreciate the artistic heritage of these ancient items without risking damage to the originals.

3. Results

3.1. 3D Scanning Process

The scanning process was meticulously performed to ensure detailed and accurate data were captured. Each artifact was scanned multiple times to produce a comprehensive data set, capturing every surface detail from various angles. The structured light scanner beamed light patterns onto the object, and the system measured the distortions in the reflected light to create an accurate 3D digital mesh of the object's surface geometry.

During scanning, the rotating platform completed multiple full rotations of the artifact, with the scanner recording data at carefully spaced intervals. This ensured comprehensive coverage of the artifact surface, including debris and indented areas that might otherwise be missed. For particularly complex sections, such as the bases of the vessels or areas with complex patterns, the scanner was manually set to handheld mode to provide additional coverage.

As mentioned before, the EinScan Pro 2X portable 3D scanner by Shining 3D (Hangzhou, China) was used for data acquisition. This device was selected due to its versatility in capturing complex geometries, its high scanning accuracy (up to 0.04 mm in fixed scan mode), and its ability to operate in both handheld and stationary configurations, which was essential given the varying shapes and surface details of the artifacts. For the scanning parameters, we used structured light scanning mode with a resolution setting of 0.2 mm to balance detail capture and processing efficiency. The exposure time and sensitivity settings were adjusted based on surface reflectivity, particularly for the glass vessel, where a chalk spray was applied to reduce reflections and improve data acquisition. Multiple scans were taken from different angles and later merged to ensure complete surface coverage.

One of the key challenges during this phase was managing reflective surfaces or irregular textures, which can affect scanning accuracy by causing unpredictable light scattering. To achieve a high-quality 3D scan of the ancient glass cup, a thin layer of chalk spray was strategically applied to its surface. Glass artifacts present unique challenges in 3D scanning due to their transparent and reflective nature, which often interferes with the accuracy of scanned data by causing glare and refractions that distort captured images. By adding a temporary matte layer of chalk spray, the surface of the cup was temporarily altered to reduce reflections, enhancing the scanner's ability to detect the delicate contours and intricate details of the object. This temporary coating was instrumental in achieving an accurate digital replica that maintained the integrity of the artifact's original features.

The chalk spray used was specially selected for its ability to evaporate on contact with ambient air within a few hours, leaving no residue or permanent effects on the glass surface. This temporary intervention allowed us to capture a high-quality digital model without compromising the material of the object, ensuring both preservation and accuracy. Evaporative chalk spray serves as an ideal solution to heritage and conservation efforts, as it offers a noninvasive way to enhance scanning results, while fully respecting the conservation requirements of the object. By allowing a highly accurate 3D model to be obtained, this process ensures that the artifact can be studied, analyzed, and even reproduced in detail for educational and conservation purposes, without risking any damage to the original piece. On the contrary, for the artifact, it was not necessary to apply the above process due to the ceramic, porous construction material that by itself gave a matte texture, which is considered ideal for the 3D scanning process. Figure 2 depicts the 3D scanning process of the AMAL 2113 artifact.

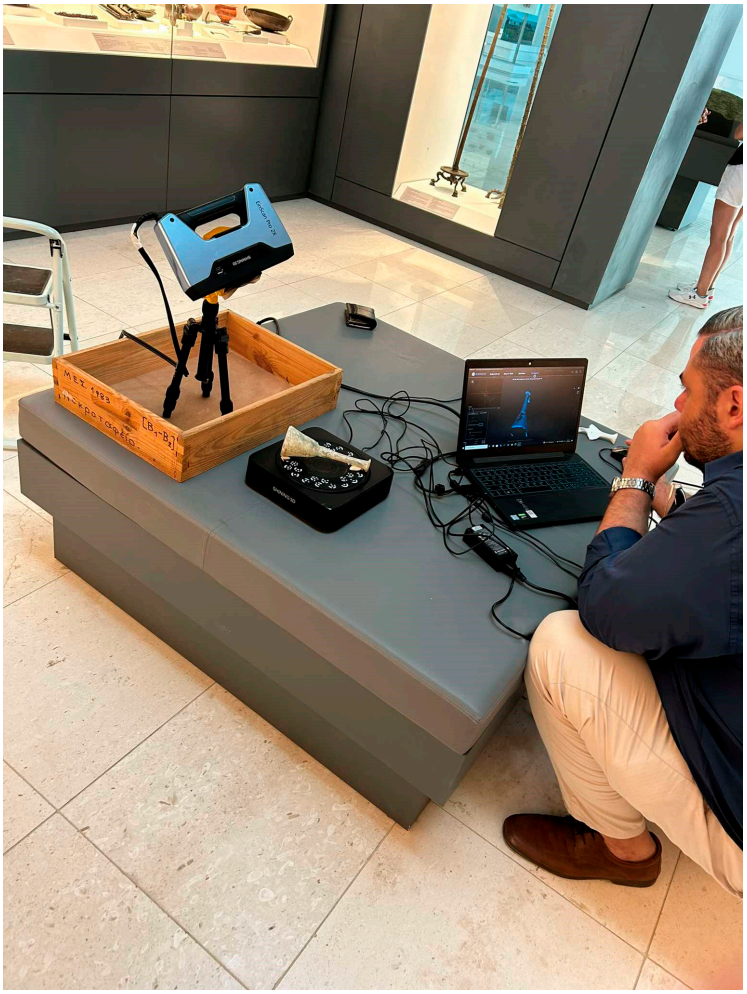


Figure 2. The AMAL 2113 vessel during 3D scanning on the rotating platform of the 3D scanner after applying chalk spray.

3.2. Post-Processing

Post-processing of scanned data is a critical step in converting raw scan files into usable digital models. EXScanPro 3.7.4.0 software, developed by shining 3D^{TM}, was used to handle the raw data enhancement. The first stage of post-processing involved cleaning the raw scan files to remove any unwanted artifacts or noise created during the scanning process. This noise often results from surface imperfections, movement during scanning, or reflections from light sources.

After the cleaning process, the individual scans were aligned using a technique known as registration, where multiple scans are combined into a single digital grid. This step requires precision to ensure that the different scans overlap correctly, preserving the geometry and details of the artifact. The alignment process often involves matching key points on the surface of the object across different scans, ensuring that the individual data sets are seamlessly integrated.

