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THE USE OF DESKTOP 3D SCANNERS AND PRINTERS IN THE RESTORATION OF ARCHAEOLOGICAL CERAMICS: AN EVALUATION FROM THE PERSPECTIVE OF THE CONSERVATOR

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Abstract

Restoration of archaeological ceramics involves assembling the recovered pieces and reconstructing the missing ones. Conventionally, reconstructing the missing pieces involves risky processes like molding and casting. This study examines the use of desktop-type 3D scanners and printers as cost-effective and non-industrial tools for restoring archaeological ceramics, aiming to avoid the potential damage caused by conventional methods. To this end, contemporary pots, resembling archaeological ceramics, were randomly shattered, with some pieces reassembled and others left out to simulate missing fragments. Reassembled pieces were scanned using a 3D scanner employing the structured light technique. Various modeling techniques, some of which were based on existing literature, were employed to reconstruct the missing pieces in 3D. The reconstructed 3D models were printed using FDM-type and SLA-type 3D printers, PLA and ABS filaments and liquid resin. Some of the printed pieces effectively filled the gaps and matched the shapes of the missing pieces. The results demonstrate that this approach can successfully manufacture missing pieces of archaeological ceramic pots without the risks associated with conventional methods, using affordable 3D scanning and printing equipment, modest PC hardware and inexpensive printing materials. Thus, this technology is expected to become widely used in restoration practices in the near future.

Keywords: *Archaeological Conservation; Ceramic Repair; Reconstruction of Cultural Property; Completion of Heritage Objects; Reintegration of Cultural Assets; Molding and Casting*

Introduction

Subject, objective and scope

Restoration implementations, i.e., the reassembling of recovered pieces and the completion (complementation) of the gaps formed due to missing pieces with various materials, represent a crucial stage in the conservation of fragmented archaeological ceramics. A significant portion of the time dedicated to the restoration of ceramic artifacts unearthed from archaeological excavations is typically allocated to completion, which comprises reconstructing the missing pieces and/or filling the gaps revealed by the missing pieces. However, conventional ceramic completion methods pose a risk of damaging the artifacts during and after application due to the potential side effects of the materials and mechanical processes involved. Indeed, the molding, casting and shaping of casting materials—typically executed through repetitive mechanical processes such as scraping and chiseling—are often performed directly on the artifact. When performing these practices, which are the usual phases of completion, damage may be inadvertently inflicted on the invaluable artifact.

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Moreover, the materials utilized during mold-making and casting have the potential to contaminate the original artifact, necessitating cleaning processes to remove their residues. The cleaning procedures, aside from entailing extra costs and time, can contribute to the wear of the artifact. Besides, they may leave behind harmful remnants of cleaning agents that cannot always be completely eliminated. Furthermore, both finishing techniques (consisting of abrading processes like plaster sanding and scraping) and cleaning methods release substances, including fine dust and solvent vapors, that pose health risks to practitioners.

On the other hand, there are a considerable number of fragmented ceramic artifacts in excavation storages or museums that are in need of repair. Additionally, each year, numerous newly discovered fragmented ceramic finds from archaeological excavations are added to these collections. Consequently, there is a pressing need to undertake completion work using innovative methods that prevent adverse side effects, can be carried out quickly and yield appropriate outcomes. Presently, 3D printing technology offers faster production compared to conventional processes across various fields, including industrial and architectural design, automotive, aerospace, dental and medical industries. However, the purpose of this study is to assess the effectiveness of using a non-professional utilitarian 3D scanner and printer in conjunction with a modest laptop to reconstruct missing pieces of ceramic pots and to determine whether this process would facilitate rapid, harmless and cost-effective ceramic restoration processes. Although successful replicas of cultural properties have been produced using this technology [1-3], research on restoration practices remains limited. The motivation for this study stemmed from the observation that only a small number of studies were conducted, with a specific concentration on ceramic restoration practices [4-6]. Within the scope of this study, four distinct present-day ceramic pots were used to simulate archaeological ceramic pots and the procedures carried out for modeling and printing their missing pieces were assessed. Consequently, the study aimed to investigate the compatibility of the 3D printing process as an alternative to conventional completion methods. The stages of this study involve the following: breaking ceramic pots; reassembling the broken pieces, excluding the pieces reserved as missing pieces; creating 2D drawings of assembled pots without missing pieces using freehand drawings and computer software; scanning the assembled pots using a 3D scanner; creating 3D models of the missing pieces using computer software; manufacturing the created 3D models by using two different 3D printers and checking whether the manufactured pieces fit and can be placed in the original locations.

Purpose and common types of ceramic artifact completion methods

Deteriorations such as erosion, loss and disintegration impede the perception and interpretation of cultural properties by damaging both their structural and aesthetic integrity. Reconstructing the missing pieces is a crucial step of the conservation process, which seeks to preserve and sustain the readability, aesthetic and visual integrity of cultural property in addition to safeguarding its physical integrity. In the case of fragmented ceramic objects unearthed from archaeological excavations, the reconstructed missing pieces are incorporated into the reassembled fragments, i.e., the objects are completed to reveal their original form for display and research purposes and to facilitate their handling and transportation. Through this completion process, not only is the artifact restored to its formal and aesthetic integrity, but it is also strengthened [7-8]. The reconstruction of missing pieces of archaeological ceramics relies on the information and evidence gathered about their original forms. Missing pieces are replicated by creating molds from existing parts, utilizing the symmetry of the artifact or by applying the extrapolation method in reference to other excavated contemporary intact artifacts with comparable forms [7].

As with all cultural assets, the completion process of ceramic objects varies according to their characteristics, including their historical, archaeological, technical and artistic significance, as well as their state of preservation, size, form and the dimensions of their missing parts. Completion operations can be classified under three main categories in general [8-10]:

a) Partial completion: This method is employed for structural purposes and involves filling only the gaps necessary to be filled to be able to reassemble the surviving pieces adjacent to these gaps.

b) Full completion: In this approach, the integrity of the entire form is restored by reconstructing all missing pieces.

c) Decorative/aesthetic/chromatic completion: This type of completion focuses on enhancing the visual integrity of the artifact with greater aesthetic consideration after the physical integrity of its entire form has been provided through full completion. It is a pictorial completion method involving the recreation of the original color, motifs or ornaments corresponding to the reconstructed missing pieces. However, when inspected closely, the distinguishability of the reconstructed section from the original is also a criterion sought for this type of completion, particularly in the restoration of archaeological objects. This approach was shaped by the influence of Brandi's restoration theory [11].

Disadvantages of conventional ceramic completion methods and filling materials

Conventional completion methods are applied to ceramic artifacts in two primary ways: directly or indirectly. In the direct method, all procedures for completing the missing pieces are carried out directly on the artifact. Firstly, a mold is created in reference to either the inner or outer surface of any symmetrical section of the artifact to represent the missing part. This mold is then fitted into the gap formed by the missing part and the casting material decided to be used is poured into the mold, typically forming a thicker mass than the original thickness of the artifact. Once the cast material has hardened, the shape of the cast is refined using various scraping tools and sandpaper to closely resemble the original missing piece. This application involves numerous interventions, as the entire molding, casting and modeling operations are performed directly on and in contact with the artifact, so this high-risk-bearing process is most likely to inflict damage on the artifact. If an appropriate mold is not prepared or if the process is not controlled precisely, the casting material may inadvertently affect the artifact by contaminating it. Additionally, tools like cutters, scrapers and sandpaper used during the refinement of the cast's shape may unintentionally come into contact with the original material, causing damage. Although it is possible to protect the surface of the artifact by covering it with layers of reversible films or tapes, which should be laid before the work commences and removed after it is finished, this approach prolongs the restoration process, increases costs and subjects the artifact to additional interventions like the application and removal of the protective layers.

Inversely, in the indirect method, the mold representing the missing piece is created by either employing the method described above or in a more complex manner using both the inner and outer surfaces of the symmetrical part of the ceramic artifact. The casting process and refinement of the roughness and excess material of the cast piece are then carried out in a space apart from the artifact. Since the cast piece is integrated into the artifact at the end of the process, the artifact undergoes less interference, thus reducing the risk of damage. However, this method requires more time for implementation and ensuring the successful fitting of the cast piece to the original body can be challenging, unlike the direct method.

Missing parts of heritage objects can be reconstructed using materials that are either similar to or different from the original. Ideally, the reconstruction material should be compatible with the original, free of side effects, inert and chemically stable. However, in ceramic restoration practices, a variety of materials with certain drawbacks are used, as outlined below.

