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Manufacturing of ceramic venus figurine replica from a mold by combining traditional and digital technologies

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Abstract

In this paper, we propose a method for creating a ceramic Venus figurine replica from a mold in the Museum of Ceramic Techniques collection in Koło, Poland stored at the museum for many years. Moreover, none of the Venus figurines in this collection have been preserved to the present day. Our process starts with partially degraded mold fragments and ends with an actual copy of the Venus figurine in three forms: faience kilned to bisque, porcelain, and glazed faience. The entire process involves understanding old manufacturing technology, conservation supervision, and state-of-the-art 3D scanning, data processing, and 3D printing technologies. We began with a preservation state evaluation that included a technical analysis of the degradation state of the mold. Then, we applied 3D scanning technology using the structured light method. Later, we integrated all mold fragments into front and back 3D models. These 3D models were optimized for 3D printing technology and were used to manufacture the mold. Finally, the printed fragments were corrected using traditional techniques performed by art conservators. This process took comparatively less time and produced a more realistic result than would have been observed if only 3D software had been used. This process also enabled us to create educational materials for the Koło museum about old manufacturing technologies. From the point of view of museum visitors, the copies are made with sufficient detail that they are indistinguishable from handmade artifacts. Our estimates show that combining both techniques (traditional and digital) saved approximately 25% of the time that would have been used if the individual techniques had been used separately. We also believe that our use case could be transferred to a broader group of objects that use molding in their production processes.

Keywords Reconstruction, 3D scanning, Reverse engineering, 3D printing, Conservation, Plaster mold

Introduction

Many objects in the world provide representations of old manufacturing processes, and thus conditions of these artifacts are deteriorating yearly [1]. This is especially true of abandoned and neglected objects, particularly plaster molds. Due to a lack of access to suitable methods that do not threaten the original matter, museums often decide to wait for an appropriate solution to appear before taking action. The preservation state of a mold determines the techniques that can be used for reconstruction [2]. In the case of advanced damage states, using traditional conservation methods, such as filling in minor surface defects, seems complicated and questionable based on the expected results. Interference in the form of restoration could disrupt the modeling details preserved on the surface of the mold [2]. Any attempt to make a replica using traditional methods, such as silicone casts, could expose the original to further damage. On the other

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hand, making a replica is necessary to show museum visitors the actual outcome of the mold casting rather than just the mold. And the use of digital technologies in this regard will accelerate the virtual reconstruction and visualization of complex shape while also maintaining documentation [3, 3], which is essential.

Advanced developments in imaging techniques provide many solutions to conservation issues, along with new opportunities and more efficient and adequate support to end-users [5]. There are several non-contact, active, and passive optical methods for collecting 3D surface data [6], among which the most popular are laser scanning (LS) [7], structured light (SL) scanning [8], and structure from motion (SfM) [9]. Laser scanning is an active technique based on projecting a laser point/line or set of strings and further analysis of captured images representing a deformed line from another perspective. Its main limitation is the error caused by speckle noise from the laser source [10]. Structured light is an active technique providing the ability to establish geometrical relations between all pixels of the camera and the projected 2D pattern coordinates. Its main limitation is low light efficiency in the presence of sunlight or other efficient light sources [8]. Structure from motion is a passive photogrammetric technique that requires photos of a reconstructed object from many directions. Its main drawback is the varying quality of reconstruction depending on the presence of salient points on the reconstructed surface. In areas of their absence, the quality of reconstruction is very low [9].

The research provided in this paper was inspired by an attempt to recreate a ceramic Venus figurine from the Museum of Ceramic Techniques collection in Koło, Poland. A destroyed plaster mold in the museum's collection was used in the past for slip-casting small figurines depicting Venus. The original plaster mold was in such poor condition that further usage was impossible. The data acquisition technologies mentioned above can provide a virtual model of the surface of a destroyed mold without interfering with the original structure of the plaster. It should be emphasized, however, that precise imaging of the surface of the original mold also registers all traces of its destruction, including defects and surface pitting, which in effect presents the state of preservation and does not provide a true basis for the reconstruction of the figurine itself. It is feasible to create a replica from a mold casting using both traditional and digital methods depending on the preservation state of the mold. In the case of heavily degraded mold, digital methods are preferred. However, any additional corrections to the digital generated model of the mold would require from the operator an appropriate sculptural background. The artistic skill of the operator would have a substantial impact on the quality of the replica. In such case, a sculpture carrying out corrections would be more reliable. However, it should be emphasized that applying corrections to the model (positive) is much easier for the sculptor than shape remodeling on the mold's surface, which is the negative of the representation.

This work aims to provide the best method for producing Venus copies. The work is unique in combining traditional conservation techniques with 3D scanning and printing technology to achieve satisfactory reconstruction quality while minimizing the effort required throughout the process. The proposed pipeline for the work includes three stages: 3D scanning, mold reconstruction, and creation of the Venus figurine replica. To achieve this goal, we used 3D scanning technology to noninvasively digitize the mold into a virtual representation with an approximate accuracy of 0,5 mm. To achieve a more realistic result, conservators corrected the prepared 3D printing of the object at the stage of filling and retouching defects. In our opinion, making a copy based on recorded scans provides an appropriate level of accuracy while maintaining artistic care to detail, which is ultimately judged by the viewer's eye. Additionally, one of the important goals was to reduce the processing time required to recreate the figurine.

Literature review

Due to their function, plaster molds are usually not treated as works of art and are rarely found in museum collections. Often treated as redundant objects made of material vulnerable to destruction, plaster molds slowly degrade in storage. Although their expositional value is often underestimated, they carry considerable educational value that contributes to understanding the complicated arcana of the casting methods. Above all, plaster molds have documentary value and are often the only material evidence of objects that have not been preserved or have been destroyed over the years. A negative preserved in a mold makes it possible to determine what kind of object the mold was originally used for. However, due to the complexity of the inner surfaces, the shape presented inside the mold is often difficult or even impossible to identify.

