Non-contact restoration of missing parts of stone Buddha statue based on three-dimensional virtual modeling and assembly simulation

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Abstract

Three-dimensional (3D) digital technology is one of the most essential conservation methods that complements the traditional technique of the restoration of cultural artifacts. In this study, 3D scanning, virtual restoration modeling, and 3D printing were used as a non-contact approach for the restoration of a damaged stone seated Bodhisattva (stone Buddha statue). First, a three-dimensional model with an average point density of 0.2 mm was created by integrating the fixed high-precision scanning of the exterior and the handheld mid-precision scanning of the interior excavated hole. Through a 3D deterioration map of the stone Buddha statue, the area of the missing parts was measured as 400.1 cm 2 (5.5% of the total area). Moreover, 257.1 cm 2 (64.2% of the missing part area) of four parts such as the head, the surrounding area of the Baekho, the right ear, and the right eye, for which symmetry was applicable for modeling or there could be ascertainable historical evidence for the total missing parts, was selected for restoration. The virtual restoration of the missing parts of the stone Buddha statue was performed using a haptic modeling system in the following order. First, the location of the three fragments detached from the head was determined. Next, the reference model was selected, and its symmetrization and modification with respect to the original were conducted. Also, estimation modeling and outer shape description were performed through historical research and consultation with experts. The created virtual-restoration model's (461 cm 3) heuristic-based assembly suitability was verified by design mock-up printing and digital–analog simulation. In particular, to address the assembly interference, the interface surface was modified and reprocessed several times. Accordingly, the final design mock-up's volume size was decreased by 5.2% (437 cm 3). Photopolymerization 3D printing technology was used for the actual restoration of the stone Buddha statue and the layer thickness of the material used was set as 0.10 mm considering the surface roughness. Finally, the surface of the printed output was colored to prevent yellowing and joined to the missing part of the stone Buddha statue. This study presents a great case to shift from the traditional manual-contact method to the contactless digital method for the restoration of artifacts and is expected to largely contribute to increasing the usability of digital technologies in the restoration of cultural artifacts.

Introduction

Cultural artifacts are often damaged by exposure to natural or artificial environmental factors, which might lower their historical value or significance [1–4]. Traditionally, functional repair and aesthetic restoration are undertaken to recover the original form of damaged cultural artifacts [5,6]; recently, various conservation methods using advanced technologies and new materials are being applied in the process of restoring damaged cultural artifacts [7–10]. In particular, when a cultural artifact loses its historical value and shape, the restoration effort focuses on recovering the whole or partial shape of a certain period by thorough historical research and consultation with experts [11–13].

The restoration of a cultural artifact is usually realized by a manual method that relies on conservators' intuition and their techniques [14,15]. Using this method, physical contact with the material is inevitable, and if the restored part looks inappropriate, it would have to be unavoidably removed. Here, the original artifact can suffer a secondary damage either from the frequent physical contact or from the excessive force applied during the removal of the parts.

Fortunately, with the advancement of digital technology, many solutions have emerged to complement traditional restoration methods. The most prominent technologies are three-dimensional (3D) scanning and printing. In particular, 3D scanning is widely used in areas of digital documentation, shape analysis, visualization, and digital restoration [16–23]. Also, 3D printing is being adopted in a wider area, including the establishment of restoration planning, supplementing the lost area, replication, and exhibition. Because of a wide variety of printing materials, it is used for the actual restoration of damaged artifacts [24–33].

In this study, the non-contact restoration of a damaged stone seated Bodhisattva (stone Buddha statue) was realized using 3D scanning, virtual restoration modeling, and 3D printing technologies. To achieve this goal, 3D high-precision scanning was used to record the original shape of the stone Buddha statue and the missing parts were virtually restored using a haptic modeling system. Also, the restoration of the stone Buddha statue was completed using the 3D printing outputs of the virtual restoration model. In particular, a systematic design mock-up and simulation approach was used to enhance the heuristic-based assembly suitability and the convergence of digital and analog technologies.

Status of the study object

The study object is a stone seated Bodhisattva excavated in Pyeongchang, Gangwon province in Republic of Korea (Fig. 1). In general, wood, clay, and metal are the common materials used to create a small Buddha statue; however, this Buddha statue is made of zeolite [34]. The statue was discovered in several fragments in 1974 and has been maintained in almost full form through a conservation treatment. However, four fragments that are estimated to be part of the crown and one fragment in an ear have been stored separately without joining [35].