Once aligned, the digital model underwent mesh refinement, which involves filling in any gaps or holes in the data. These gaps can occur in areas where the scanner was unable to capture sufficient detail, such as deep recesses or areas covered by shadows during scanning. Mesh refinement is crucial to produce a complete and accurate digital model that can be used for further analysis or 3D printing. A specialized small object filter was applied to remove small imperfections from the mesh, ensuring that the final model accurately reflects the true form of the artifact.

One of the innovative aspects of this work was the simultaneous acquisition of color data along with the geometric scan. The built-in camera on the EinScan Pro 2x scanner was used to capture high-resolution images of the object's surface during scanning, allowing the software to map the color data directly to the digital model. The inclusion of color data is essential for a more holistic representation of objects, especially for ceramic objects where color patterns and decoration can have significant historical meaning.

Post-processing of the color data involved texture mapping, where the captured color images were aligned and wrapped around the 3D geometry. This process is delicate and requires precise matching of the texture to the contours of the surface to avoid distortion. The final model, with geometric and color data, was saved in formats such as OBJ and 3MF, which support color information, as opposed to the more commonly used STL format, which only preserves geometry.

Figures 3–7 show artifacts AMAL 2113–AMAL 2131, and depict screenshots of the aforementioned process after 3D scan processing.

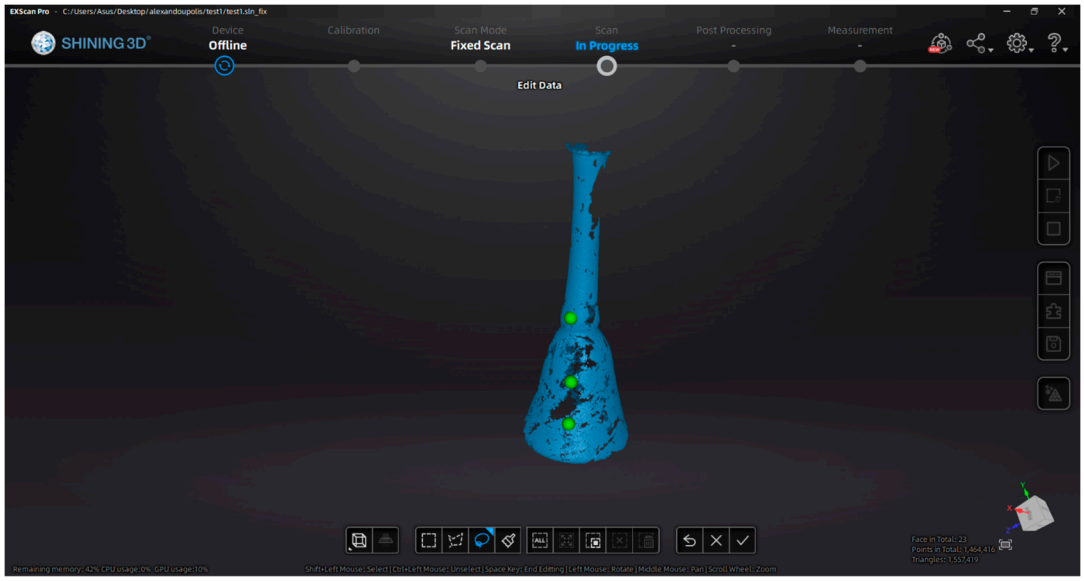


Figure 3. The AMAL 2113 vessel during processing in the 3D scanner software.

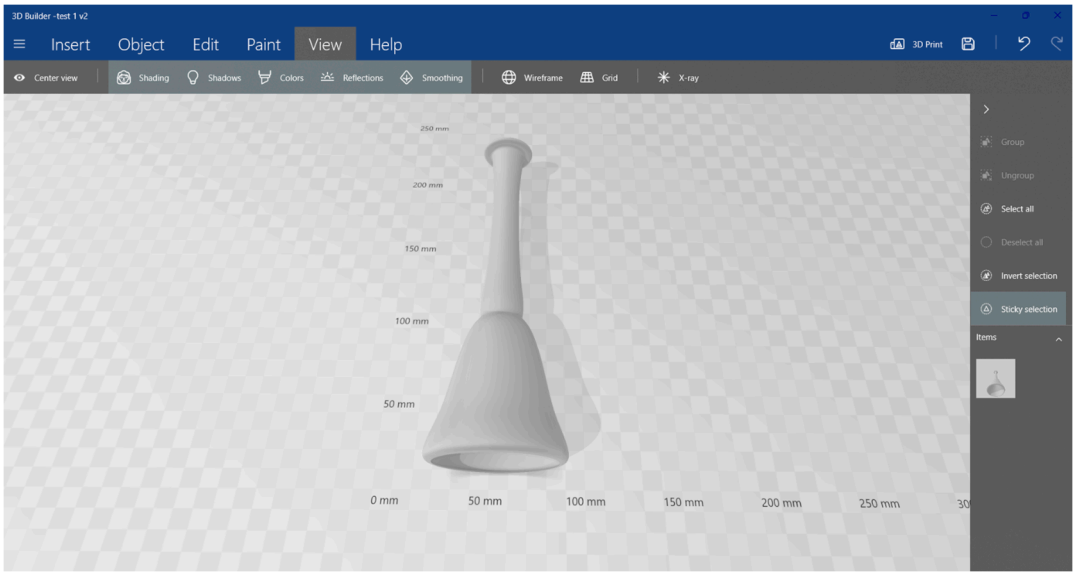


Figure 4. The AMAL 2113 vase after its successful digital reconstruction in the 3D scanner software.