In the past, the identification of objects cast in plaster molds was limited to the use of traditional recasting techniques to obtain a positive result. This method was used in the 1960–1968 period during the Campana Campaign in the Richard Ginori Manufactory collection. The project used historical plaster molds to cast over 2000 porcelain artifacts [11]. The recasting method, however, leads to the wear of plaster molds; thus, in the case of historical objects, traditional methods are often rejected out of concern for the welfare of the historical matter.

Moreover, the advanced degradation state of plaster molds often makes it impossible to reproduce the image preserved in the negative state using traditional materials and methods. These concerns underlie conservator and restorer's choice of modern techniques [12].

The adaptation of 3D technologies for CH objects has revealed a growing interest in preservation, valuation, documentation, and heritage transmission [3–13]. High-resolution 3D scanning has been used on CH objects for several purposes, such as for digital documentation [14, 15] and monitoring change [16, 17]. Several industries are dedicated to manufacturing objects using a reverse engineering approach [18] to preserve, replicate, and document museum objects. However, there are also dedicated research that have also been studied in this regard [13–19, 13]. Hernández-Muñozet al. [19], showed the use of 3D technologies in the replication of wax artifacts [20] from an original mold which was used for medical treatment purposes. Abrace et al. [13], also showed the use of innovative 3D technologies to assist the restoration of the damaged parts of terracotta statue. Neumüller et al. [21], replicated museum collections using 3D technologies; however, their study was only based on replication focused on preservation and accessibility for research and education. Balletti et al. [22], studied the museum experience and created replicas of CH objects, but their study did not show the reconstruction of missing parts using 3D printing.

Higueras et al. [23], digitally restored the missing part of a Hispano-Roman architectural ornament using a non-invasive method. In their work, 3D modeling was performed using photogrammetry, and material restoration of the losses was performed by using 3D printing to create a piece for reintegration. However, this work required the appropriate choice of printing materials, as the object itself required restoration.

An alternative to the 3D printing process could be using CNC machines that cut a pattern from a gypsum block according to a scan. However, it should be noted that the use of CNC machines is much more expensive than 3D printers. At the same time, as previous studies indicate that the final work requires additional manual processing [23].

3D scanning is also applied to preserve and document plaster molds for slip casting. In Balleri et al. [24], 3D scans were used to document the collection of piece molds and link them to models. The project's authors assumed further use of the acquired data to make physical copies of the molds using 3D printers and to make new molds from digital 3D models, as well as for conserving the artistic heritage of gypsum molds. It should be noted that this method offers great possibilities; however, when gypsum molds show traces of damage, the image of the scanned object is marked by losses, and deformations resulting from surface degradation are reobtained.

One of the most interesting projects using 3D technology in the reconstruction of plaster molds was carried out at the Smithsonian Institution [25]. In this project, the 3D technique was applied for documentation of an incomplete nineteenth-century plaster piece mold of a figurine Venus, virtual replacement of missing mold pieces, and virtual recreation of the lost cast. During the stage of modeling the mold cavities, it was decided to correct them in a graphics program based on the scale changes of other parts preserved in the mold itself. As the authors noted in the article, at this stage, the method produced a convincing image of a hand, but it was not perfect: the geometry was proportional, but the model was too smooth. Moreover, an image of the negative contained imperfections that were part of the original creative process and signs of wear. In a further step, the imperfections were smoothed using graphics programs. The article's authors do not provide the time necessary to make all the corrections in the parts of defects and deformations registered on the surface of the mold. This raises the obvious question of whether the remodeling process would ultimately take less time if the corrections were performed on a physical preprinted imperfect model.

Reconstruction, which involves recreating an artwork from preserved matter or sources, necessitates special care on the part of the art conservator. The decision-making process for restoration activities is extremely complex, relying primarily on aesthetic and ethical arguments and, to a lesser extent, technological ones.

Materials and method

Case study and background

Clay is the most common raw material on the Earth's surface [26] and has been used by humans since the dawn of civilization to make practical and artistic products. Due to its plasticity, clay is susceptible to molding, and a given shape is fixed through firing. There are several methods for forming the desired shape. One of these methods involves shaping clay in appropriate molds. This method was already known in antiquity, as its origins date back to 700 BC [27]. However, a considerable breakthrough in the development of clay molding occurred in Europe in the middle of the eighteenth century [28], when casting from a slip in gypsum molds was introduced. This method allows one to multiply complicated shapes in a simple way. Clay casting is currently the most common technique used in the pottery industry mass production and is also applied in the production of unique artistic products [29].

In the second half of the twentieth century, this common method was most likely used to make a series of small Venus's figurines in one of the ceramic workshops in Koło (Poland). Making a figure of such a complicated shape required the use of a multielement plaster mold. The mold, preserved to this day, consists of four elements connected to each other by a system of locking keys—male and female. The dimensions of the mold are 33.1 × 16.4 × 11.8 cm. The front part of the mold consists of three separate sections, as shown in Fig. 1a (1, 2, 3), while the back part of the mold consists of a single element, as shown in Fig. 1b. In the lower part, there is an inlet through which the slip was applied after the mold was assembled.

The method of manufacturing ceramic products with the use of slip and gypsum molds has many advantages. It entails low production costs and ensures a high level of repeatability of the shapes and dimensions of the final product, which is extremely important, especially in mass production. The possibility of dividing gypsum molds into sections makes it possible to produce complex shapes without the use of additional joints. However, the main disadvantage of this method is its low production efficiency. Gypsum molds deteriorate quickly and must therefore be replaced. The gypsum degradation process is irreversible, and changes in the material occur after several casting cycles [30]. The method of exploitation is no less important and is influenced by the procedures used during the pouring and drying of molds [31, 32]. In the process of destruction, the number of casting cycles and the mass composition play an important role [33]. Gypsum is a material that dissolves under the influence of water; hence, every time water is absorbed during the casting process, it is softened, and the surface layer is partially damaged. Thus, the preservation state of gypsum molds is greatly affected by the repeated dissolution and drying of the material [29]. As a result, changes in the gypsum microstructure occur, which affects its properties. Moreover, gypsum is a relatively delicate material that is easily destroyed by mechanical impact.