When creating the missing parts of the ceramic artifacts, often gypsum and occasionally filler (e.g., clay, silica fume and gypsum) containing cellulose ethers (e.g., carboxymethyl cellulose), synthetic resins (e.g., polyvinyl acetate, acrylics, epoxies), animal glues and wax mixtures are used both as casting and filling materials, whereas clay, plasticine, dental wax and silicone are commonly employed as mold materials [7, 9, 10, 12-14]. The mentioned binders containing filler materials are not extensively used to reconstruct large missing parts due to their high shrinkage rates after drying, limiting their application to filling small gaps only [7]. On account of its low cost and ease of modeling, gypsum plaster is commonly utilized as a filling material for completing gaps caused by missing pieces of ceramic items. Gypsum plaster is derived from heating calcium sulfate, which naturally occurs with two molecules of crystal water and is called gypsum, at moderate temperatures (≤130ºC) [15-16]. Upon mixing with water, it quickly hardens and barely shrinks after hardening and its density, hardness and thermal expansion properties are compatible with terracotta [7].

The shaping process commences while the plaster is still wet and is finalized using various scrapers and sandpapers after it has dried. Gypsum can be colored by incorporating pigments or painted. The most significant risk associated with completing artifacts using gypsum plaster is that if the displayed or stored artifact is exposed to a humid environment permanently or comes into contact with liquid water, the gypsum may permeate the ceramic body, albeit to a small extent, as it is slightly soluble in water. In such a case, the crystallization of calcium sulfate (gypsum) on the surface and subsurface of the ceramic, forming pressure in the pores, can lead to damage such as powdering, crumbling, cracking and detachment. Additionally, the accumulation of gypsum deposits on the surface (efflorescence) can alter the original appearance [7]. Consequently, applying another conservation process becomes necessary. To prevent this, the completed portion using gypsum must be separated from the original ceramic [7], typically by applying a film of a reversible polymer such as acrylic resin as a barrier to the joints before pouring gypsum plaster. In any case, it is essential to ensure that the artifacts completed with gypsum are not kept in a humid environment.

When it becomes necessary to remove the gypsum-reconstructed missing part, mechanical methods such as scraping and crumbling are employed. However, if not careful, these mechanical methods can result in scratches, cracks and breakages in the ceramic, while gypsum residues can contaminate the artifact. Additionally, removing gypsum contamination from porous artifacts can be challenging.

Though not as prevalent as gypsum, epoxy resins are also used in completion works. Unlike gypsum, these materials do not pose a risk of soluble salt formation when exposed to water. However, unlike gypsum, these resins are difficult and time-consuming to cast and shape. If their surface is left unpainted after hardening, yellowing occurs over time due to light exposure [17]. Moreover, once hardened, it adheres quite well to the artifact through covalent bonding and mechanical hooking [16, 17]. Removing epoxy from the artwork mechanically can risk damaging it. Swelling it with certain solvents, such as dichloromethane [18] and then its controlled removal is a possible but time-consuming and also risky process in the case of fragile items. To prevent its direct adhesion to the original ceramic, a reversible resin is applied to the areas where it will come into contact with the artifact, as in the case of the application of gypsum. When the removal of epoxy is required, the reversible film between the epoxy mass and ceramic can be dissolved using an appropriate solvent, facilitating separation. These inconveniences contribute to epoxy resins not being as widely used as gypsum in archaeological ceramic restoration practices.

Experimental part

Materials

Ceramic Pots

In the studies conducted, four ceramic pots in different forms produced in the present day were used to represent archaeological ceramic pots (Fig. 1). These pots were randomly broken by pounding and one piece each from the neck/rim, body and base regions was selected as the missing piece. Excluding these selected pieces, considered missing pieces, the other pieces were assembled and documented in 2D with drawings, then modeled in 3D using a scanner. In the documentation stage, freehand drawings as well as drawings using CAD software were produced. A 3D scanner utilizing the structured light technique was employed. Based on the 3D models obtained without the missing pieces, software commonly used for 3D modeling was utilized to model the missing pieces in 3D. For printing the 3D models, two different types of 3D printers were used. These 3D printers employ fused deposition modeling (FDM) and stereolithography (SLA) technologies. The purpose of choosing two different types of 3D printers is to compare their positive and negative aspects.

Fig. 1. The selected ceramic pots, numbered from 1 to 4 from left to right

Laptop

An Acer brand TravelMate TMP215-52G model laptop was used to create the 3D model of both the missing pieces to be reconstructed and the ceramic pots that were erected without these pieces and to run the software required to create 3D models ready for manufacturing in the 3D printer. This laptop, equipped with the Windows operating system, features an Intel Core i5-10210U processor with 4 cores and a speed of 1.60GHz, an NVIDIA GeForce MX230 graphics card with 2GB of memory capacity, 8GB of RAM and an SSD hard drive with 512GB of storage capacity.

Software

To create the 3D model of the ceramic pots erected by joining their pieces with paper tape without the missing pieces, EXScan S software produced by Shining 3D, the manufacturer of the 3D scanner used in the study, was run. To complete the missing pieces of the ceramic pots by using the 3D modeling method, Autodesk's 3DS Max software's 2021 version was employed. To prepare the 3D models of the missing pieces of the ceramic pots for printing on an FDM-type 3D printer, Creality Slicer (Creality) slicing software was used and for printing on an SLA-type 3D printer, Lychee Slicer (Mango 3D) slicing software was preferred.

3D scanner

3D scanning was conducted by a Shining 3D Einscan SE brand 3D scanner employing the structured light technique (Fig. 2).

Fig. 2. Structured light 3D scanner (Shining 3D EinScan SE)

Featuring an automatic rotary table/turntable, the accuracy of this 3D scanner is 0.1mm. The point distance on the 3D model it generated from the data obtained during the scanning ranges from 0.17 to 0.2mm. In addition to creating the 3D model, the device is able to overlay the texture of the scanned object onto the 3D model as well. The resolution of the camera that the equipment uses for 3D scanning is 1.3 megapixels.

3D printers and printing materials

3D printers can manufacture 3D models by using plastic powder, resin, clay, metal alloys, biomaterials, cement and various composite materials [19]. To be able to compare their positive and negative aspects, PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene) filaments, as well as resin, were used as raw materials in FDM-type and SLA-type 3D printers.

Creality's CR-10S Pro V2 model printer was the FDM-type 3D printer used (Fig. 3). This device has a print size of 30×30×40cm and a print precision of ±0.1mm. With a nozzle diameter of 0.4mm, the print speed of this device can be adjusted between 30mm/s and 180mm/s and the nozzle/extruder temperature can be raised up to 260°C, while the heat bed temperature can be raised up to 100°C. For printing from this 3D printer, PLA and ABS filaments, which are among the most commonly used materials in FDM-type printers, have been selected [20, 21]. PLA is a type of bioplastic produced from sugar and cornstarch [20, 22, 23]. Not only is PLA more brittle and less durable compared to ABS filament, but its heat resistance is lower as well [19, 22, 23]. The Microzey brand's white-colored PLA filament was used. For this filament, using a nozzle temperature of 190-220°C and a heat bed temperature of 60-80°C is recommended. As for the ABS filament, Filamentto brand's white-colored filament was utilized, which is recommended for use at a nozzle temperature of 220-255°C and a heat bed temperature of 80-100°C.

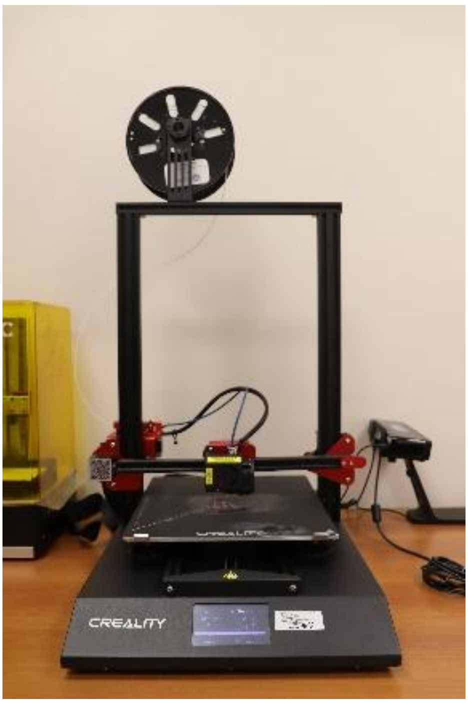

Fig. 3. FDM-type 3D printer (Creality CR-10S Pro V2)

Anycubic's Photon Mono X model was chosen as the SLA-type 3D printer (Fig. 4) in the study. This 3D printer utilizes LCD-based SLA technology and has a printing area of

19.2×12×24.5cm. It uses UV resin cured at a wavelength of 405nm as the printing material. The Z-axis resolution of the device is 0.01mm. With an XY resolution of 0.05mm and 3840×2400 (4K), it is capable of manufacturing detailed outputs. Its layer resolution varies between 0.01 and 0.15mm. ABS-like resin was preferred in the study. The viscosity of the resin used (Alias Model Sharp & Rigid, Dokuz Kimya) is 573cPs at 25°C, its heat deflection temperature is 95°C and its Shore D hardness is 91.