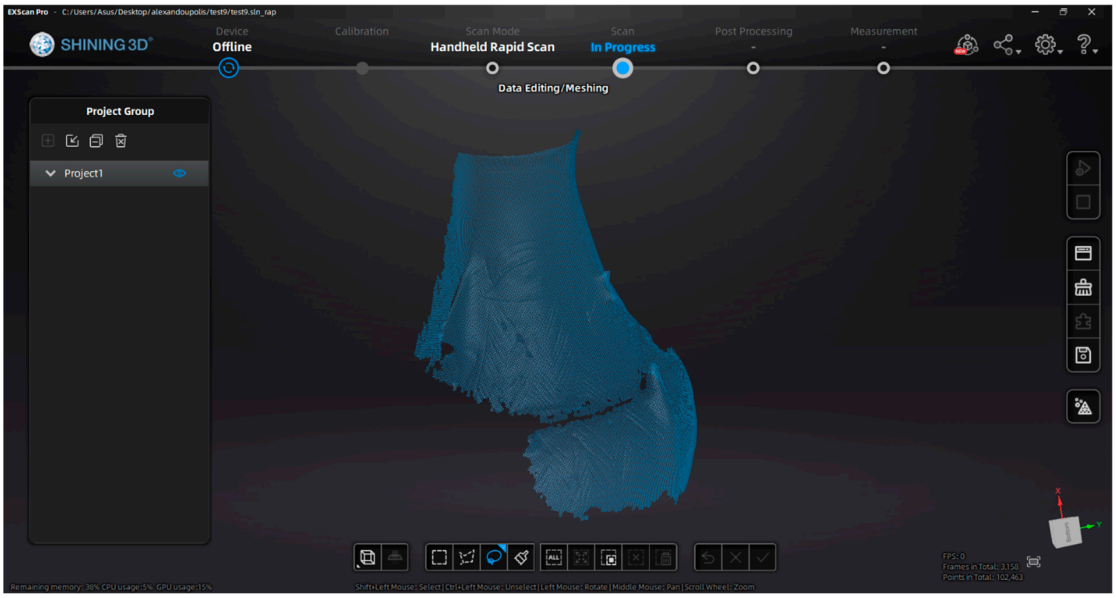


Figure 5. The AMAL 2131 vessel during processing in the 3D scanner software.

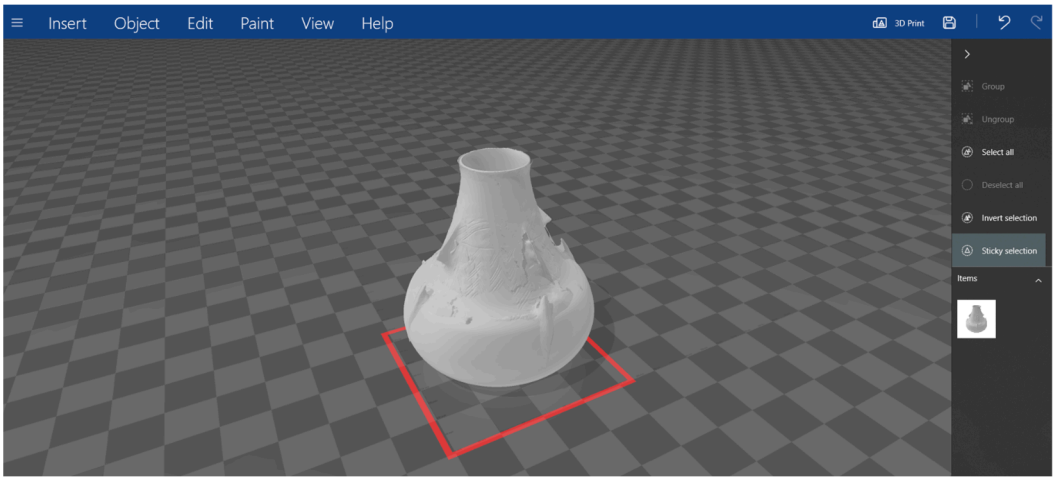


Figure 6. The AMAL 2113 vessel after its successful digital reconstruction in the 3D scanner software.

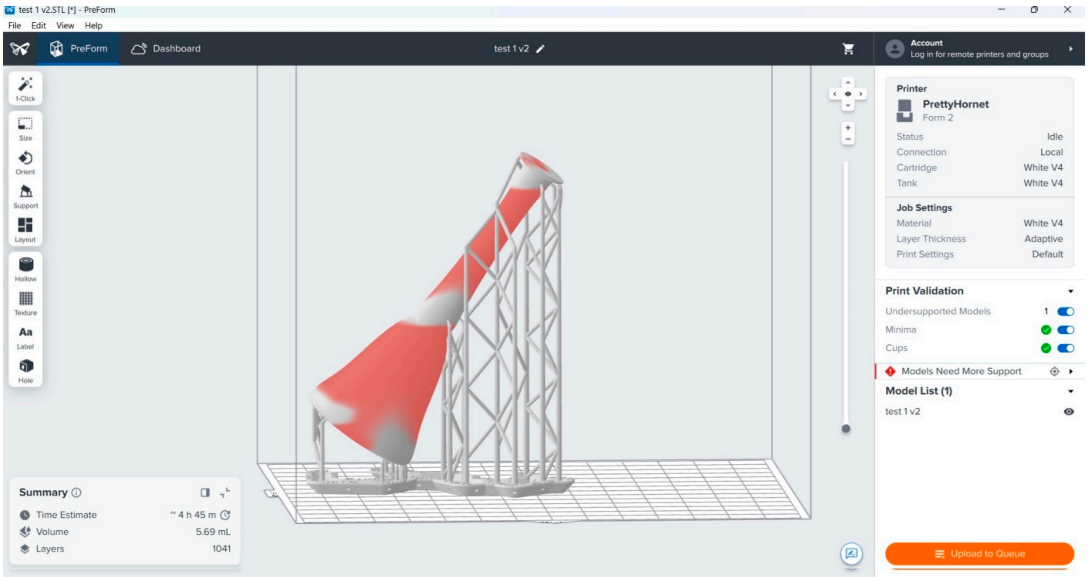


Figure 7. The replica of glass vessel AMAL 2113 during the print preparation process.

3.3. 3D Printing Process

As mentioned earlier, the replica of the glass vessel (AMAL 2113) was created using a Formlabs (Boston, MA, USA) Form 2 SLA 3D resin printer, renowned for its precision and ability to capture intricate details, like every other SLA 3D printer. High-quality white resin and adaptive layer thickness technology were used, ensuring a smooth finish with fine detail. This approach accurately reproduced the vessel's unique shapes and delicate textures, making the 3D-printed replica not only visually faithful to the original artifact, but also valuable for researchers and educators studying ancient glasswork craftsmanship.

In contrast, the replica of the humanoid ceramic vessel (AMAL 2131) was produced with a Creality (Shenzhen, China) CR20 FFF 3D printer, using white PLA filament. This method offered a sturdy and effective representation of the vessel, capturing its robust form and distinctive textures. The choice of PLA, known for its eco-friendly properties and ease of use, enabled the museum to create a durable and visually appealing replica. Both replicas were fabricated on a one-half scale of the original items.

Figure 7 depicts the replica of glass vase AMAL 2113 during the print preparation process.