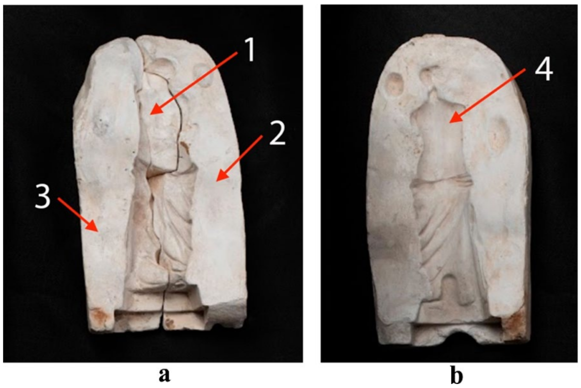


Fig. 1 **a**. The original multielement plaster mold front **b**. The original plaster mold back

On the inner surface of the gypsum mold from Koło, Poland, numerous traces of degradation were observed, and an evaluation of the preservation state of the plaster mold was performed under a 3D microscope. This damage (Fig. 2a and b) indicates that an advanced plaster degradation process has made future mold use impossible. Additionally, on the edges of elements of the mold, spalling and chipping were observed, most likely caused by mechanical impact.

In the case of such a degraded plaster mold, the use of traditional conservation methods poses a threat to the artwork. To provide optimal methods for reconstructing the Venus figurine, it is necessary to apply innovative solutions while optimizing the entire process, which was the final goal of our project.

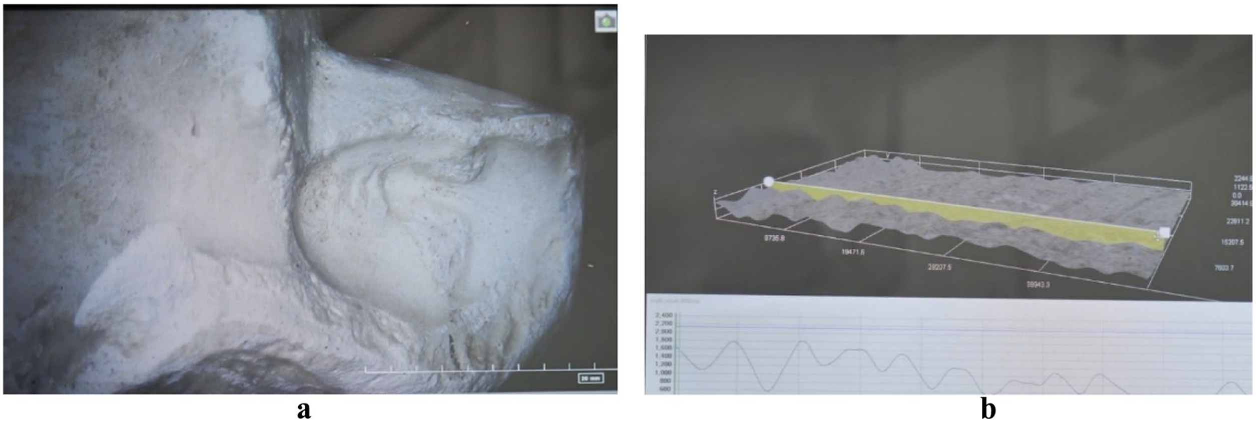


Fig. 2 **a**. Microphotography of the inner surface of the gypsum mold with hollows **b**. Profile of the inner surface of the gypsum mold

Replication of the Mold

Reverse engineering is a powerful way to create digital models from physical parts. This was shown to be a valuable tool in prototyping CH object preservation using the technologies of 3D scanning and 3D printing technologies. To combine 3D technology and traditional conservation, we created an interdisciplinary team and used existing techniques to reduce cost and processing time. In this section, we walk through the step-by-step reverse engineering tools we used from 3D scanning to generating the mesh and 3D printing. The pipeline for the replication of the mold is as presented in Fig. 3.

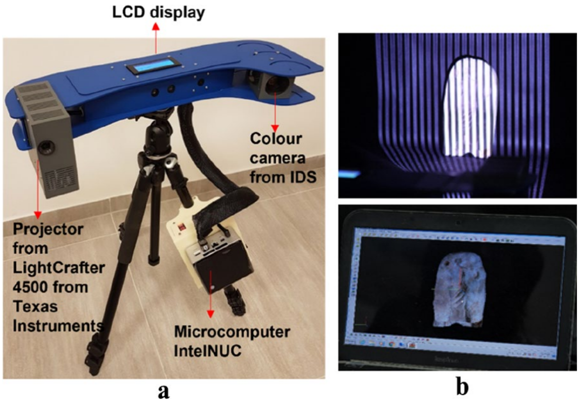


Fig. 4 **a**. Custom designed 3D scanner **b**. 3D scanning of the pieces of the mold and the respective scans

3D scanning

Among all the data acquisition methods proposed in Section. 1, structured light scanning has received the most attention for the pixel size on the object's surface for better quality digitization and documentation of small objects as the considered case study [8]. We performed the scanning step using a custom-made 3D scanner, Fig. 4a, developed at the Virtual Reality Technique Division (VRTD) of the Faculty of Mechatronics, Warsaw University of Technology, Poland, which uses structured light scanning. The decision was made to collaborate and use this existing device, which meets the accuracy expected from the conservators. The main units in the 3D scanner are the projector and detector. They are mounted on a special base made from carbon fiber composites. Custom-made software for calibration and measurement is saved on a microcomputer attached to the scanner. To assist the operator with the measurement volume, the scanner is attached to an ultrasonic sensor that can display the distance of the sensor from the object on the LCD display. The estimated maximum permissible error (EMPE) of the used scanner was 0,25 mm [34, 35] and its measurement volume is 350 mm × 220 mm × 160 mm. The output of the scanner is collected in the form of point cloud (.ply) for each scan containing 400 points per mm^2 from the scanned surface. Using the 3D scanner, the broken pieces of the mold were scanned at the Faculty of Conservation and Restoration of Works of Art, Academy of Fine Arts in Warsaw, Poland, as shown in Fig. 4b. It was challenging to collect the surface information from the unsmooth parts of the mold which required multiple measurements (on average 6 –10 scans from each fragment) from the surface producing approximately 1 GB of data in total.