A huge excavated hole exists inside the statue from the bottom to below the chest, which is believed to have stored relics. Traces of coloring and gilding are found on the exterior of the statue, however, its exact form is difficult to discern, as most of them were peeled off and deteriorated. Also, the crown, face, and left finger are missing, and several physical damages due to stone crack and exfoliation are observed. Owing to its current status, this statue has been maintained in a museum storage for decades and has not been used for exhibition. Therefore, aesthetic and functional restoration of the damaged parts is necessary to use the statue for exhibition or display.

Methods

The restoration of the missing parts was performed by a non-contact approach using digital technologies (Fig. 2). First, the digital model of the statue was created using a 3D fixed high-precision scanner and handheld mid-precision scanner. Among these, the fixed high-precision scanner (LMI TECHNOLOGIES, HDI Advance R3X) is based on triangulation using white structured light and two stereo cameras (2.8

MP). In this study, scanning was performed with a field of view (FOV) of 400 mm and an accuracy of 65 μm. Also, the handheld mid-precision scanner (Artec3D, Eva) using a white structured light and a camera (1.3MP) has a 0.1-mm accuracy and a maximum 0.5-mm point resolution. Software used for the operation of the scanners included FlexScan3D and Artec Studio 13, and the 3D model was edited with Geomagic Design X 2019. The high-resolution digital scanning results were used to identify the manufacturing techniques and analyze the shape of the statue.

A haptic device (3D SYSTEMS, Geomagic Touch X) and voxel-based software (3D SYSTEMS, Geomagic Freeform Plus) were used to virtually restore the missing parts. The device provides a haptic feedback when the user interacts with the virtual environment. In particular, voxel-based modeling using a virtual clay material provides design flexibility. Therefore, this system was applied to both 3D modeling and virtual assembly simulation, and the suitability of the 3D restoration model was evaluated.

Material extrusion and photopolymerization 3D printing technologies were used to output the virtual restoration model. A material extrusion 3D printer (Ultimaker 3 Extended) was used to verify the modeling result through the output of a design mock-up, and the mock-up was printed using PLA material at a resolution of 0.10–0.15 mm. Also, the 3D printer (3D SYSTEMS, Projet 6000 HD) used for the final restoration employed photopolymerization that provides a very high level of surface precision. The 3D model was printed using UV-hardened plastic material, with 0.10-mm layer thickness. The final printed output was applied to the restoration of the statue and its exhibition after strengthening and joining.

Results

3D scanning and digital documentation

Fixed and handheld scanning was performed to record the 3D shape of the statue and its missing parts (Fig. 3). First, the exterior of the statue (scanned 101 times) and the five fragments (scanned 34 times) were digitized using a fixed high-precision scanner based on stereo vision. However, the fixed high-precision scanner based on the binocular lens could not reach deep enough to record the shape of the excavated hole from the bottom to deep inside. Therefore, a handheld mid-precision scanner based on a single lens with depth scan capability was used to record the shape of the excavated hole.

Each image acquired by on-site scanning provides only misaligned raw shape information. Therefore, the post-processing of the raw scans was performed to complete a single model from the raw scan data. The processing was executed in the following order: filtering, aligning, registering, merging, filling holes, and RGB texture mapping. In particular, registering, which is the most important stage in scan processing, was processed with an average of 66% overlap ratio and within an error value of 45 μm.

Moreover, the high-precision scanning of the exterior of the statue and the mid-precision scanning of the excavated hole needed to be integrated into a single model because they created separate 3D models. Accordingly, a deviation analysis between the two scanning models to evaluate the registering error revealed that most deviations were within ±0.1 mm and the average RMS was 0.28 mm. This is similar to the accuracy of general precision scanners, so the convergence model was created based on an ICP algorithm.

The converged 3D model comprises 36,556,604 poly-faces with an average point distance resolution of 0.2 mm. According to Fig. 4, the 3D scanning result clearly reveals the complete shape of the statue and the polygon mesh and RGB texture mapping models show excellent quality. In particular, the final 3D scanning result had a high resolution with millions of polygons, which well revealed the surface texture, manufacturing technique, and the detailed shape of the damaged area.

Based on the 3D scanning, the stone Buddha statue was measured as 410-mm wide, 310-mm thick, and 580-mm high, and its calculated area and volume were 7,250 cm^2 and 20,040 cm^3, respectively. Also, the excavated hole was measured as 188-mm wide, 155-mm thick, and 195-mm high, and its area and volume were measured as 1,228 cm^2 and 2,401 cm^3, respectively. In particular, the cone-shaped excavated hole showed traces of chisels whose average sizes were 10.5 and 15.4 mm. Therefore, the excavated hole may have been carved using these two chisels.