This image shows information about the 3D printing process such as completion times (4 h and 45 min), the amount of construction material (5.69 mL) as well as the number of layers that make up the total volume of the object. In this case, adaptive layer thickness was chosen, where the printer selects the optimal layer thickness in different areas of the object using digital intelligence (A.I.) technology. The adaptive layer thickness option in an SLA resin 3D printer offers several important advantages that enhance the quality and efficiency of the printing process. This approach allows for variable layer heights throughout the print, allowing thicker layers in less detailed areas and thinner layers in areas that require high precision and fine detail [18]. As a result, adaptive layer thickness optimizes print time while maintaining complex model features, reducing material consumption without compromising quality [19]. This option results in improved surface finishes and better overall accuracy on complex geometries, making it particularly beneficial for applications where detail is paramount, such as jewelry design, dental models, and complex prototypes. Additionally, the ability to adjust layer thickness based on model requirements helps minimize the risk of print failure, leading to higher success rates and more reliable results. Overall, applying adaptive layer thickness to SLA 3D printing not only optimizes the workflow, but also enhances the fidelity and visual appeal of the final object [20].

Correspondingly in Figure 7, the supporting structures (supports) are depicted with a view of thin pillars. The choice of support density and placement in an SLA resin 3D printer is critical to achieving successful prints while minimizing material waste and post-processing efforts [21]. Props are essential for protrusions and complex geometries, and their density can be adjusted based on the specific needs of the model. A higher support density provides robust stability for complex designs, preventing distortion during the printing process, but may increase material usage and require more extensive cleanup after printing [22]. Conversely, a lower support density reduces hardware consumption and simplifies post-processing, but may risk insufficient support for sensitive features. Additionally, strategic placement of supports is essential. Optimal placement can enhance stability while minimizing the effect on the final surface finish of the printed part. By carefully considering both support density and placement, users can effectively balance strength and ease of removal, ensuring that the final print maintains its intended quality without unnecessary imperfections or damage from support structures [23]. Accordingly, Figure 8 depicts the object immediately after the completion of the printing process, before its removal from the platform.

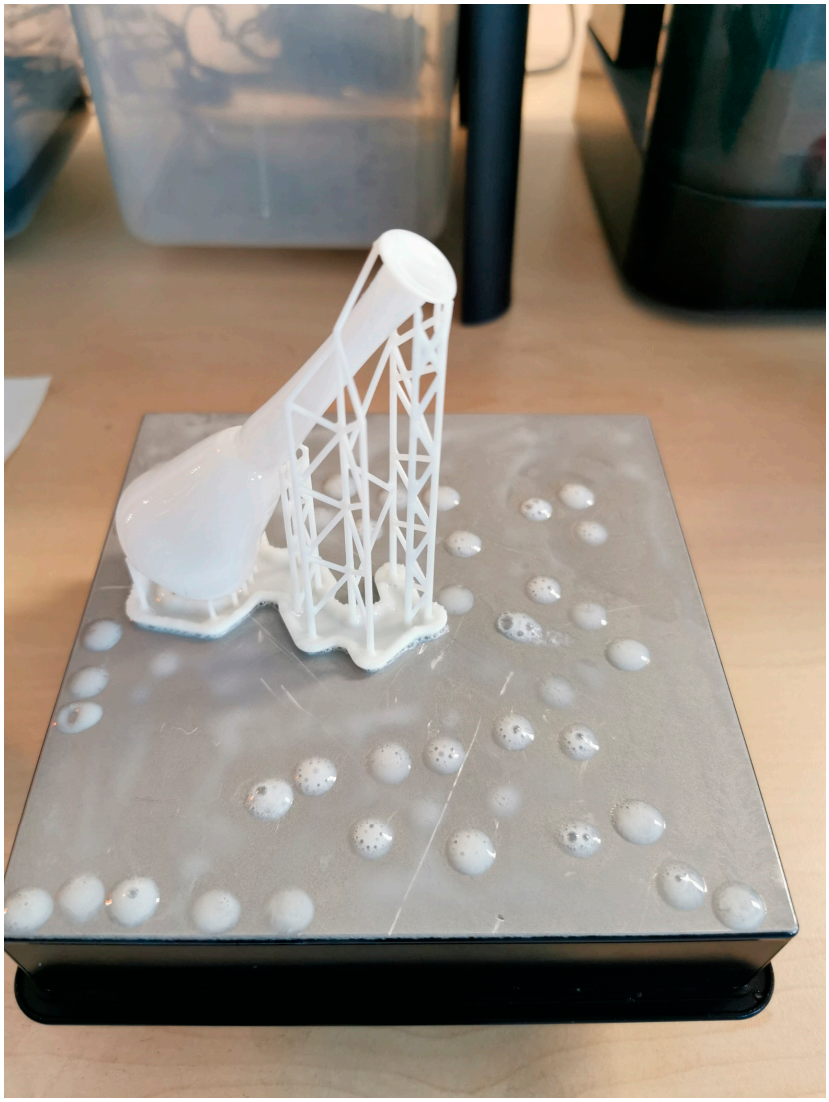


Figure 8. The replica of glass vessel AMAL 2113 after the completion of the fabrication process.

Then, the object was immersed in a cleaning device with isopropyl alcohol (IPA) solvent in order to clean it of residual resin that had not undergone polymerization. Figure 9 illustrates the object in the process of initial placement in the aforementioned device.

The object was then advanced into a UV irradiation device. Exposing an object to UV radiation after it has been 3D printed using a 3D SLA (stereolithography) printer is an essential step in ensuring the final properties of the printed object, including strength, durability, and stability [24]. As mentioned above, SLA 3D printing works by using a UV laser to solidify a liquid resin layer by layer, resulting in a solid 3D object. However, this initial curing process during printing does not fully solidify the resin, leaving it partially reactive and susceptible to structural weaknesses. Post-print curing, which usually involves exposing the object to additional UV radiation, completes the polymerization process, thereby stabilizing and hardening the printed object.

Curing strengthens the mechanical properties of the SLA-printed object, making it more resistant to stress, deformation, and environmental conditions such as humidity and temperature changes [25]. Without UV exposure, an SLA print can remain soft and sticky, possibly warping even under moderate pressure. This process also helps the object achieve its optimum hardness and improves its impact resistance, a key factor in applications where durability is crucial [26].



Figure 9. The replica of glass vessel AMAL 2113 immediately before undergoing cleaning.

In addition, hardening helps to improve the aesthetic finish of the object. During UV exposure, any residual resin solidifies completely, often resulting in a smoother and more polished surface [27]. For parts that require precise dimensional accuracy, this process is vital, as expansion and contraction of the material can otherwise lead to warping or shrinkage. Proper curing minimizes these problems, providing a stable, reliable end product with consistent and accurate dimensions [28]. Figures 10 and 11 illustrate the object being placed in and exposed to UV radiation in a UV chamber apparatus. The object remained there for 60 min at a temperature of 50 °C.