3D reconstruction

After collection of the scans from each separate fragment of the mold, the scans were stitched together to create 3D models of the surfaces of the pieces. Manual alignment and the optimized iterative closest point (ICP) algorithm [36] were used to stitch the scans. The stitching was performed using FRAMES, which is written in C+ +and developed at the VRTD lab of the Faculty of Mechatronics, Warsaw University of Technology Poland. For the stitching of each scan, conditions were set as value to the ICP algorithm parameters (Fig. 5).

Each fragment (Fig. 1a, b) was modeled individually using the 3D scans, as shown in Fig. 6. Each 3D scan was presented in random colors for each mold fragment.

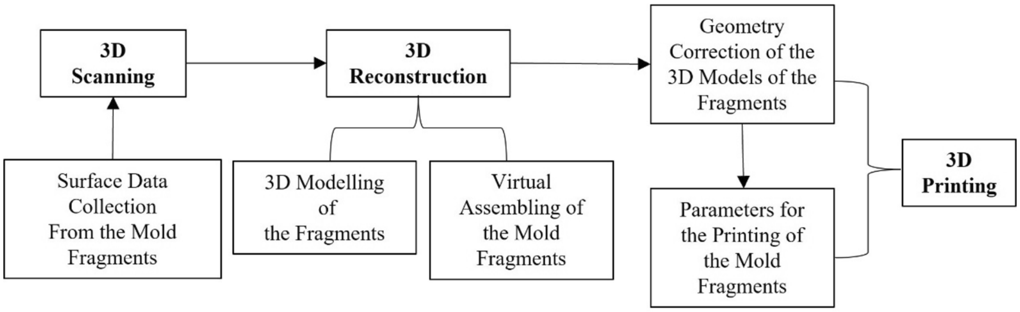
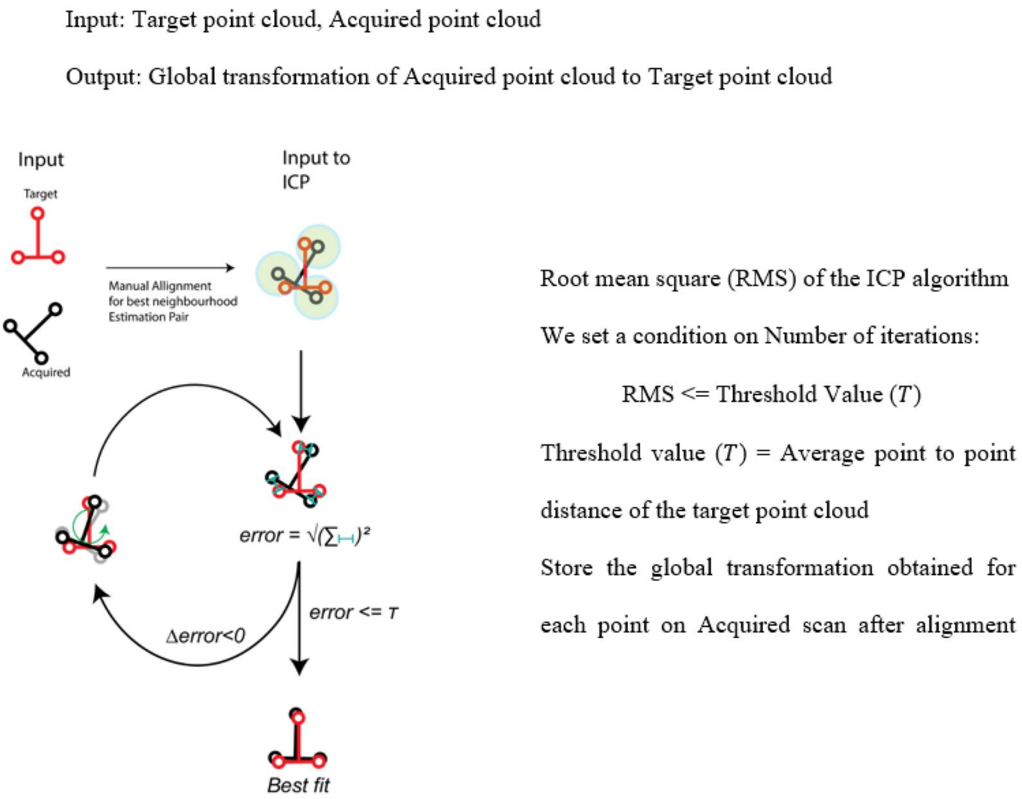


Fig. 3 Pipeline for the replication of the mold



Input: Target point cloud, Acquired point cloud

Output: Global transformation of Acquired point cloud to Target point cloud

Root mean square (RMS) of the ICP algorithm

We set a condition on Number of iterations:

RMS <= Threshold Value (T)

Threshold value (T) = Average point to point distance of the target point cloud

Store the global transformation obtained for each point on Acquired scan after alignment

Fig. 5 ICP algorithm for the modelling of the fragments as well as assembling of the fragments (Source: [16][16])