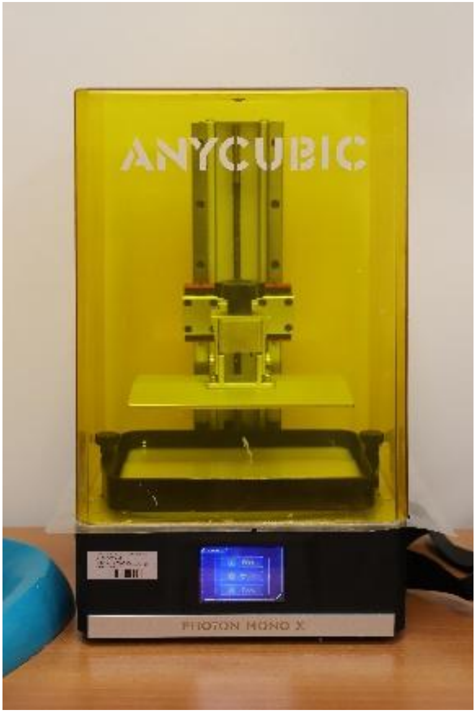

Fig. 4. SLA-type 3D printer (Anycubic Photon Mono X)

Methods

Removing pieces from ceramic pots

Initially, four pots, each in a different form, were broken intentionally to yield random broken pieces. Some pieces belonging to the neck/rim, body and base of the pots were selected and reserved as missing pieces and the remaining pieces were joined together using paper tape, starting from the base up. By doing so, the intent was to 3D scan the completed pots without the missing pieces and following that, firstly, to generate 3D models of the gaps formed by the missing pieces and then to fill those gaps with pieces manufactured from a 3D printer. The easy removal of the paper tape holding the pieces together facilitates the process of placing the manufactured pieces in their corresponding places.

Pot number 1 yielded large pieces when broken. Two large pieces from the neck/rim and body of this pot were selected and subtracted to represent missing pieces. From Pot number 2, three pieces broken from the neck/rim, body and base were subtracted. These pieces were adjacent to each other. The gaps formed by these pieces were planned to be filled one by one separately, rather than filling them as a whole in their entirety. Also from Pot number 3, the neck/rim, body and base pieces were subtracted, whereas only one singular neck/rim piece was subtracted from Pot number 4. The images of the pots, whose pieces were joined without including the subtracted pieces, are shown in figure 5.

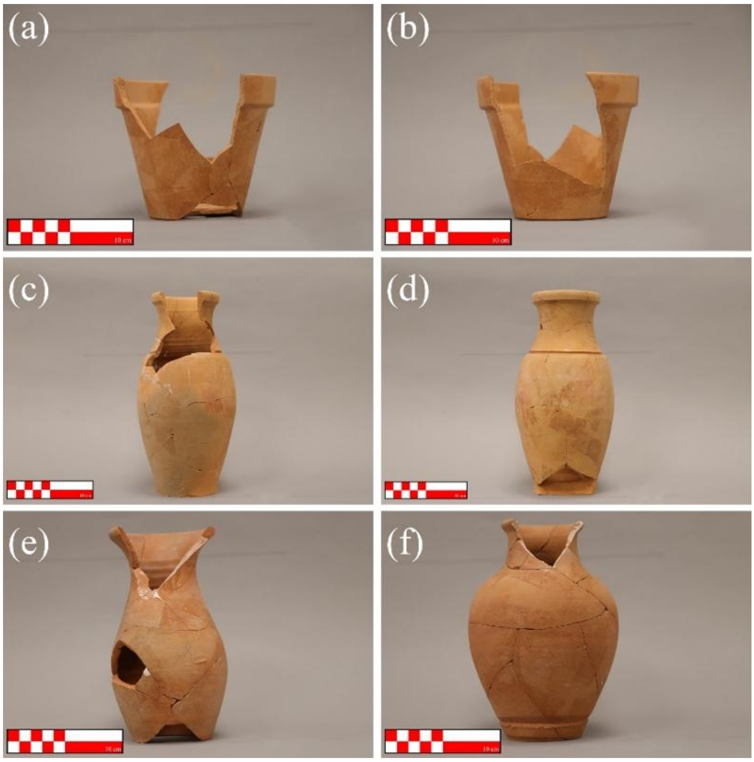

Fig. 5. The appearance of the pots after assembling their pieces without including the missing pieces to be reconstructed for completion

2D drawings

Freehand illustrations of the pots numbered from 1 to 4 were drawn on paper using tools such as soldering wire, calipers and a compass (Fig. 6), similar to the process utilized for the freehand drawings of archaeological findings. These drawings were digitized in AutoCAD software at a 1:1 scale (Fig. 7). The intent was to generate 3D models from the cross-sections obtained from these drawings, illustrating the pots in their intact (original) state.

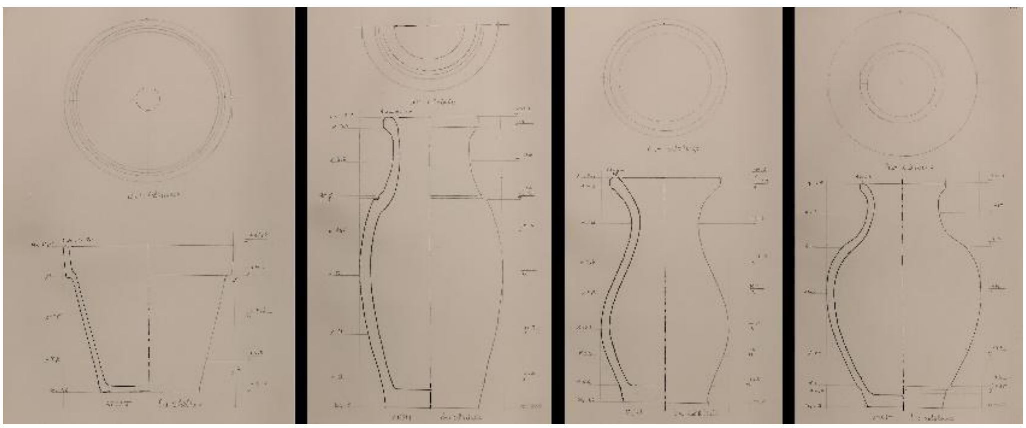

Fig. 6. Freehand drawings of the ceramic pots at a 1:1 scale

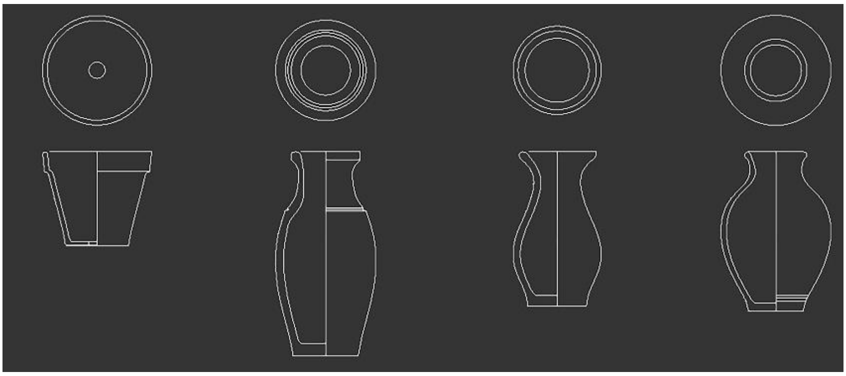

Fig. 7. CAD drawings of the ceramic pots at a 1:1 scale

3D scanning

For the 3D scanning, the pots, pieces of which were assembled, were placed on the 3D scanner's rotary table/turntable (Fig. 8) and they were scanned as the turntable completed a 360° rotation in 16 steps. Sections of the pots that were out of range of the scanning area of the 3D scanner were scanned a few more times by placing them in different positions on the rotary table each time. The 3D scans for each pot were then merged into a single 3D model using the scanner's software, EXScan-S.

Fig. 8. 3D scanning of a ceramic pot whose pieces are secured with paper tapes

3D modeling of the missing pieces

The 3D models obtained from scanning the pots erected with paper tape without the missing pieces were wielded to generate 3D models of the missing pieces. Five methods described below were tried to generate models of the missing pieces of the pots. The techniques practiced are listed in Table 1.