In the case of the humanoid vessel AMAL 2131, Figures 11 and 12 illustrate the corresponding 3D print preparation process through the introduction of the 3D model into the corresponding Simplify3D^{TM} v.4.1.2slicing software of the 3D printer, as acquired from the 3D scanning process. Figure 13 shows the final 3D-printed scaled replica.

Creating a one-half scale replica of the AMAL 2131 anthropomorphic vase via 3D printing required a precise and methodical approach using Simplify3D as the preparation software. The process began by importing the 3D model of the object, ensuring its correct orientation and scale. As this replica was to be produced at half the size of the original

object, the model was uniformly reduced by 50%, retaining all of the proportions and details critical to an accurate representation of the original object.



Figure 10. The glass vessel replica of AMAL 2113 artifact during placement and exposure to UV radiation in a UV chamber apparatus.

Next, the main printing parameters were set to ensure maximum quality and efficiency. PLA was chosen as the material for the replica, setting a layer height of 0.1 mm to achieve maximum resolution and fidelity. After the layer height was adjusted, the print speed was set to 60 mm/s. This speed was chosen to avoid excessive vibrations or deviations that could compromise the fidelity of the surface details of the scale copy, but was efficient enough to limit print time. Given the structural requirements of the model, an infill rate of approximately 30% was chosen to strike a balance between durability and material economy, providing adequate internal support without unnecessary weight. Additionally, the software's preview function was used to inspect each layer and support structure placement, which allowed for detail prior to the final piece.

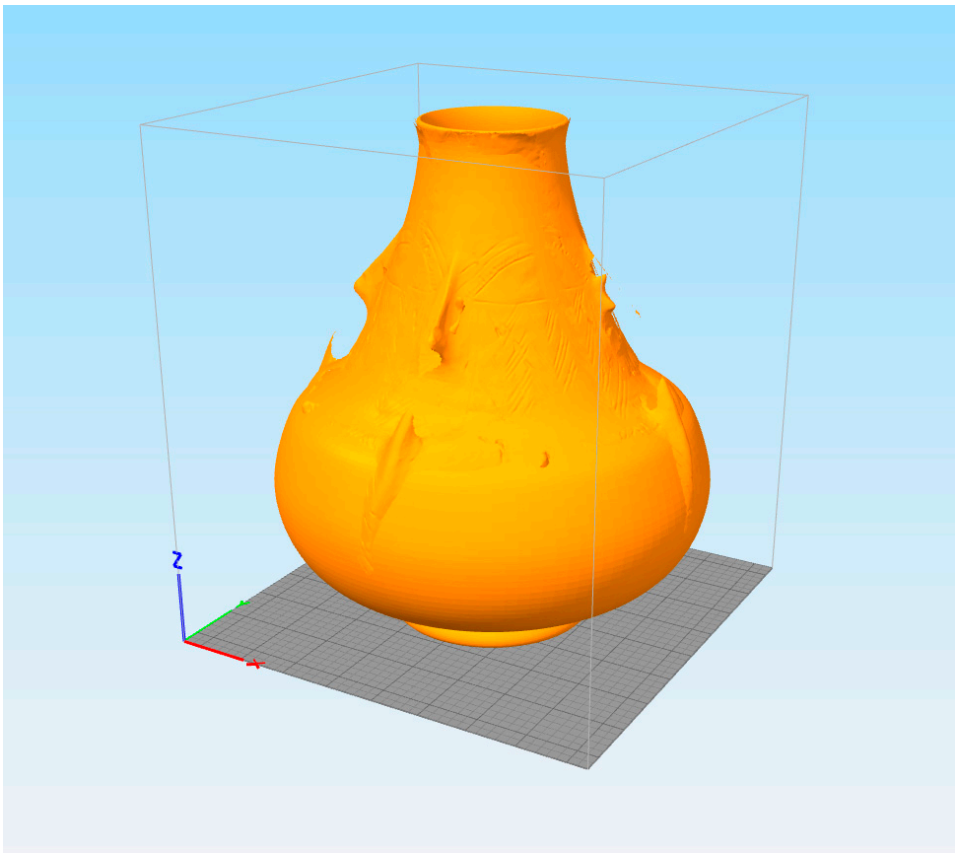


Figure 11. The replica of humanoid vessel AMAL 2131 during the 3D printing preparation process.

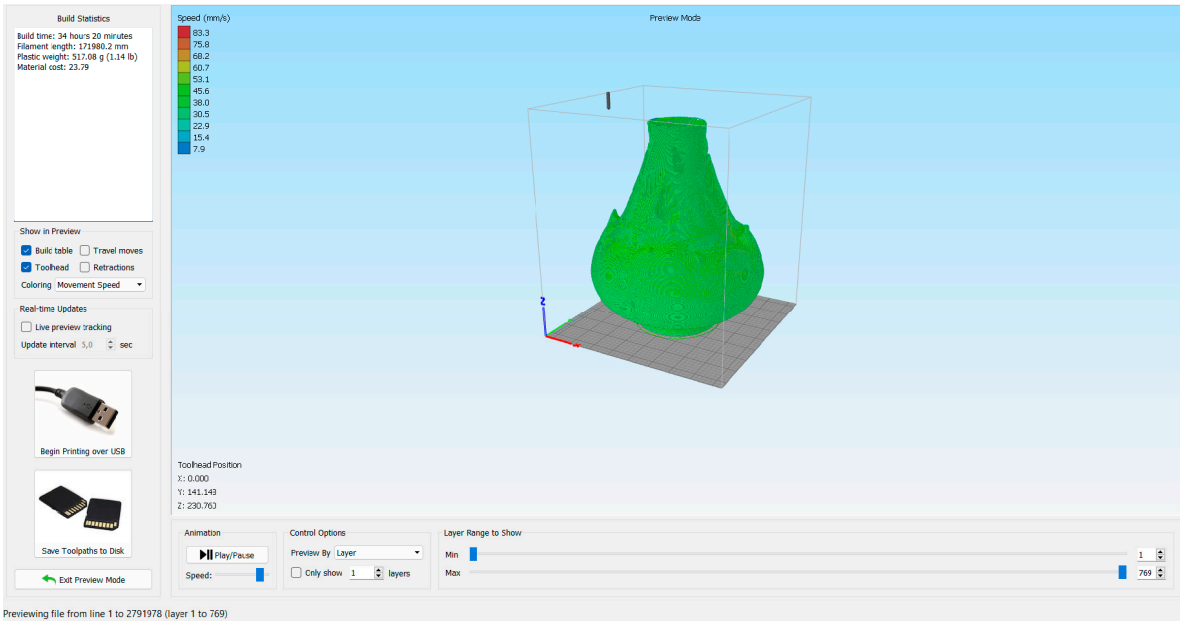


Figure 12. The replica of humanoid vessel AMAL 2131 during the print preparation process after the slicing process.