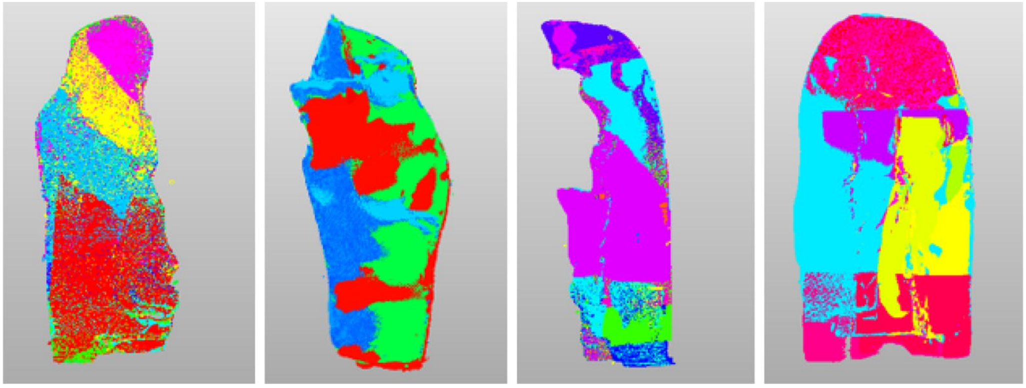


Fig. 6 Stitching of each scan collected from each fragment of the mold

After modeling each fragment separately, we assembled the pieces from Fig. 1a (1, 2, 3) together digitally using the ICP algorithm and obtained the results presented in Fig. 7a. The resulting 3D models of the front and back of the mold are shown in Fig. 7b.

3D printing

The 3D modeling result was saved in OBJ file (.obj) format and sent for 3D printing. The 3D printing was performed on the SLS FORMIGA P100 device made of PA 2200 material, which was available within the collaboration and was cost-effective. The layer resolution was 0.1 mm, and the method of filling the volume of the "Mechanical" model was uniform production over the entire surface of the layer (no division into contour and filling). The calculated model files were loaded onto the device software to verify geometric correctness and the possibility of arranging it in the working space.

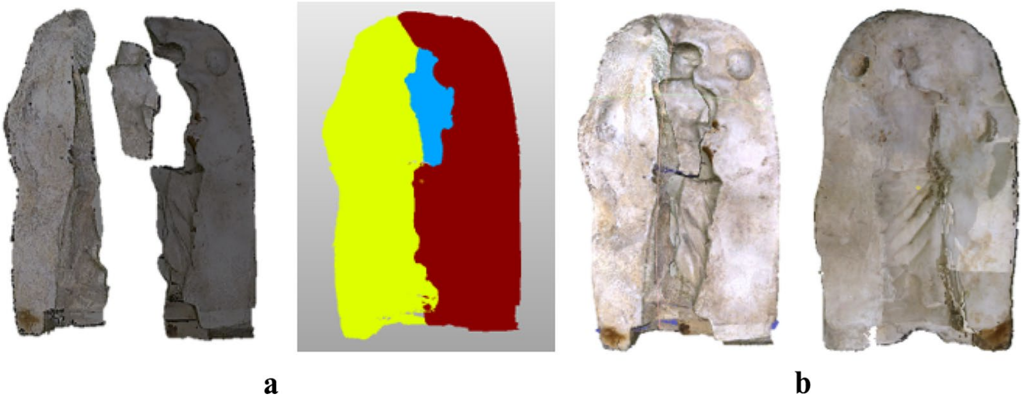


Fig. 7 **a**. Assembly of the fragments from the front part of the mold **b**. 3D models of the two fragments of the mold (front and back)

Table 1 The parameters for the printing of the mold and respective values

Printing parameters	Values
Occupied height of the model in the working space	190,776 mm
Model volume	174 170,365 mm^3
Model area	241 747,373 mm^2
Number of triangles	2.434, 040

After the digitally assembled pieces were obtained, geometric corrections were performed. Actions consisting of removing the contour surface and splitting the element were applied. Due to the impossibility (and lack of necessity) of distinguishing the particularly indicated division boundary, a rectilinear division was made based on best fit to the working space Additional file 1: (Fig. A.1).

Due to the free shapes of the models and the inability to distinguish or indicate the preferred direction of laying the layers, the arrangement was based on the best volumetric adjustment of the elements to each other allowable while maintaining the minimum distance of 0.9 mm Additional file 1: (Fig. A.1.1).

The next step was to divide the model into layers with a resolution of 0,1 mm. The errors result from the quality of the triangle mesh representing the model surface and from the method of mapping the layer when dividing individual areas of the model. The list of errors provides information but does not constitute a basis for abandoning further steps leading to the creation of the model Additional file 1: (Fig. A.1.1).

At each level of designing the manufacturing process, it is possible to view its parameters understood as the location and occupancy of the working space by the model (Table 1). In this section, we have listed the final numerical parameter of the stacked models, from which it is possible to read the following important information in terms of material consumption can be obtained and thus also the cost parameters of the process Additional file 1: (Fig. A.1.1).

The manufacturing process lasted 17 h, and the result is shown in Fig. 8a and b, where Fig. 8a shows the model divided into five front and two back parts. Although this can be printed in two pieces, we have chosen to use the 3D printer as indicated above and further process the printed portions manually due to the limited volume of the printer and the low cost. A rectilinear boundary was applied without considering the specific geometric connectors. Figure 8b shows an exemplary image of mapping the intricacies of the model geometry.

Processing of 3D prints to reconstruct the figurine

The data collected during the scanning would have been completely reasonable and sufficient for documentation of the original mold. Printing plastic polyamide elements based on scans was the first step in the intended multistage process. Each of the seven printed elements was an actual negative image of the surviving original plaster mold.