Establishment of restoration scope

A 3D deterioration map was created to define the scope of the conservation treatment and the restoration. According to the map, cracks and missing parts were observed around the head, and the body was damaged mainly owing to cracks (Fig. 5). Out of the total area, the deterioration rates of missing parts were 4.8% (348.3 cm^2) in the eye and head and 0.7% (52.9 cm^2) in the body.

The general rule of the conservation treatment and restoration of cultural artifacts states minimum and passive intervention only under inevitable conditions. Therefore, in this study, among the damaged areas, minimum scope was selected for aesthetic restoration and exhibition. The cracks in the statue were left without conservation treatment, as they were not severe in depth and therefore determined not to cause any severe physical and structural problems.

However, the missing parts have a critical impact on the aesthetic value of the statue. Therefore, some parts that could be recreated using symmetry modeling or assured significant evidence through a historic research were restored. In particular, the whole stone fragments that were stored separately were used for the restoration. Accordingly, for the restoration, the big missing parts in the head, the surrounding area of the Baekho, the right ear, and the eye were selected, accounting for 64.2% (257.1 cm^2) of the total surface area of the missing parts (400.1 cm^2).

Virtual restoration modeling

The haptic modeling system used to create the virtual model of the missing parts enables intuitive modeling because it helps recognize conflicts and interference of data. Compared with the existing method that uses a mouse, this method is much better and excellent for creating a complex shape. In particular, a user can feel a force feedback similar to that experienced in actually carving a virtual object because the system uses a voxel engine to create a model. This system is mainly used in the medical field, design, car industry, exhibition technology, and restoration of cultural artifacts [33, 36–39].

In this study, the digital virtual restoration of the four selected parts was performed based on a haptic modeling system. In the process of modeling, Boolean operation was applied for combining several complex models into a new complete model. Boolean operation is an essential method for original-based modeling requirements such as the restoration of the cultural artifacts, and therefore, the operation was mainly applied to the symmetry modeling of the missing part.

During the examination of the virtual restoration modeling process of missing parts in the head (Fig. 6), first the original stone fragments were placed by referring to the shape and pattern of the stone Buddha statue. Then, a reference model for the missing part was selected and copied using symmetry modeling. However, since the original statue was created manually, it was not perfectly symmetrical. Therefore, Boolean operation was performed to modify the model, matching it exactly to the original shape. Because symmetry modeling could not be applied to the center of the crown part, a statue similar to the study object was selected as a reference and the estimated restoration was applied.

The restoration of the right ear has aesthetic well as functional purpose to support the original fragment. Accordingly, for the virtual restoration, the original fragment was placed in the right ear and a shape of the missing part was acquired through the symmetry of the well-preserved left ear. Next, the angle and height from the front view was adjusted to match those in the left and completed after partial revision (Fig. 7a, 7b). Finally, the aesthetic restoration of the surrounding area of Baekho and the right ear was performed by filling up the inner part and retouching the outer part. In particular, their restoration was completed after several modifications in consultation with art history experts because the overall impression of the stone Buddha statue can change owing to minor shape differences (Fig. 7c).

Design mock-up and assembly simulation

Design mock-up helps to intuitively understand the influence of interference caused by components and to reduce completion time by solving a making-related problem in advance. Also, preliminary verification through design mock-up minimizes unnecessary consumption of materials and time in the restoration process and maximizes work efficiency. In this study, to enhance the restoration completeness by the non-contact approach, digital–analog based assembly simulation was performed by creating a design mock-up. Material extrusion 3D printing, which can minimize time, shape error, and costs, was used to create the design mock-up.

To summarize the assembly simulation process, first an alternative model for the original statue was printed based on the 3D scanning model to minimize direct physical contact with the statue. Also, heuristic-based assembly suitability was examined several times by printing the virtual restoration model. When an error was detected during the verification, the virtual restoration model was modified and reprinted to enhance the assembly completeness. However, when no error or aesthetic issue was detected, a design mock-up was directly applied to the statue for further verification, and after using the photopolymerization 3D printing, the restoration process was completed (Fig. 8).