Table 1. Techniques practiced for modeling the missing pieces of the pots

Pot No.	Method No.	Modeling technique	Number of missing piece(s) attempted to be modeled	Place of the missing piece(s) attempted to be modeled
1	1	Spline Modeling + Boolean Modeling	2	neck/rim + body
3	2	Spline Modeling + Boolean Modeling	1	neck/rim
1	3	Scan-based Modeling + Boolean Modeling	1	neck/rim + body
2	4	NURBS Modeling + Boolean Modeling	1	neck/rim
2	5	Box/Primitive Modeling + Boolean Modeling	2	body, base
3	5	Box/Primitive Modeling + Boolean Modeling	2	body, base
4	5	Box/Primitive Modeling + Boolean Modeling	1	neck/rim

Method 1: 1:1 scale cross-sectional drawings generated in AutoCAD were transferred to 3DS Max. Applying the "lathe" modifier to these cross-sectional drawings, 3D models of the pots were generated. These 3D models, showing the pots in their original intact states, were then superimposed on the 3D models with missing pieces obtained from scanning in 3DS Max. The purpose of this process was to fill the missing sections of the 3D models obtained from scanning. Subsequently, by applying the "boolean" modifier, sections from 3D models showing the intact states of the pots, created with the "lathe" modifier, were deleted based on the shapes of the 3D models obtained from scanning. With the deleting process, the intent was to have only the pieces that would fill the missing sections remain at the end. The "boolean" modifier has been used for similar purposes in other studies as well [4, 6]. In the study by Lee and Wi, missing pieces from two different parts of a ceramic artifact were modeled by applying Method 1 and using ZBrush software, then 3D prints were manufactured and the artifact was successfully completed [6]. Whereas, in Burgess's study, the missing piece of the ceramic pot was attempted to be created in the Blender software. A solid model that has the shape of the edge of the missing part but has a larger volume was created and the gap formed by the missing piece was temporarily filled. Then, using the "boolean" modifier, a model was manufactured with the intent to properly fill the gap. However, when the printer-created missing piece was compared to the ceramic's original, some defects were found on the 3D printer-manufactured piece and as a result, the models did not fit well with the ceramic and the parts did not align properly [4].

Method 2: 3D models with missing pieces obtained from the 3D scanning process were imported into 3DS Max and their cross-sections were taken. To prepare the cross-section, the "slice" modifier was applied to the model and the model was split in half. The walls of the split model were exposed and these walls were converted into 2D lines. The "lathe" modifier was then applied to the created lines to obtain the complete (whole) versions of the pots without missing pieces. Subsequently, using the "boolean" modifier, a deletion process was performed on the models created with the "lathe" modifier based on the shapes of the 3D models obtained from the scanning. This way, retaining only the model of the missing piece projected to fill the gap was intended.

Method 3: The 3D model with missing pieces obtained from the 3D scanning was transferred to 3DS Max to create a copy. The created copy was rotated to cover the missing pieces of the original 3D model. The "boolean" modifier was planned to be used exactly in the same manner as it was used in Method 1.

Method 4: The 3D model with missing pieces obtained from the 3D scanning was transferred to 3DS Max and its polygon count was reduced using the "multires" modifier to render a less detailed model. Then, the opposing walls of the parts where the missing pieces belong and were detached were drawn from the 3D model using the "line" tool. To merge these drawings, a line-format 2D cross-section of the 3D model was obtained using the "slice" tool and it was then copied and the copies were placed between the drawings prepared using the "line" tool. These copies of the wall drawings were also placed over the broken edges of the 3D model obtained from the 3D scan. All these 2D lines were merged with each other using the "attach" tool. Lines were drawn at different height levels within this line group using the "line" tool. The unified line group was converted into a 3D model using the "surface" modifier. Finally, the shape of the 3D model created from the lines was erased from the 3D model obtained from the 3D scan using the "boolean" modifier.

Method 5: The 3D model obtained from the 3D scan was imported into 3DS Max and circles were drawn around the edges of the missing parts using the "circle" tool to connect them from the outside. Then, using the circles as references, the 3D model of the missing parts was created using the box modeling technique. In this process, the corners, edges and surfaces of the box were made editable using the "editable poly" mode and tools such as "extrude" and "move" were used to first create a rough model and then a detailed model. The "turbosmooth" modifier was applied to the detailed 3D model to achieve a smooth and polished appearance. Finally, the 3D model of the pot was deleted using the "boolean" modifier, leaving behind only the 3D model of the part, completing the missing section.

Results and discussion

3D scanning

The initial attempt to scan the assembled pieces of the pots, excluding the pieces eliminated, was unsuccessful. The failure was due to the insufficient size of the openings in the neck and rim parts and of the gaps created by the missing pieces, which prevented the complete scanning of the interior of the pots (Fig. 9). Following this unsuccessful attempt, the paper tapes holding the pieces together were removed and the neighboring pieces adjacent to the missing sections, which required 3D modeling, were reattached using paper tapes. The remaining pieces were grouped according to the rim, body and base sections and then reassembled using paper tape. Those that could not stand on their own were supported with plasticine. By scanning these grouped and reassembled pieces, the thickness of the pots was obtained.

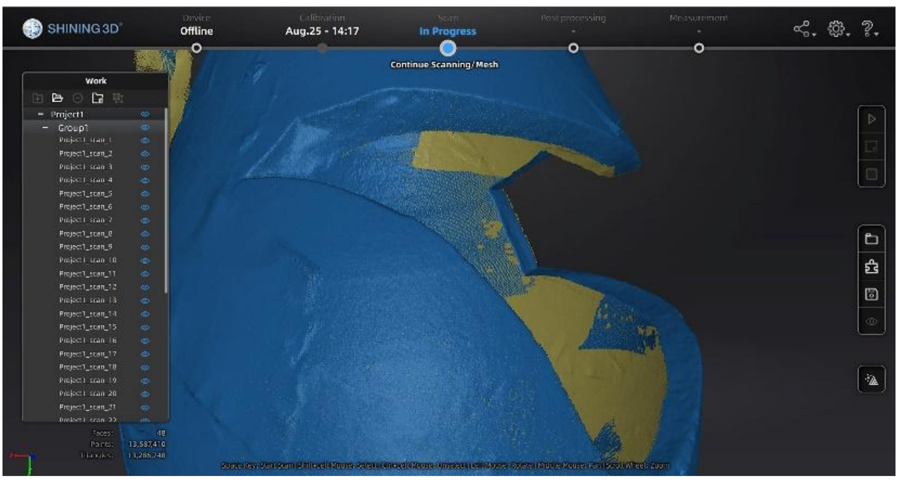

Fig. 9. The regions of the pot that were scanned without any problems are shown in blue, while the regions that could not be scanned appear yellow. (The irregularities on the blue surfaces are due to the temporary paper tapes used in assembling the pieces)

3D modeling

The 3D models of the pots, excluding the missing pieces, were saved in OBJ format with medium and high detail using the EXScan-S software and then imported into 3DS Max. Based on these models, attempts were made to model the missing pieces in 3D using five different methods discussed below. Using medium- and high-detail 3D models for modeling the missing pieces did not significantly impact the restoration quality.

Method 1

The process of overlaying the 3D models obtained from the 1:1 scale cross-sectional drawings in AutoCAD (Fig. 10) with the 3D models of the pots reconstructed without missing parts (Fig. 11) was not successful. This is because the 3D models prepared using the "lathe" modifier from the 1:1 scale section drawings are entirely symmetrical, whereas the pots, like archaeological ones, are not perfectly symmetrical. Consequently, only the pieces needed to fill the missing areas of Pot number 1 were prepared using this method (Fig. 12).

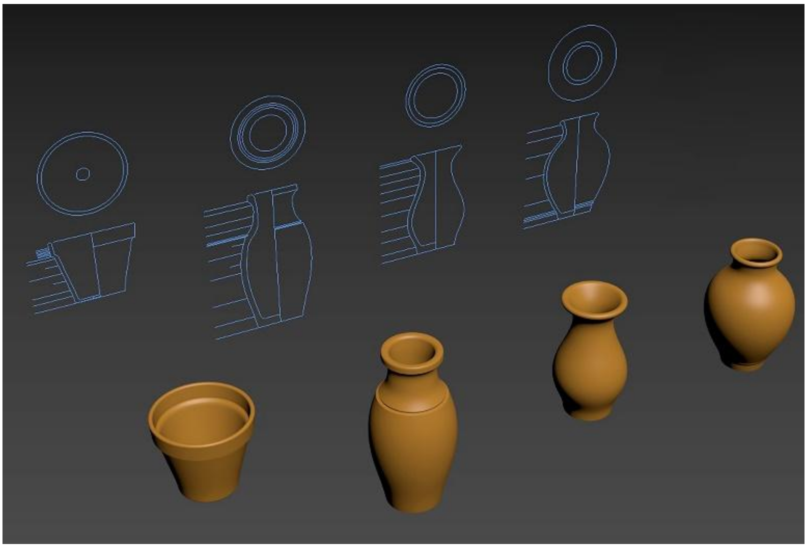

Fig. 10. The 3D models obtained from the cross-sections of 1:1 scale AutoCAD drawings

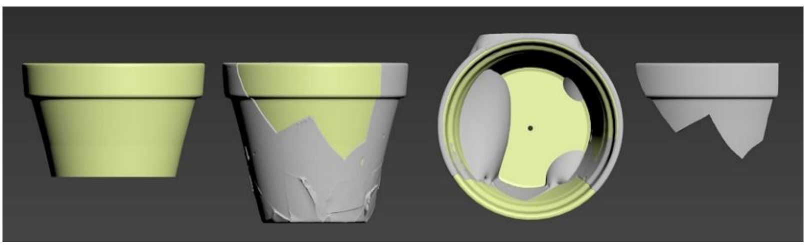

Fig. 11. Overlaying the 3D model obtained from the 3D scanning of Pot 1 with the 3D models produced from the 1:1 scale AutoCAD drawings. (The irregularities on the gray surface are due to the paper tapes.)