Finally, the estimated weight and time were provided by the software, confirming that the print would weigh approximately 517.08 g and require 34 h and 20 min to complete. After all settings were verified, the model was edited and the G code was exported for printing. This methodological approach in Simplify3D software ensured that the replica

achieved both structural integrity and an accurate, detailed representation of the original object, suitable for educational or display purposes.

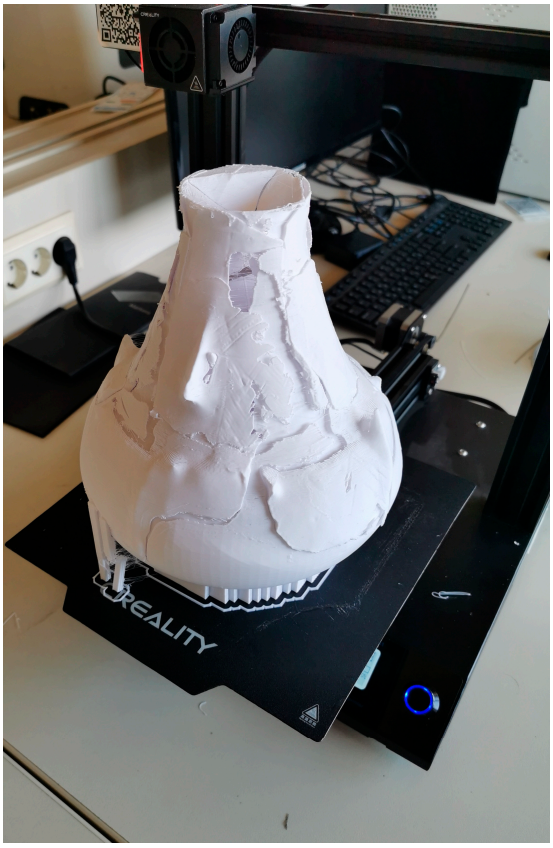


Figure 13. The replica of humanoid vessel AMAL 2131 upon the end of the 3D printing process.

4. Discussion

One of the most significant technical challenges encountered during the 3D scanning process was addressing the fine details and reflective surfaces of the artifacts. While the structured light scanner is highly accurate, certain surface textures—particularly very reflective or very dark surfaces—can create difficulties in capturing precise data. Reflective surfaces can cause unpredictable light scattering, leading to incomplete scans or noisy data [29]. To mitigate these issues, future projects could consider implementing additional techniques, such as the use of matte spray or polarizing filters, to reduce reflection problems without damaging the artifacts. This would not only enhance the quality of the scans, but also broaden the range of objects that could be effectively digitized [30].

Another challenge was the time-consuming nature of the scanning process. Each artifact required multiple scans to ensure comprehensive coverage, and subsequent post-processing added to the overall time commitment [31]. The complexity involved in aligning, cleaning, and refining the digital models necessitates significant computational resources and specialized knowledge in 3D scanning technologies. High-performance computer setups with advanced graphics processing units (GPUs) and ample memory were essential for processing the large datasets generated by the scanner. The demands of this workflow highlight the need for improved efficiency and possibly the exploration of automated or semi-automated processes to expedite both the scanning and post-processing stages.

Additionally, while the initial scanning yielded high-quality geometrical data, the integration of color information from the scanning process proved to be another layer of complexity. Capturing the color accurately requires careful calibration of the scanner and

a consistent lighting environment. Future research should investigate the effectiveness of various lighting setups and post-processing techniques to enhance color fidelity in the scanned models.

The surface characteristics of cultural heritage artifacts vary significantly depending on material composition, age, and environmental exposure. In this study, structured light scanning was chosen due to its effectiveness in capturing fine details on ceramic and glass surfaces, but other methods, such as laser 3D scanning and photogrammetry, are often employed for different types of heritage objects. For example, laser 3D scanning is more suitable for large-scale architectural elements and stone carvings due to its ability to capture depth with high accuracy, while photogrammetry is widely used for organic materials like wood and textiles, where non-contact imaging is crucial. Future studies could benefit from a comparative analysis of these techniques applied to various artifact surfaces, helping to establish optimized workflows tailored to different materials in cultural heritage documentation.

In addition to the challenges faced during the 3D scanning process, the production of replica artifacts through 3D printing presented its own set of technical hurdles. The choice of printing technology significantly influenced the fidelity and accuracy of the replicas. For example, the glass artifact (AMAL 2113) was printed using an SLA resin printer, known for its precision and ability to capture intricate details. However, achieving the desired level of detail in the final prints required meticulous calibration of the printer settings and careful selection of high-quality materials. Any misalignment or deviation in the printing parameters could lead to inaccuracies in the final product, particularly in reproducing the unique shapes and delicate textures inherent in the original glass artifact.

Conversely, the ceramic anthropomorphic vessel (AMAL 2131) was created using the Creality CR20 FFF printer, which employs a different method—Fused Filament Fabrication. While this technology is more accessible and cost effective, it often falls short in replicating fine details when compared to SLA printing. The challenge, therefore, was to optimize the use of PLA filament to ensure that the robust forms and characteristic textures of the vessel were accurately represented. This involved experimenting with various layer heights, print speeds, and temperatures to achieve a satisfactory level of detail while maintaining the durability of the print [32].

Moreover, post-processing techniques played a crucial role in enhancing the visual and tactile quality of the printed replicas [33]. For both artifacts, surface finishing methods, such as sanding and painting, were employed to improve the aesthetics and to better approximate the original materials [34]. However, these processes are time consuming and require skilled labor to avoid damaging the fragile details of the prints. The trade off between achieving a visually appealing replica and preserving the intricate features of the originals remains a critical consideration in the 3D printing process [35].

Another important factor to consider is the environmental impact of the materials used in 3D printing [36]. While PLA is praised for its eco-friendly properties, the long-term sustainability of resin materials and their impact on the environment necessitate further investigation [37,38]. Future projects should explore alternative materials that provide both high quality prints and lower ecological footprints, potentially incorporating biodegradable or recyclable options.