When the printed virtual restoration model was applied to the mock-up statue, the interference between the two surfaces was severe owing to the non-structured form (Fig. 9a). This indicates the high quality of the virtual restoration model, but it was insufficient for the restoration of the original artifact. Therefore, the area in the virtual model, where interference occurs, should be corrected so that the printed output fits the missing part of the statue. In addition to the revision of the virtual model, the assembly suitability to the 3D-printed mock-up statue was intuitively checked and verified by directly modifying the mock-up of the virtual restoration model (Fig. 9b). The 3D model, which was verified for digital–analog assembly suitability, was completed as the final design mock-up through the outer design modification (Fig. 9c).

In a quantitative analysis of the shape difference between the virtual restoration model and the final design mock-up of the head, the volume of the virtual restoration model was measured as 461 cm^3 and the volume of the design mock-up that was assembled on the original stone Buddha statue was measured as 437 cm^3 (Fig. 10a). The volume reduction by 24 cm^3 (5.2%) is the amount of interfering surface removal along the assembly interface. In the deviation analysis of the final design mock-up against the virtual restoration model, the size of the joining surface removed was as much as 5.41 mm, with the RMS and standard deviation being 0.67 and 0.59 mm, respectively (Fig. 10b). Approximately 66.6% of the virtual restoration model, whose tolerance range was within ±0.1 mm, was not modified. The interfering surface of the joining interface was removed for 33.4% of the virtual restoration model. This deviation-mapping result enabled the visualization of the modification range and the deviation amount of the initial virtual restoration model, providing quantitative information about the digital–analog simulation process.

Restoration of the missing parts and their use for exhibition

The Athens Charter (1931), Venice Charter (1964), and Nara Document on Authenticity (1992) were prepared to establish the principles for the restoration of cultural artifacts, and countries around the world have restored their cultural artifacts according to their own rules following international recommendation [40]. In general, damaged cultural artifacts can be restored only when their historical and cultural value can be retrieved through sufficient and direct historical research. Any restoration that might distort the value or cause a controversy should be limited. Therefore, restoration should be minimum and only when it is inevitable, using materials that are identifiable and maintain harmony when applied to the original. In this regard, it is a principle to use a traditional technique and the original material for the restoration. However, if the traditional technique is not applicable and the original materials cannot be supplied, modern technologies and materials that have been scientifically and experientially proven can be used.

The study object, i.e., the stone Buddha statue owned by Chuncheon museum, was made of zeolite; however, zeolite quarrying was illegal in the source area according to the local forestry law. Therefore, in this study, 3D printing technology was used for the restoration to serve an educational effect in exhibition and enhance aesthetic and functional completeness. The material extrusion 3D printing used to create the design mock-up played a critical role in analyzing the shape of the missing parts to design the assembly planning. However, this technology uses a material having relatively high surface roughness and weak physical properties to functionally support the original stone fragments owing to its light weight. To complement this, photopolymerization 3D printing technology was used to create the final restoration model.

The model was printed using opaque UV-hardened plastic whose color was similar to that of the original statue, with a layer thickness of 0.1 mm (Fig. 11a). After about 15 h of printing, the supporters were removed from the printed output and the surface that was in contact with the supporter was carefully smoothed with soft sandpaper with more than 3000 mesh. Finally, additional UV hardening was applied to enhance the surface strength of the output (Fig. 11b).

The finished 3D printing output had a smooth and glowing surface, which was disparate with that of the original statue (Fig. 11c). The initiator used in photopolymerization can cause yellowing from the surrounding light. Therefore, to modify the surface texture of the 3D-printed output and prevent yellowing, the surface was colored with acrylic painting and varnished to prevent the colored layer. In addition, the surface strength of the original statue, with which the 3D-printed output was interfaced, was enhanced by consolidation treatment, and the 3D-printed output was joined to the missing part of the statue using acrylic resin and cyanoacrylate instant adhesive (Fig. 12a).

In this study, various digital data and mock-up of the original statue were obtained using 3D scanning and printing technologies. This wide variety of contents shifted the exhibition, which used to consist of simple display of artifacts, into an educational exhibition that focuses on the restoration procedure. Combined with unique storytelling, the exhibition has provided a new experience to museum visitors (Fig. 12b). This is an important case, which shows that proven modern technologies and materials can be used for the restoration, education, and exhibition of cultural artifacts.

Discussion

The stone Buddha statue, owned by Chuncheon museum, was largely damaged and not in its original shape, as many stone fragments were stored separately. Therefore, the stone Buddha statue has been managed in a museum storage and not used in exhibitions. Fortunately, the value of the stone Buddha statue has been appreciated from the perspective of art history; accordingly, the necessity of the restoration of its missing parts based on historic research has been raised. Therefore, in this study, a non-contact restoration of the stone Buddha statue was performed by converging various digital technologies, including 3D scanning, virtual restoration modeling, assembly simulation, and printing restoration.