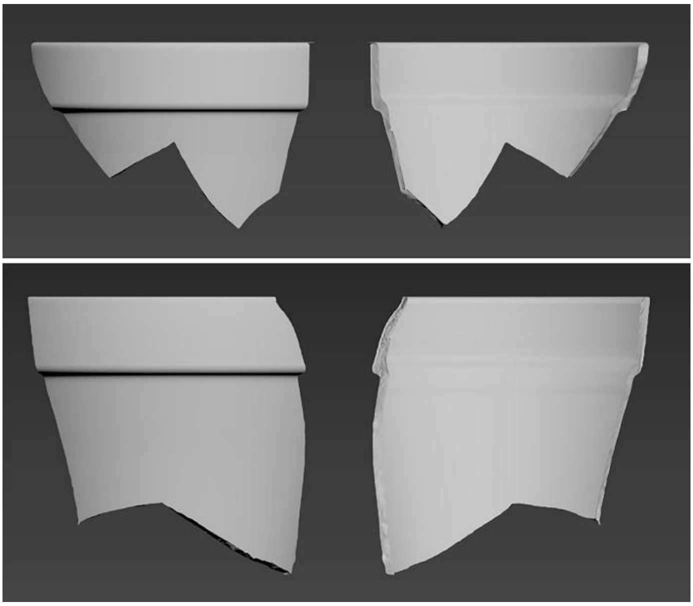

Fig. 12. External (left) and internal (right) views of the 3D models of the missing parts of Pot number 1 prepared with Method 1

Method 2

Following the failure of Method 1, cross-sections were taken from the 3D models produced through 3D scanning instead of AutoCAD drawings. To obtain its cross-section, the model was split into two by applying the "slice" modifier to reveal its walls, which were then converted into 2D lines (Fig. 13a).

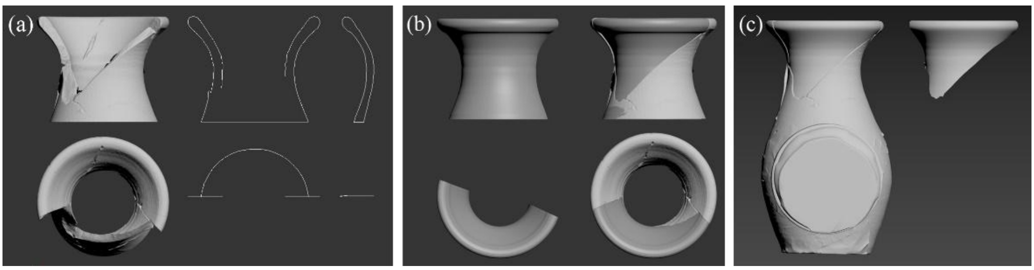

Fig. 13. (a) cross-section of the 3D model obtained from the 3D scanning of pot number 3; (b) combination of the 3D model obtained from the cross-section with the 3D model obtained from the 3D scanning result; (c) remaining neck/rim piece after applying the boolean" modifier and its version fitted to the pot

The "lathe" modifier was then applied to these lines, resulting in complete 3D models of the pots based on their achieved cross-sections. The 3D models created with the "lathe" modifier were overlaid with those obtained from 3D scanning (Fig. 13b), but the gaps caused by the missing pieces could not be completely filled. Due to slight differences in the sections of the pots, some regions had gaps between the two models or experienced minor overlapping or intersecting. To solve this problem, which is at a smaller scale than in the case of Method 1, the points creating the cross-sectional drawing were adjusted, allowing for modifications to the shape of the 3D model. As a result of the trials, only the rim opening of Pot number 3 could be filled. After the filling process was completed, the 3D model that was created with the “lathe” modifier and all regions of the model that were obtained by 3D scanning, except the regions belonging to the missing part, were deleted by applying the “boolean” modifier. Thus, only the 3D model to be used as the missing neck/rim piece of Pot number 3 was retained (Fig. 13c). While success was achieved in the neck/rim piece with this method, production in the correct form could not be provided for the other pieces in a reasonable time.

Method 3

The 3D model obtained from the 3D scanning was imported into 3DS Max and a duplicate was created. The models were overlapped and one of the models was rotated in order to fill in the missing pieces of the other. However, the merging of the models was unsuccessful; there were issues such as gaps, interpenetration and protrusion between the models (Fig. 14). With this method, none of the pots’ missing parts were successfully filled.

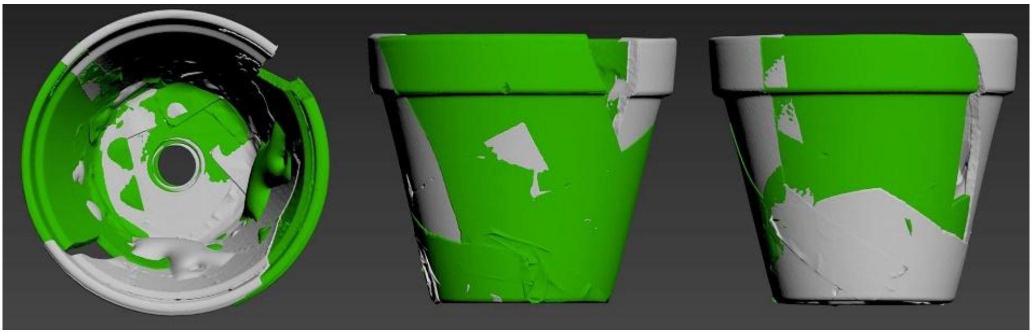

Fig. 14. Unsuccessful completion effort

Method 4

The 3D model of the neck/rim part of Pot number 2 was imported into 3DS Max. The polygon count of this 3D model was reduced using the "multires" modifier, making the model less detailed. The edges of the missing parts on the rim were outlined using the "line" tool on the 3D model (Fig. 15a). To merge these drawings, the "slice" tool was used to obtain a cross-section of the 3D model in 2D lines and these lines were then copied and placed between the drawings of the edges of the missing part prepared with the "line" tool (Fig. 15b). To ensure smooth application of the "boolean" modifier to define the shape of the broken edges, copies of the edge drawings of the missing parts were also placed over the broken edges of the 3D model obtained from the 3D scan. All these 2D lines were merged using the "attach" tool. The group of lines needed to be connected with each other to form a 3D solid model and for this purpose, lines were drawn between them at different height levels using the "line" tool (Fig. 15c). After merging into a single entity, the line group was converted into a 3D model by applying the "surface" modifier. Using the "boolean" modifier, the shape of the 3D model obtained from the 3D scan was subtracted from the shape of the 3D model created from the 2D lines. This process allowed the shape of the broken edges to be transferred to the 3D model created from the lines, resulting in a 3D model that filled the missing part of the pot according to its form (Fig. 15d).

S. Fragkos et al. have used a similar method in their study [5]. In this study, it is stated that the shape of the broken edges can be given to the 3D model created with lines, a 3D model filling the missing part in accordance with the form of the pot can be obtained and the piece produced by the 3D printer fits smoothly into the desired area. Although a satisfactory result was achieved in the present study with a method similar to that used by *S. Fragkos et al.* [5], the method is not without problems. Three cross-section drawings placed between two edge drawings did not fully capture the mouth shape of Pot number 2 (Fig. 15e). Increasing the number of cross-sectional drawings placed between the edge drawings and bringing them closer together is able to solve this problem. However, since the edge drawings are not on a single plane, their juxtaposition with the cross-sectional drawings hinders the creation of a flawless solid 3D model. This method used in modeling the neck/rim piece of Pot number 2 has not been applied to the pieces from the body and base sections because modeling would take a considerably long time. When dealing with complex parts that are more difficult to model, the use of freeform modeling tools can ease and expedite the process. Software such as Rapidform XOR, which allows triangle mesh control and manipulations and ZBrush, which is sculpting software, can be given as examples of such tools [6].