In conclusion, the integration of 3D scanning and printing technologies represents a significant advancement in the preservation and study of cultural artifacts. The challenges encountered during both processes highlight the complexities involved in accurately capturing and reproducing the intricate details of historical objects. While 3D scanning allows for the meticulous documentation of artifacts, the subsequent 3D printing of their replicas

offers an innovative means of facilitating research and education while safeguarding the original artifacts.

5. Conclusions

This study has demonstrated the potential of integrating 3D scanning and printing technologies to advance the preservation, study, and accessibility of cultural heritage artifacts. By digitizing and replicating two historically significant items—the humanoid ceramic vessel and the glass cup from the Archaeological Museum of Alexandroupolis—this research highlights a sustainable approach to artifact preservation that converges the digital and physical domains.

The structured light scanning process effectively captured the artifacts' complex geometries, while the adaptive use of 3D printing techniques, including both SLA and FDM methods, allowed for the production of high-fidelity replicas. These replicas are invaluable for multiple applications: they offer a means to safely display artifacts to the public, enable detailed research without compromising original objects, and serve as educational tools to deepen public engagement with cultural heritage. Furthermore, the experimental approach to handling materials, such as using chalk spray to enhance the scan quality of reflective surfaces, provided practical insights into optimizing scanning accuracy for varied artifact types.

This study also underscores several key challenges, such as the intricate post-processing required for both digital and physical model creation, the need for efficient data management, and the environmental impact of materials used in 3D printing. Addressing these challenges will be essential for future research, particularly in exploring alternative materials that reduce ecological footprints while maintaining high-quality output. Improvements in automated scanning workflows, color integration, and rapid post-processing will further streamline the process, making it more accessible to heritage institutions with limited technical resources.

In conclusion, 3D imaging and printing represent transformative tools in the field of cultural heritage preservation. By enabling precise replication and versatile applications, these technologies ensure that invaluable cultural artifacts are preserved, studied, and appreciated in new ways, supporting both conservation and education. Continued advancements and collaboration across fields will be crucial in harnessing the full potential of 3D technology for heritage preservation, ultimately contributing to the longevity and accessibility of our shared cultural heritage.

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References

1. Zhou, M.; Geng, G.; Wu, Z. *Digital Preservation Technology for Cultural Heritage*; Springer: Berlin/Heidelberg, Germany, 2012; ISBN 9783642280986.
2. Hobsbawm, E.; Ranger, T. (Eds.) *The Invention of Tradition*; Cambridge University Press: Cambridge, UK, 2012; ISBN 9781107604674.
3. Ioannides, M.; Patias, P. (Eds.) *3D Research Challenges in Cultural Heritage III: Complexity and Quality in Digitisation*; Springer International Publishing: Cham, Switzerland, 2023; ISBN 9783031355929.
4. Douros, P.; Kaldis, P. *Cultural Heritage and Contemporary Creative Management and Sustainable Economic Development*; Kallipos: Athens, Greece, 2023. [CrossRef]
5. Ioannides, M.; Patias, P. The Complexity and Quality in 3D Digitisation of the Past: Challenges and Risks. In *Lecture Notes in Computer Science*; Springer International Publishing: Cham, Switzerland, 2023; pp. 1–33. ISBN 9783031355929.
6. Kantaros, A.; Ganetsos, T.; Petrescu, F.I.T. Three-Dimensional Printing and 3D Scanning: Emerging Technologies Exhibiting High Potential in the Field of Cultural Heritage. *Appl. Sci.* **2023**, *13*, 4777. [CrossRef]
7. Remondino, F. Heritage Recording and 3D Modeling with Photogrammetry and 3D Scanning. *Remote Sens.* **2011**, *3*, 1104–1138. [CrossRef]
8. Kantaros, A.; Piromalis, D.; Tsaramirsis, G.; Papageorgas, P.; Tamimi, H. 3D Printing and Implementation of Digital Twins: Current Trends and Limitations. *Appl. Syst. Innov.* **2022**, *5*, 7. [CrossRef]
9. Kantaros, A.; Papageorgiou, M.I.; Brachos, K.; Ganetsos, T.; Mouzakiotou, S.; Soulis, E. The Use of 3D Scanning and 3D Color Printing Technologies for the Study and Documentation of Late Bronze Age Pottery from East-Central Greece. *J. Mechatron. Robot.* **2024**, *8*, 11–19. [CrossRef]
10. Kantaros, A.; Soulis, E.; Alysandratou, E. Digitization of Ancient Artefacts and Fabrication of Sustainable 3D-Printed Rep-licas for Intended Use by Visitors with Disabilities: The Case of Piraeus Archaeological Museum. *Sustainability* **2023**, *15*, 12689. [CrossRef]
11. Finnes, T. High Definition 3D Printing—Comparing SLA and FDM Printing Technologies. *J. Undergrad. Res.* **2015**, *13*, 3.
12. Kafle, A.; Luis, E.; Silwal, R.; Pan, H.M.; Shrestha, P.L.; Bastola, A.K. 3D/4D Printing of Polymers: Fused Deposition Mod-elling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA). *Polymers* **2021**, *13*, 3101. [CrossRef]
13. Balletti, C.; Ballarin, M. An Application of Integrated 3D Technologies for Replicas in Cultural Heritage. *ISPRS Int. J. Geoinf.* **2019**, *8*, 285. [CrossRef]
14. Ballarin, M.; Balletti, C.; Vernier, P. Replicas in Cultural Heritage: 3d Printing and the Museum Experience. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *XLII–2*, 55–62. [CrossRef]
15. Kantaros, A.; Soulis, E.; Ganetsos, T.; Petrescu, F.I.T. Applying a Combination of Cutting-Edge Industry 4.0 Processes to-wards Fabricating a Customized Component. *Processes* **2023**, *11*, 1385. [CrossRef]
16. Dey, A.; Yodo, N. A Systematic Survey of FDM Process Parameter Optimization and Their Influence on Part Characteristics. *J. Manuf. Mater. Process.* **2019**, *3*, 64. [CrossRef]
17. Kantaros, A.; Petrescu, F.I.T.; Brachos, K.; Ganetsos, T.; Petrescu, N. Evaluating Benchtop Additive Manufacturing Processes Considering Latest Enhancements in Operational Factors. *Processes* **2024**, *12*, 2334. [CrossRef]
18. Pelzer, L.; Hopmann, C. Additive Manufacturing of Non-Planar Layers with Variable Layer Height. *Addit. Manuf.* **2021**, *37*, 101697. [CrossRef]
19. Xiong, J.; Yin, Z.; Zhang, W. Closed-Loop Control of Variable Layer Width for Thin-Walled Parts in Wire and Arc Additive Manufacturing. *J. Mater. Process. Technol.* **2016**, *233*, 100–106. [CrossRef]
20. Gohari, H.; Kishawy, H.; Barari, A. Adaptive Variable Layer Thickness and Perimetral Offset Planning for Layer-Based Additive Manufacturing Processes. *Int. J. Comput. Integr. Manuf.* **2021**, *34*, 964–974. [CrossRef]
21. Kirschman, C.F.; Jara-Almonte, C.C.; Bagchi, A.; Dooley, R.L.; Ogale, A.A. Computer Aided Design of Support Structures for Stereolithographic Components. In Proceedings of the ASME 1991 Computers in Engineering Conference: Volume 1—Artificial Intelligence, Expert Systems, CAD/CAM/CAE, Computational Fluid/Thermal Engineering, Santa Clara, CA, USA, 18–22 August 1991; American Society of Mechanical Engineers: New York City, NY, USA, 1991; pp. 443–448.
22. Cao, X.; Yu, M.; Zhang, S.; Zhang, T.; Chen, Y.; Wang, Y.; Han, X. Hierarchical Clustering Evolutionary Tree-Support for SLA. *J. Manuf. Process.* **2024**, *125*, 189–201. [CrossRef]
23. Jiang, J.; Xu, X.; Stringer, J. Support Structures for Additive Manufacturing: A Review. *J. Manuf. Mater. Process.* **2018**, *2*, 64. [CrossRef]
24. Quan, H.; Zhang, T.; Xu, H.; Luo, S.; Nie, J.; Zhu, X. Photo-Curing 3D Printing Technique and Its Challenges. *Bioact. Mater.* **2020**, *5*, 110–115. [CrossRef] [PubMed]
25. Riccio, C.; Civera, M.; Grimaldo Ruiz, O.; Pedullà, P.; Rodriguez Reinoso, M.; Tommasi, G.; Vollaro, M.; Burgio, V.; Surace, C. Effects of Curing on Photosensitive Resins in SLA Additive Manufacturing. *Appl. Mech.* **2021**, *2*, 942–955. [CrossRef]
26. Miedzińska, D.; Gieleta, R.; Popławski, A. Experimental Study on Influence of Curing Time on Strength Behavior of SLA-Printed Samples Loaded with Different Strain Rates. *Materials* **2020**, *13*, 5825. [CrossRef] [PubMed]