The plastic fragments had to be further processed to make the new plaster mold. Some of the prepared printed models had equal contact edges, while others were printed with excess material. The processing of the plastic prints would have been easier if the front and the back would be printed only in two fragments. Excess material at the edges was removed manually, and each piece of the 3D prints was joined together. A strong and not very flexible bond glue was chosen to make the joint sufficiently solid and durable. The edges of the joined elements were further strengthened by gluing cotton gauze soaked in gypsum crosswise to the line of fractures. After applying a thin layer of hydrophobic substance, the polyamide mold was suitable for making a cast of the model from plaster. The plaster model retained all traces of the

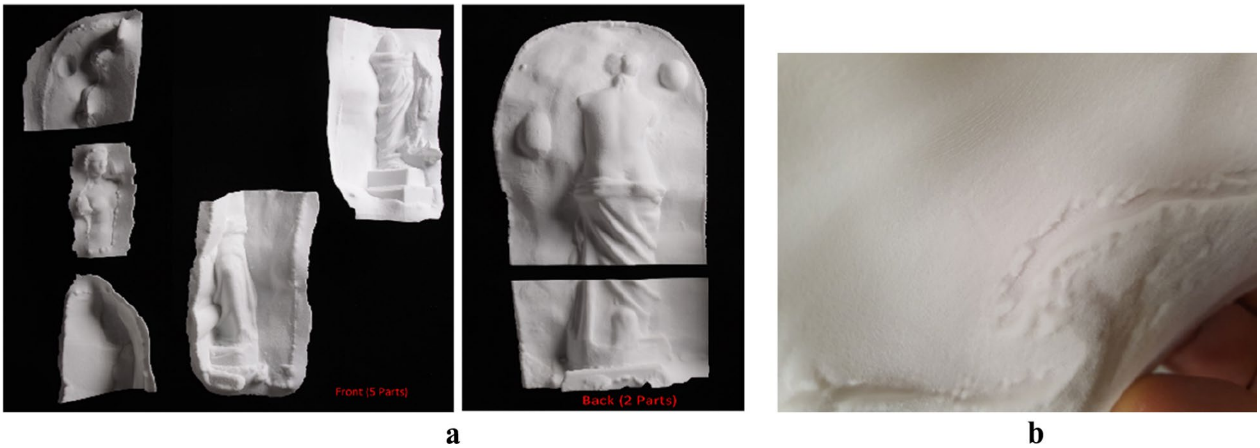


Fig. 8 **a**. Model element divided into 5 front parts and 2 back parts **b**. View of the method of mapping the complexities of the model geometry

use of the original plaster form, captured faithfully by means of scans of plastic models. These imperfections are an important historical testimony; however, an attempt to preserve them in the reconstructed figure would disturb the shape intended by the artist and, consequently, the reception of the work. With the museum's consent, the plaster prototype was appropriately corrected. First, small losses at the edges were filled in with plaster putty applied by tools to smooth the surface and eliminate deep pits, the evidence of the degradation of the original plaster form. These adjustments were necessary and indispensable to the further process of making the reconstruction from the cast. Since the extent of the repair work undertaken could have influenced the final reception of the work, the process of restoration was characterized by reliability and an approach free from subjective creation on the part of the conservator, which meant that the corrections in the plaster model were made to a minimum and necessary extent.

Fig. 9 New plaster mold (front and back)

The professional molding workshop made a new plaster mold from the plaster model. The new gypsum mold consists of four elements connected, as the original is, by a system of keys (Fig. 9). The final reconstruction of the Venus figurine was performed using the traditional ceramic technique of slip casting. However, it should be noted that ceramic objects are one of the few where full reconstruction could be justifiable. The validity of the reconstruction of historical objects made of clay and slip results from the original technique, which consisted of multiple multiplications of products from one mold. Thus, the idea of multiplication lies at the very basis of the method of making casts from slip.

Similar to the original, the inlet for the slip was designed at the lower part of the mold. The new mold repeated the shape of the historical figurine; however, due to the repair works at the stage of the plaster model, its internal surfaces were free of visible traces of damage characteristic of the original. The reconstructed plaster form was transported to the Ceramics Design Studio at the Faculty of Design, Academy of Fine Arts in Warsaw, Poland. In the studio, a trial figurine was made with the use of slip. The clay figurine taken out of the mold had a smooth and homogeneous surface but also a few seams in places where the joints of individual mold elements were located. The presence of seams in mold casts is a characteristic feature and is relatively easy to correct. Before firing, the excess material in the seams was removed by gentle polishing with felt Additional file 1: (Fig. A.2). The cast figurine was fired after it dried completely. The firing conditions were adapted to the individual requirements of the casting slip.

Results and discussion

The original mold, as well as a new plaster mold, was donated to the collection of the Museum of Ceramic Techniques in Koło, Poland after the project was completed. As previously agreed, only three versions of the Venus figurine were cast during the project. Two figures were cast from two types of clay used in slips: faience and porcelain, which were fired to bisque. Additionally, one figurine was made of faience mass, which was covered with powder glaze in an ivory color after firing and fired again (Fig. 10). In 2021, three copies were displayed in a temporary exhibition in the Museum's gallery. The exhibition was devoted to new technologies in ceramics conservation. Each version on display was appropriately labeled as a copy, along with an explanation of the methods of its creation. In the future, the museum plans to use the copies as educational aids, each time the fact that it is a copy will be emphasized by the staff.

The reconstructed figurines and the new plaster mold are intended to be educational aids, and they will be used as teaching materials by the museum's education department in the future. The 3D models and data collected (raw scans) during the scanning process will be given to the museum as an additional form of digital documentation of the conservation status of the object. The use of the 3D scanning method made it possible to use the historical mold without physically interfering with its surface. This case study indicates the possibility of applying this method to other artworks whose state of preservation does not allow any other form of attempt to show the original appearance.

Fig. 10 Venus's figurine, from left faience kilned to bisque, porcelain, glazed faience

The application of 3D scanning in reconstructing the original appearance of the Venus figure based on the preserved gypsum mold for slip casting yielded positive results. The results of 3D measurements and 3D prints based on these measurements allowed us to reliably reconstruct the appearance of the sculpture from the point in production where the original manufacturer decided to discontinue using the mold. The performed measurements, 3D prints, and final replication of the Venus figurine in the ceramic technique point to an interesting issue in correlating scanning accuracy with subsequent technological processes related to ceramic production.