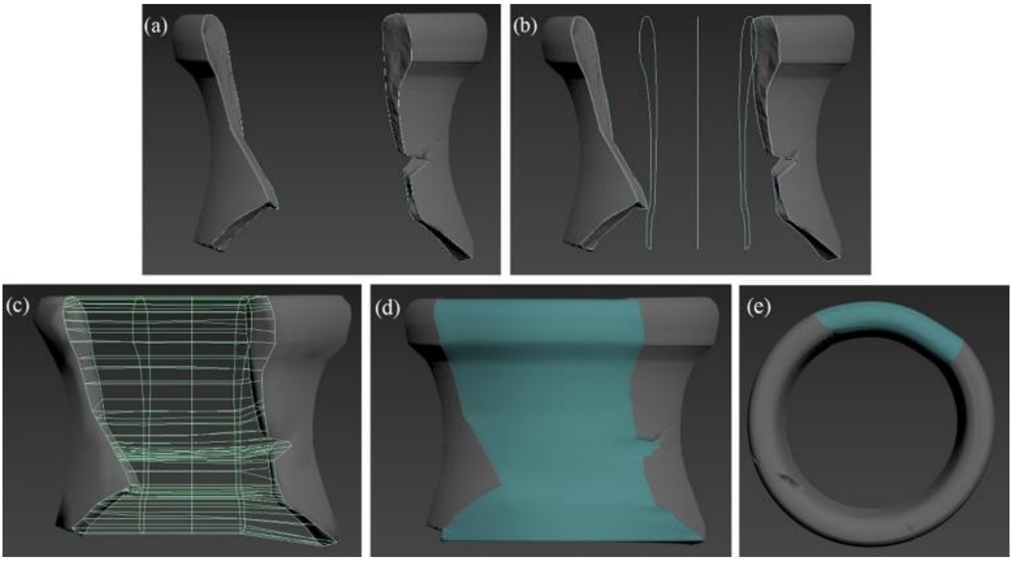

Fig. 15. (a) drawing the opposing edges of the broken part with the "line" tool; (b) filling the space between the edge drawings with cross-section drawings; (c) the situation after drawing lines at different height levels to connect all lines; (d) the 3D model filling the missing part after applying the "surface" and "boolean" modifiers; (e) the incorrectly formed mouth shape

Method 5

In the study, solid modeling was used as the final method. In this context, the model obtained from 3D scanning was transferred to 3DS Max and circles were drawn using the "circle" tool to connect the edges of the missing part from the outside (Fig. 16a). Circles were placed at intervals from the bottom to the top of the missing part at the same height internally and externally (Fig. 16a and 16b). In this way, reference lines were created for the solid modeling method. Subsequently, a box was created and solid modeling began. The box was positioned at the lowest point of the reference lines, fitting slightly into the 3D model obtained from the 3D scanning (Fig. 16c). By converting the box to "editable poly" mode, its corners, edges and faces became editable. The polygons of the box were duplicated by creating new protrusions to the left and right using the "extrude" tool and its edges and corners were moved to the reference lines using the "move" tool (Fig. 16d). The extension process to the right and left was continued until the outermost points of the box entered the 3D model obtained from the 3D scanning (Fig. 16e). As the formation of the 3D model was started according to the reference lines at the bottom, the model was extended upwards by raising the upper polygons using the "extrude" tool (Fig. 16f). The corners of the newly formed polygons were moved to the reference lines using the "move" tool. This process was continued until the missing part of the pot was filled (Fig. 16g). Since the edges of the prepared 3D model were not as detailed as the broken edges of the 3D model obtained from the 3D scanning, this 3D model was considered a rough model.

To enhance the detailing of the areas where the rough model intersects with the 3D model obtained from the 3D scanning, the number of reference lines was increased. The new reference lines were positioned according to the edges of the 3D model obtained from the 3D scanning. Therefore, new polygons were created on the rough model and their corners were moved to touch the reference lines. To give the detailed 3D model (Fig. 16h) a smooth and soft appearance, the "turbosmooth" modifier was applied (Fig. 16i). Finally, as described in other methods, the "boolean" modifier was applied, leaving behind a piece that completes the missing part (Fig. 16j). Among the methods tested in the study, this method yielded the best results. The body and base pieces of Pot number 2 and Pot number 3 and the neck/rim piece of Pot number 4, were 3D modeled using this method (Table 1).

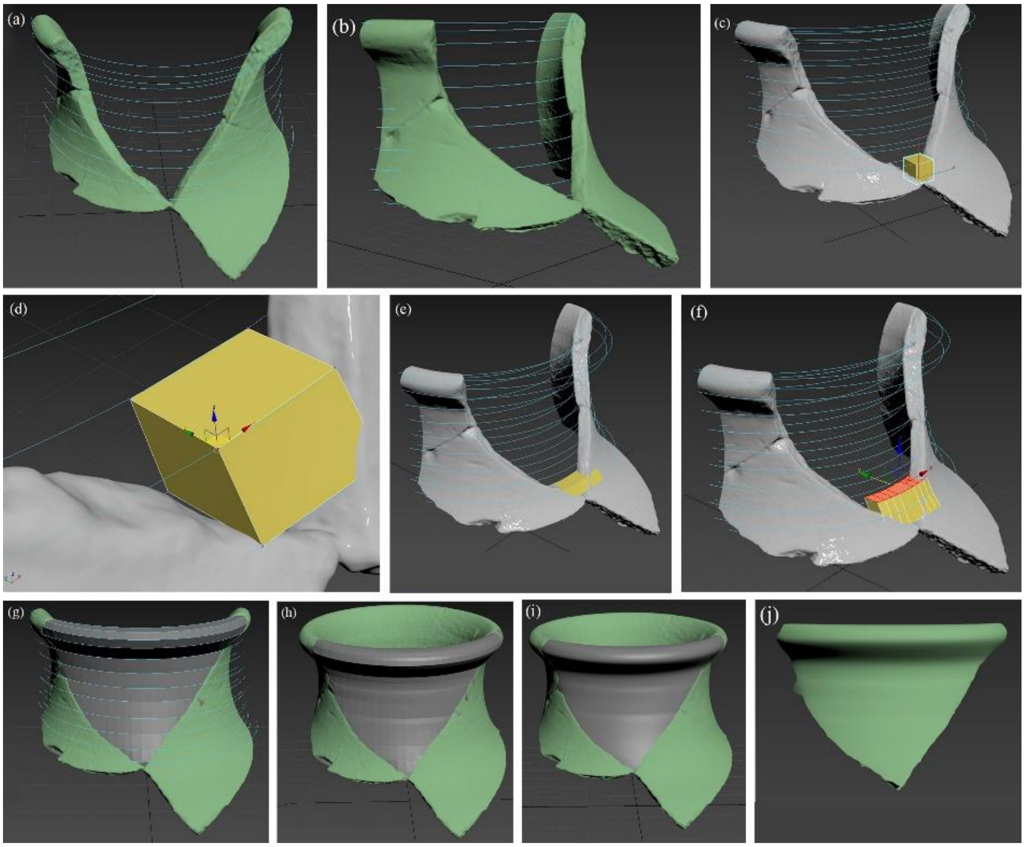

Fig. 16. (a) reference lines connecting the broken edges from the outside; (b) reference lines connecting the broken edges from the inside; (c) placement of the box to be shaped at the starting point; (d) shaping of the box according to the reference lines; (e) expansion of the box to fill the gap; (f) raising of the box to fill the gap; (g) rough model filling the gap; (h) detailed 3D model; (i) 3D model with "turbosmooth" modifier applied; (j) 3D model remained after applying the "boolean" modifier

3D printing

The prepared 3D models for 3D printing were saved in OBJ format and transferred to the software of FDM-type and SLA-type 3D printers for printing settings. For the FDM-type 3D printer, the super quality setting of Creality Slicer was preferred, with a print speed of 75mm/s, an initial layer speed of 15mm/s and a retraction speed of 50mm/s. For prints using PLA filament, the nozzle temperature was set to 190°C and the heat bed temperature to 70°C, while for prints using ABS filament, the nozzle temperature was set to 230°C and the heat bed temperature to 90°C. The supports automatically added to the 3D models by the software were used to facilitate printing. After the slicing process was completed, the 3D models were saved with the GCODE extension and transferred to the FDM-type 3D printer.

Lychee Slicer software was used for the SLA-type 3D printer. During printing, cone-shaped supports with a tip diameter of 0.7mm and a tip length of 3mm were used to support the 3D models. The layer thickness of the print was set to 0.05mm, the exposure time of the layers to UV light was set to 2 seconds and the exposure time of the layer adhering to the printing platform was set to 4 seconds. The descent speed of the platform was set to 150mm/min and the ascent speed of the platform was set to 65mm/min. After the slicing process was completed, the 3D models were saved with the PMWX extension and transferred to the SLA-type 3D printer.