27. Uzcategui, A.C.; Muralidharan, A.; Ferguson, V.L.; Bryant, S.J.; McLeod, R.R. Understanding and Improving Mechanical Properties in 3D Printed Parts Using a Dual-cure Acrylate-based Resin for Stereolithography. *Adv. Eng. Mater.* **2018**, *20*, 1800876. [CrossRef]
28. Chen, Q.; Zou, B.; Lai, Q.; Zhao, Y.; Zhu, K. Influence of Irradiation Parameters on the Curing and Interfacial Tensile Strength of HAP Printed Part Fabricated by SLA-3D Printing. *J. Eur. Ceram. Soc.* **2022**, *42*, 6721–6732. [CrossRef]
29. Jiang, H.; Zhao, H.; Li, X. High Dynamic Range Fringe Acquisition: A Novel 3-D Scanning Technique for High-Reflective Surfaces. *Opt. Lasers Eng.* **2012**, *50*, 1484–1493. [CrossRef]
30. Mendřický, R. Impact of Applied Anti-Reflective Material on Accuracy of Optical 3D Digitisation. *Mater. Sci. For.* **2018**, *919*, 335–344. [CrossRef]
31. Lavelle, J.P.; Schuet, S.R.; Schuet, D.J. High Speed 3D Scanner with Real-Time 3D Processing. In Proceedings of the ISA/IEEE Sensors for Industry Conference 2004, New Orleans, LA, USA, 27–29 January 2004; IEEE: Piscataway, NJ, USA, 2004; pp. 102–108.
32. Kantaros, A.; Karalekas, D. FBG Based in Situ Characterization of Residual Strains in FDM Process. In *Residual Stress, Thermomechanics & Infrared Imaging, Hybrid Techniques and Inverse Problems, Volume 8. Conference Proceedings of the Society for Experimental Mechanics Series*; Springer International Publishing: Cham, Switzerland, 2014; pp. 333–337. ISBN 9783319008752.
33. Kantaros, A.; Ganetsos, T.; Petrescu, F.; Ungureanu, L.; Munteanu, I. Post-Production Finishing Processes Utilized in 3D Printing Technologies. *Processes* **2024**, *12*, 595. [CrossRef]
34. Malagutti, L.; Ronconi, G.; Zanelli, M.; Mollica, F.; Mazzanti, V. A Post-Processing Method for Improving the Mechanical Properties of Fused-Filament-Fabricated 3D-Printed Parts. *Processes* **2022**, *10*, 2399. [CrossRef]
35. Diniță, A.; Neacșa, A.; Portoacă, A.I.; Tănase, M.; Ilinca, C.N.; Ramadan, I.N. Additive Manufacturing Post-Processing Treatments, a Review with Emphasis on Mechanical Characteristics. *Materials* **2023**, *16*, 4610. [CrossRef] [PubMed]
36. Gil Muñoz, V.; Muneta, L.M.; Carrasco-Gallego, R.; de Juanes Marquez, J.; Hidalgo-Carvajal, D. Evaluation of the Circu-larity of Recycled PLA Filaments for 3D Printers. *Appl. Sci.* **2020**, *10*, 8967. [CrossRef]
37. McKeown, P.; Jones, M.D. The Chemical Recycling of PLA: A Review. *Sustain. Chem.* **2020**, *1*, 1–22. [CrossRef]
38. Beltrán, F.R.; Arrieta, M.P.; Moreno, E.; Gaspar, G.; Muneta, L.M.; Carrasco-Gallego, R.; Yáñez, S.; Hidalgo-Carvajal, D.; de la Orden, M.U.; Martínez Urreaga, J. Evaluation of the Technical Viability of Distributed Mechanical Recycling of PLA 3D Printing Wastes. *Polymers* **2021**, *13*, 1247. [CrossRef]

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