It is also worth performing a comparative analysis of the entire reconstruction and manufacturing process with the individual digital and traditional techniques approaches. Table 2 identifies the required resources (working days) for each approach. In Table 2, we also highlight (in green) the stages of our project and the reasons for combining both techniques. It should be noted that the time estimation for each individual approaches are based on previous experience and consultation with conservators-restorers and software engineers. The hybrid option was chosen to have better outcome and save at least a little time than doing it at individual level.

This study shows that the combination of modern and traditional techniques significantly reduced the amount of time used at each stage of work. At the stage of reproducing the shape of the original gypsum form, the 3D scanning process proved to be much faster than using traditional techniques. On the other hand, correcting the 3D prints using traditional techniques took comparatively less time and produced a better, more realistic result than would have been observed if this process were carried out by software. Our estimates show that the combination of both techniques saves approximately 25% of the time. The involvement of 3D technologies also allowed a digital documentation of the state of the mold and would allow for another copy of the mold to be made if needed.

Conclusion and future perspective

The case studies conducted indicate the possibility of applying this method for historic plaster molds over a wider range of objects. In our experience, the process presented in the paper could be improved if 3D models were printed in only two parts (front and back). In our case, printing five parts for the front part of the mold and two parts for the back part considerably prolonged the whole process due to the required edge corrections and merging of the individual prints. The process

Table 2 Comparison of working days required for the manufacturing process of the mold using digital and traditional techniques individually (the green color indicates the stages selected in our approach)

Task	Technique	Method	Time	Reason for using the proposed approach
Replication of the **Mold**	Physical replication	Silicon, plaster	Depends on the state of preservation of the plaster mold (3-4 days).	The preservation state of the mold caused us to select the digital technique at this stage to avoid further damage of the mold.
	3D digitization	3D scanning and 3D modeling	1 day	
		3D printing	17 hours	
Corrections of missing surface parts and voids of the **Figurine**	Manual corrections	Silicon, plaster	1 day	Corrections at the software level depend on the input parameters with comparatively less control over final effect, making surface of the figurine too smooth. Therefore, in this stage, we decided to perform the corrections using traditional techniques to have more artistic control over the corrections to the surface.
	Digital corrections	Virtual correction of the 3D model of the mold fragments to obtain the shape of the figurine from the mold	2 days	
Manufacturing of the **Figurine**	Traditional replication	Silicon, plaster	2 days	3D printing of the figurine would not be as real as the handmade artifacts, which also depends on selection of the material for the printing. Therefore, we decided to adapt the traditional technique to have a more realistic outcome for the human's eye.
	Additive manufacturing from 3D model	3D printing	1 day	

presented in this paper could be improved if it was possible to print the positive from the 3D scan with all missing parts and deformations. However, such a solution would be even more effective if a different material were to be used for printing; for example, instead of a hard and insoluble polymer, 3D printing from clay may be used.

In a future note, it would be interesting to develop a reverse engineering method that compares the physical reconstructed mold to the initial digital model (after assembly). Furthermore, the morphological differences between two retro-engineering models: the reconstructed mold and the original mold used for this work, could be quantified.

Abbreviations

LS	Laser scanning
SfM	Structure from motion
SL	Structured light
EMPE	Estimated maximum permissible error
ICP	Iterative closest point

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-023-00870-2.

Additional file 1: Figure A.1.1 a. Arrangement of an element in the working space b. Limiting the model outline c. Division of the model d. Elements fitted into the working space. **Figure A.1.2** a. Arrangement of elements in the working space - view parallel to the layer plane b. Arrangement of elements in the workspace - isometric view c. The overall model prepared for division into layers. **Figure. A.1.3**a shows an example image of a single-layer surface with the model outlines extracted. **Figure. A.1.3**b shows the list of errors generated from splitting the model into layers. **Figure. A.1.3**c shows an example layer view prepared for transfer directly to the generating device. **Figure A.1.3** a. An example layer with the model outline extraction b. List of mesh errors resulting from the division of the model into layers c. View of an exemplary layer seen by the manufacturing system. **Figure A.1.4** Numerical parameters of the manufacturing process. **Figure A.2.1** Correcting and removing seams from the surface of a cast figurine using felt

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Author contributions
All authors designed the methodology. SS carried out the 3D scanning and modeling of the mold. AT carried out the manual correction of the printed mold. SS and AT wrote the initial draft of the article. All authors read and approved the final manuscript.