The time and material spent on printing varied depending on the shape and size of the models. The printing times for FDM-type and SLA-type printers are provided in Table 2, while the amount of material consumed is listed in Table 3.

Table 2. Printing durations of the reconstructed parts of the pots in minutes

	Reconstructed Part and Printing Material								
	Neck/Rim			Body			Base		
Pot	Filament		Resin	Filament		Resin	Filament		Resin
no.	PLA	ABS	ABS-like	PLA	ABS	ABS-like	PLA	ABS	ABS-like
1	198	227	260	-	-	-	-	-	-
2	128	141	210	99	107	167	132	137	203
3	170	188	300	97	105	120	143	152	166
4	91	99	157	-	-	-	-	-	-

Table 3. Amount of consumed printing materials (g: gram; m: meter; mL: milliliter)

	Reconstructed Part and Printing Material														
	Neck/Rim					Body					Base				
	PLA		ABS		ABS-like	PLA		ABS		ABS-like	PLA		ABS		ABS-like
Pot no.	m	g	m	g	mL	m	g	m	g	mL	m	g	m	g	mL
1	5.8	17	7.3	19	29.5	-		-		-	-		-		-
2	3.6	11	4.4	12	20.4	2.4	7	2.8	7	19.41	3.9	12	4.4	12	30.38
3	4.5	13	5.4	14	30.7	2.4	7	2.8	7	13.11	4.6	14	5	13	35
4	2.3	7	2.8	7	13.5	-		-		-	-		-		-

Condition of the 3D-printed pieces

All pieces manufactured by 3D printers using filament and resin are in the shapes and dimensions as modeled in 3DS Max. Therefore, with the hardware and software used in this study, it became clear that it is possible to reconstruct the pieces with the dimensional accuracy required for ceramic restoration.

In productions using ABS filament with an FDM-type 3D printer, issues such as cracking, layer separation and burning have been observed during manufacturing (Fig. 17). Although the infill setting for the FDM-type 3D printer was kept at 10% to reduce costs and save time, the strength of pieces printed with ABS and PLA filaments was not adversely affected and they did not sustain damage when dropped from a height of 1.5 meters onto a hard surface. No difference in color was observed between the pieces produced with an FDM-type 3D printer and the ABS and PLA filaments used. A layer thickness of 0.12mm used for pieces produced with an FDM-type 3D printer provided a very smooth texture, eliminating the need for surface treatment. Attempts to further smooth the surface by reducing the layer thickness to 0.05mm for pieces produced using ABS and PLA filaments resulted in unsuccessful outcomes (Fig. 18).

It is important to adjust the dimensions of the points where the supports used for printing with an SLA-type printer join the printed part appropriately. When supports with very small contact areas are used, they may not support the printed piece and the piece may fall into the resin tank, where it hardens, leading to the FEP (Fluorinated Ethylene Propylene) film sticking to the resin tank and the support pieces applying pressure to the FEP film. In this case, there is a possibility of the FEP film being pierced or deformed. When a deformed FEP film is reused, defects may occur on the manufactured piece (Fig. 19a). Additionally, after the supports are removed, some scars may remain in the areas where they made contact (Fig. 19b). As the contact area decreases, the likelihood of leaving marks when removing the supports also decreases. It is recommended to wash the printed piece with isopropyl alcohol to remove excess resin. Some support residues that cannot be removed by washing may result in slight scratches on the pieces when intervened with hand tools (Fig. 19b).

Fig. 17. Cracking and burning observed in prints obtained using ABS filament

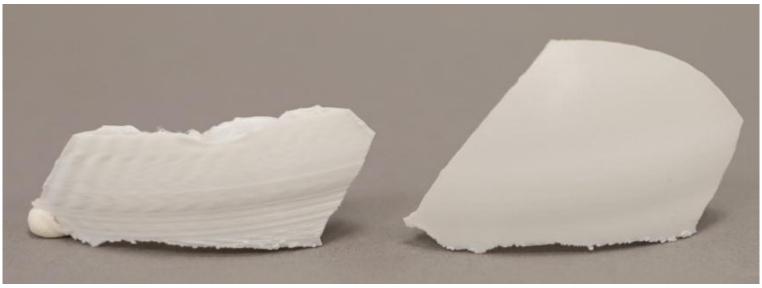

Fig. 18. Print obtained using PLA filament with a 0.05mm layer height (left) and print obtained with a 0.12mm layer height (right)

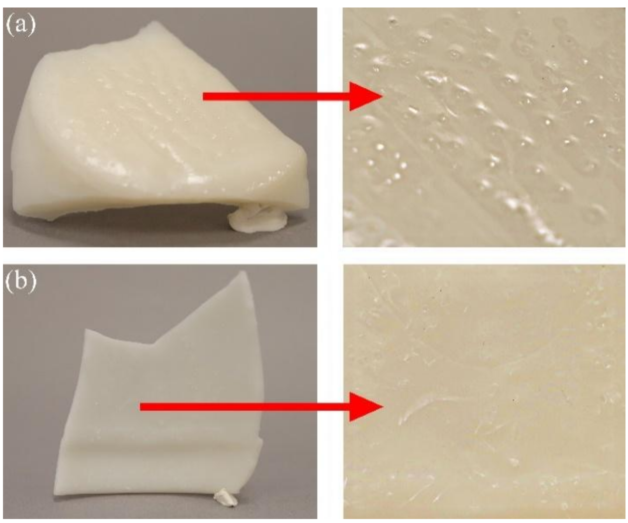

Fig. 19. On the piece printed using resin, (a) marks caused by deformed FEP film and (b) scratches formed after removing support residues

To prevent possible marks caused by supports, supports are ensured to contact the inner surface rather than the outer surface of the pieces printed with both FDM-type and SLA-type printers. Although the resin used hardens sufficiently during printing, it needs to be further exposed to UV light to complete the curing process. Without using a curing device, exposing pieces to daylight contributes to the curing process, but it has been observed that they turn yellow when exposed to daylight excessively (Fig. 20).

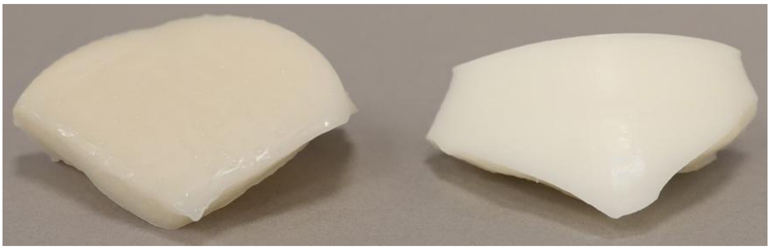

Fig. 20. The color difference in prints manufactured using resin exposed to sunlight for different durations

Assembling the manufactured pieces onto the pot

Two pieces covering the body and rim, manufactured with the same method (Method 1), can be fitted into Pot number 1 (Fig. 21). Although there may be minor imperfections in the 3D models and consequently in the manufactured pieces, it can be said that these imperfections can be tolerated by the viewer when the completed pot is viewed from different perspectives (Fig. 21a-21c).

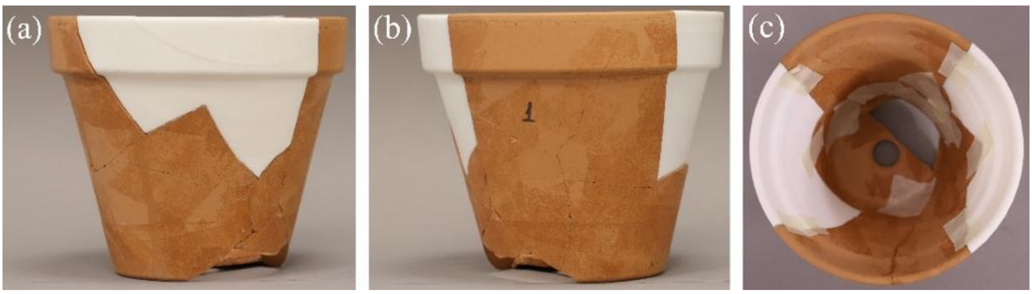

Fig. 21. Filling the missing rim and neck parts of Pot number 1 with two pieces modeled using Method 1 and printed using the PLA filament. (a) front view of the first piece; (b) side view of the first and second pieces; (c) top view of the first and second pieces

Method 4 was used for modeling the missing parts of the rim and neck sections of Pot number 2, while Method 5 was used for modeling the missing parts of the body and base sections. The shape distortion observed during the 3D modeling of the rim part (Fig. 18e) can also be seen in the printed piece (Fig. 22b). However, this piece, produced using a method similar to that used by *S. Fragkos et al.* [5], fits into place as if it were the original piece of the pot (Fig. 22a-22b). The body and base pieces also fit into their places very well (Fig. 22c-22d). With effective use of Method 4, it is possible to eliminate shape distortions at the edge of the rim and to detail the pieces that will touch the broken edges, thus completing the restoration without any gaps, but this inevitably leads to a significant increase in the 3D modeling time.

The rim piece of Pot number 3 was modeled using Method 2 (Fig. 23a). This piece fits well along the broken edges of the pot but sits slightly lower than the rim level of the pot. This flaw is only noticeable when the pot is examined closely. However, even a thin and small missing piece that has been cut off from the surface of the pot, thinning its cross-section without creating a gap, could be 3D modeled and printed to fit well on the surface of the pot (Fig. 23b). This level of detail indicates the successful outcome of the method. The body and base pieces modeled using Method 5 fit tightly into their places without any issues (Fig. 23b).

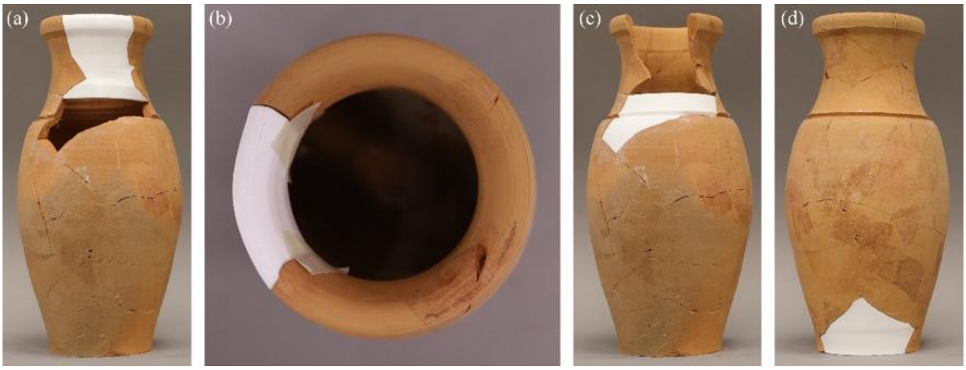

Fig. 22. Printed pieces using PLA filament. (a, b) rim and neck piece modeled with Method 4; (c, d) body and base pieces modeled with Method 5

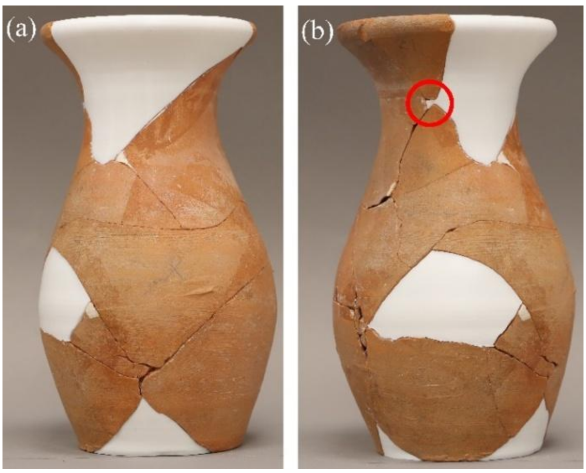

Fig. 23. (a) The pot completed with pieces printed using PLA filament, with the rim piece modeled using Method 2 and the body and base pieces modeled using Method 5; (b) another view of the same pot. The printed copy of the small and thin missing piece on the surface is marked in red

Fig. 24. (a) left side view, (b) front view and (c) right side view of the rim/neck piece modeled with Method 5 and printed using PLA filament

The missing rim/neck part for Pot number 4 has been modeled using Method 5. The modeling process, the printing of this model and the fitting of the produced piece into the pot were successfully completed without any issues (Fig. 24a-24c).

Conclusions

In the study, various methods were tried to reconstruct the missing pieces of the pots. Among these, Method 3 did not yield successful results. The attempt using Method 1 for modeling the missing pieces of Pot number 1 also failed compared to other methods. The use of such 3D models obtained with reference to 1:1 scale cross-sectional drawings created in AutoCAD may not be possible in asymmetrical archaeological ceramics but can be useful in symmetrical late-period and contemporary artifacts. Methods 2 and 4, used for modeling the rim pieces of Pots number 2 and 3, could not be used for modeling the body and base pieces. It can be said that Methods 2 and 4 are effective in the 3D modeling of the rim pieces. Modeling flaws such as the slight drop in rim level in Method 2 and shape distortion in Method 4 can be corrected by using the software more effectively, but this would prolong the modeling time, putting the 3D technique at a disadvantage in terms of time spent for restoration compared to conventional restoration methods.

Method 5 has yielded the best results because this method enabled the 3D modeling of all missing pieces and the prints obtained from these models fit seamlessly into their places in the pots. A few small gaps formed between the edges of the pot and the base pieces modeled and produced using Method 5 can be considered minor flaws that would not disturb museum visitors. Creating a 3D model at a higher detail level using a 3D scanner with higher accuracy will likely be sufficient to eliminate these flaws. However, except for Methods 1 and 2, suitable pieces with small indentations and protrusions that fit successfully into their places have been produced with other methods using both types of printers. In this regard, the best result has been achieved again with Method 5. The printed pieces containing protrusions that can fit into small gaps in the pots or indentations where the protrusions in the pots can fit were securely fixed in their places. These pieces with protrusions and indentations do not fall out of place unless subjected to physical force. Especially the printed pieces belonging to the body are snugged tightly in their places when installed due to being surrounded by the adjacent ceramic pieces. However, there is a possibility that large and heavy reconstructed pieces with a small area in contact with the pot may come dislodged due to a possible physical force. In such cases, a small amount of a reversible conservation adhesive may be required to bond them, even if weakly. Although the best results in this study were achieved with Method 5, the unique condition of each pot may require different 3D modeling methods and software to successfully print various missing pieces.

The main drawback encountered in the study is the long modeling time. However, by shortening the modeling time with alternative software specified in the relevant sections, the 3D completion process can be reduced to reasonable durations that are competitive with conventional methods. On the other hand, the 3D printing time, which can be completed within minutes, is incomparable to the casting, setting/hardening, shaping and finishing times in conventional ceramic restoration practice. As a result, a conservator-restorer with knowledge and experience in 3D modeling and 3D printing can perform ceramic restoration work using non-industrial, low-cost desktop 3D printers and 3D scanners similar to those used in this study without experiencing the disadvantages of conventional methods within a reasonable time frame. Advances in software and hardware are expected to significantly reduce the time required for similar efforts in the near future, compared to the time spent by an experienced conservator-restorer applying conventional methods.

The surfaces of both PLA and ABS prints obtained from the FDM printer exhibit layer lines visible from a close distance. These lines can be smoothed out easily with sanding. When supports are used in the FDM printer, they can be easily removed from the printed pieces without leaving any marks on the surface. There was no deformation or color deviation from the filaments' color observed in the printed objects. Additionally, time was saved due to the lack of a need for curing and surface cleaning processes. In conclusion, satisfactory and similar results were achieved using both PLA and ABS filaments. On the other hand, the resin prints obtained from the SLA printer are quite smooth; however, when supports are used, removing them can be difficult and some prints may have traces on their surfaces after the supports are removed. When the area where the supports meet the print is small enough, no traces are left by the supports, but if excessively small areas are used, there is a possibility of the print falling into the resin tank due to the supports not being able to carry the print. When dealing with large pieces, compulsorily enlarging the area where the supports meet the print to ensure they can bear the load may result in visible traces left by the removed supports. Such imperfections can be concealed by positioning the supports inside the printed parts.

Working with an SLA printer has been relatively more challenging due to issues such as the difficulty of working with resin and the tearing or deformation of the FEP film. The absence of such problems gives an advantage to FDM printers. Additionally, parts printed with FDM printers do not require UV curing like those printed with SLA printers, which makes the workflow easier.

It can be said that all pieces manufactured by 3D printers using filament and resin are in the shapes and dimensions as modeled in 3DS Max. Therefore, with the hardware and software used in this study, it became clear that it is possible to reconstruct the pieces with dimensional accuracy sufficient for ceramic restoration. Unlike conventional methods, 3D printing stands out as a method that does not produce side effects that can cause damage since it does not require working directly on the artifact during restoration and the filler material used does not contain soluble compounds like gypsum plaster, which is commonly used in ceramic restoration. Furthermore, the ease of removing integrated parts from the restorations without causing damage makes this method reversible and therefore advantageous. When choosing a polymer for printing, considering its resistance to yellowing over time due to UV and visible light sources in exhibition lighting is beneficial for implementing a long-lasting restoration. Additionally, any potential yellowing can be prevented or hidden through various painting processes.

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