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Availability of data and materials
The 3D models of the mold fragments are available and can be obtained from the corresponding author with a reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. A AC03906066, Preserving and restoring monuments and historic buildings. Unesco. 1972
2. Weeks KD, Grimmer AE. The Secretary of the Interior's Standards for the Treatment of Historic Properties: With Guidelines for Preserving, Rehabilitating, Restoring & Reconstructing Historic Buildings, vol. 2. Washington, D.C.: Government Printing Office; 1995.
3. Gomes L, Silva L, Bellon O. 3D reconstruction methods for digital preservation of cultural heritage: a survey. Pattern Recognit Lett. 2014. https://doi.org/10.1016/j.patrec.2014.03.023.
4. L Willot, D Vodislav, L De Luca, and V Gouet-Brunet, Automatic structuring of photographic collections for spatio-temporal monitoring of restoration sites: problem statement and challenges," in isprs wg ii/8 9th international workshop 3D-ARCH 3D virtual reconstruction and visualization of complex architectures, 2022, vol. 46, pp. 521–528.
5. Shehade M, Stylianou-Lambert T. Virtual reality in museums: exploring the experiences of museum professionals. Appl Sci. 2020;10(11):4031.
6. Wang Q, Tan Y, Mei Z. Computational methods of acquisition and processing of 3D point cloud data for construction applications. Arch Comput Methods Eng. 2020;27(2):479–99. https://doi.org/10.1007/s11831-019-09320-4.
7. Alshawabkeh Y, El-Khalili M, Almasri E, Bala'awi F, Al-Massarweh A. Heritage documentation using laser scanner and photogrammetry. The case study of Qasr Al-Abidit, Jordan". Digit Appl Archaeol Cult Herit. 2020;16:e00133.
8. Montusiewicz J, Miłosz M, Kęsik J, Żyła K. Structured-light 3D scanning of exhibited historical clothing—a first-ever methodical trial and its results. Herit Sci. 2021;9(1):1–20.
9. Al Khalil O. Structure from motion (SfM) photogrammetry as alternative to laser scanning for 3D modelling of historical monuments. Open Sci J. 2020. https://doi.org/10.2395/osj.v5i2.2327.
10. Swojak N, Wieczorowski M, Jakubowicz M. Assessment of selected metrological properties of laser triangulation sensors. Measurement. 2021;176:109190.
11. R Balleri, Sculpture at the Doccia Manufactory from the Eighteenth to Nineteenth Centuries: copying, revisiting, inventing and interpreting sculpt. doccia manuf. from Eighteenth to Ninet. Centuries, 1000–1024, 2010.
12. Scopigno R, Cignoni P, Pietroni N, Callieri M, Dellepiane M. Digital fabrication techniques for cultural heritage: a survey. Comput Graph Forum. 2017;36(1):6–21. https://doi.org/10.1111/cgf.12781.
13. Arbace L, et al. Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue. J Cult Herit. 2013;14(4):332–45.
14. McPherron SP, Gernat T, Hublin J-J. Structured light scanning for high-resolution documentation of in situ archaeological finds. J Archaeol Sci. 2009;36(1):19–24.
15. Yastikli N. Documentation of cultural heritage using digital photogrammetry and laser scanning. J Cult Herit. 2007;8(4):423–7.
16. Abate D. Built-heritage multi-temporal monitoring through photogrammetry and 2D/3D change detection algorithms. Stud Conserv. 2019;64(7):423–34.
17. Saha S, Martusewicz J, Streeton NLW, Sitnik R. Segmentation of change in surface geometry analysis for cultural heritage applications. Sensors. 2021;21(14):4899.
18. Balletti C, Ballarin M, Guerra F. 3D printing: state of the art and future perspectives. J Cult Herit. 2017;26:172–82. https://doi.org/10.1016/j.culher.2017.02.010.
19. Hernández-Muñoz Ó, Aranda Gabrielli D, Maruri Palacín A, Sterp Moga E, Sánchez-Ortiz A. 3D digital technologies for the elaboration of a replica of a dermatological didactic model belonging to the olavide museum from the original mould. Heritage. 2022;5(2):702–15.
20. Sterp Moga, E., Hernández-Muñoz, Ó., del Río Esteban, J. et al. 3D digital technologies applied to the design and printing of auxiliary structures for fragment adhesion strategies on wax artifacts. Herit Sci 10, 103 (2022).
21. Neumüller M, Reichinger A, Rist F, Kern C. 3D printing for cultural heritage: preservation, accessibility, research and education", in 3D Research Challenges in Cultural Heritage. Berlin: Springer; 2014.
22. Balletti C, Ballarin M. An application of integrated 3D technologies for replicas in cultural heritage. ISPRS Int J Geo-Information. 2019;8(6):285.
23. Higueras M, Calero AI, Collado-Montero FJ. Digital 3D modeling using photogrammetry and 3D printing applied to the restoration of a Hispano-Roman architectural ornament. Digit Appl Archaeol Cult Herit. 2021;20: e00179.
24. Balleri R, Di Tondo S, Adembri G, Gherardelli M. 3D Laser scanning of historic molds for documenting the Richard-Ginori factory collection. J Am Inst Conserv. 2014;53(3):145–58.
25. Wachowiak MJ, Karas BV, Baltrusch RE. Reconstruction of a nineteenth century plaster piece mold and recreation of a casting Comput Appl to Archaeol. Virginia: Williamsburg; 2009.
26. Brongniart A. Traité des arts céramiques ou Des poteries, fac-similé de l'édition de 1877. Paris: Dessain et Tolra; 1977.
27. Barr-Sharrar B. Earth and water: early traditions and uses of ancient greek clay harvard univ. Art Museums Bull. 1993;1(3):29–38.
28. Haggar RG. The concise encyclopedia of continental pottery and porcelain. New York: Hawthorn Books; 1960.
29. Martin A. The essential guide to mold making & slip casting. New York: Sterling Publishing Company; 2006.
30. Kanouni A, Saber D, Samdi A, Daoudi A, Moussa R, Gomina M. A study of plaster moulds degradation. Key Eng Mater. 2004;264:1589–92.
31. Turan S, Oezel E. Effect of different starting hemihydrate powders on the performance of gypsum moulds. Key Eng Mater. 2002. https://doi.org/10.4028/www.scientific.net/KEM.206-213.1823.
32. Ochoa RE, Gutiérrez CA, Rendón JC, Rodríguez JL. "Effect of preparation variables of plaster molds for slip casting of sanitary ware", *Boletín la Soc*. Española Cerámica y Vidr. 2017;56(6):263–72.
33. Behal L, Schelker D. "Effects of polyacrylate and sodium silicate dispersant on plaster mold characteristics", in a collection of papers presented at the 97th annual meeting and the. Fall Mee Materials & Equipment/Whitewares Ceramic Eng Sci Proc. 1995;1996:23–9.
34. Marcin A, Maciej S, Robert S, Adam W. Hierarchical, three-dimensional measurement system for crime scene scanning. J Forensic Sci. 2017;62(4):889–99.
35. Saha S, Foryś P, Martusewicz J, Sitnik R. Approach to analysis the surface geometry change in cultural heritage objects. Lect Notes Comput Sci. 2020. https://doi.org/10.1007/978-3-030-51935-3_1.
36. J Procházková and D Martišek. Notes on iterative closest point algorithm in Proc. in 17th Conference on applied mathematics, 2018. 876–884.

37. Saha S, Martusewicz J, Streeton NLW, Sitnik R. Segmentation of change in surface geometry analysis for cultural heritage applications. Sensors. 2021. https://doi.org/10.3390/s21144899.

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