Furthermore, 64.2% of the total missing parts were selected as the restoration scope, which was deemed necessary for the aesthetic and functional restoration, and the separately kept stone fragments were all used for the restoration. A digital virtual restoration of the missing parts was performed using original-based symmetry modeling. As for the partial area in the head, where symmetry application was difficult, restoration was performed through historical research and verification. In particular, throughout the whole modeling process, a haptic device and voxel software was used, facilitating an intuitive restoration process.

The assembly simulation using the design mock-up was the most focused stage in the whole restoration process. In general, virtual assembly simulation is widely used in medical and industrial fields to evaluate the impact of surface interference in advance [41], and virtual assembly based on various algorithms is used in the field of cultural heritage [42–46]. However, virtual assembly has its limitations when applied to the stone Buddha statue, the study object, whose joining surface is non-structured and complicated.

Therefore, in this study, an alternative model for the original and the virtual restoration model were 3D printed to minimize the physical contact with the original stone statue. In particular, the 3D-printed alternative model was greatly useful for identifying the problems of the virtual restoration model by verifying the design mock-up in real time, overcoming the physical constraints that did not allow assembly with the original statue. Also, the virtual restoration model was 3D printed and used for heuristic-based assembly simulation, thereby intuitively completing the restoration of the missing parts.

This study serves as a great case to shift toward using the non-contact digital method in restoration and could prevent secondary damage by minimizing physical contact with the original statue. In particular, the heuristic-based assembly simulation helped modify and improve the restoration plan and enhanced the restoration reliability, as the assembly result was intuitively reviewed and assessed. In the future, the development of an algorithm that could be used to modify the modeling of the interference between surfaces will greatly reduce the frequency of design mock-up assembly and the whole process will be executed in a digital virtual environment.

Conclusions

1. In this study, original-based digital recording was performed using the 3D scanning of the physically damaged stone Buddha statue and the digital virtual restoration of the missing parts using a haptic modeling system. Also, the missing parts were restored using 3D printing technology after the design mock-up creation and assembly simulation.
2. The 3D model of the stone Buddha statue was created by converging the fixed high-precision scanning of the exterior and the handheld mid-precision scanning of the interior excavated hole. The 3D model showed a high resolution with an average point density of 0.2 mm. In particular, the 3D scanning result of the cone-shaped excavated hole revealed that two chisels, whose sizes were 10.5 and 15.4 mm on average, were used to carve it.
3. Through a 3D deterioration map of the stone Buddha statue, the area of the missing parts was measured as 400.1 cm^2 (5.5% of the total) compared to the total area (7,250 cm^2). The restoration was performed only for 64.2% (257.1 cm^2) of the total area of the missing parts, for which symmetry modeling was applicable or original forms could be estimated based on historical research. The

restoration objects included four parts: the head, the surrounding area of the Baekho, the right ear, and the right eye.

4. The virtual restoration of the missing parts of the stone Buddha statue was performed using a haptic modeling system: first, the location of the original fragments was determined; second, a reference model was selected and symmetry modeling was conducted; finally, the virtual restoration model was modified and improved, and estimation modeling through historical research and description of the outer shape was also applied.
5. The created virtual restoration model was verified for its heuristic-based assembly suitability by design mock-up printing and digital–analog simulation. Accordingly, the initial virtual restoration model reduced its volume by 5.2%. Also, the removed surface owing to the interference effect between the virtual restoration model and the final design mock-up was 33.4%, and their RMS was calculated as 0.67 mm.
6. Photopolymerization 3D printing technology was used for the actual restoration of the stone Buddha statue, and the material layer thickness was set as 0.10 mm considering the surface roughness. In addition, the surface of the printed output was colored to prevent yellowing, and the final restoration was completed by joining the missing part of the statue.
7. This study serves as a great case to shift from the traditional manual-contact method to the non-contact digital method in the restoration of artifacts, and heuristic-based assembly simulation helps in modifying and improving the restoration plan and enhances the restoration reliability. In the future, it is assumed that digital–analog-based restoration technology will be extensively used in the conservation of cultural artifacts.

Declarations

Author's contributions

All authors contributed to the planning and design of this article. YHJ and SH performed the data acquisition and data analysis. SYJ and YMK performed the conservation treatment. YHJ wrote the manuscript and all authors revised it critically. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Figures

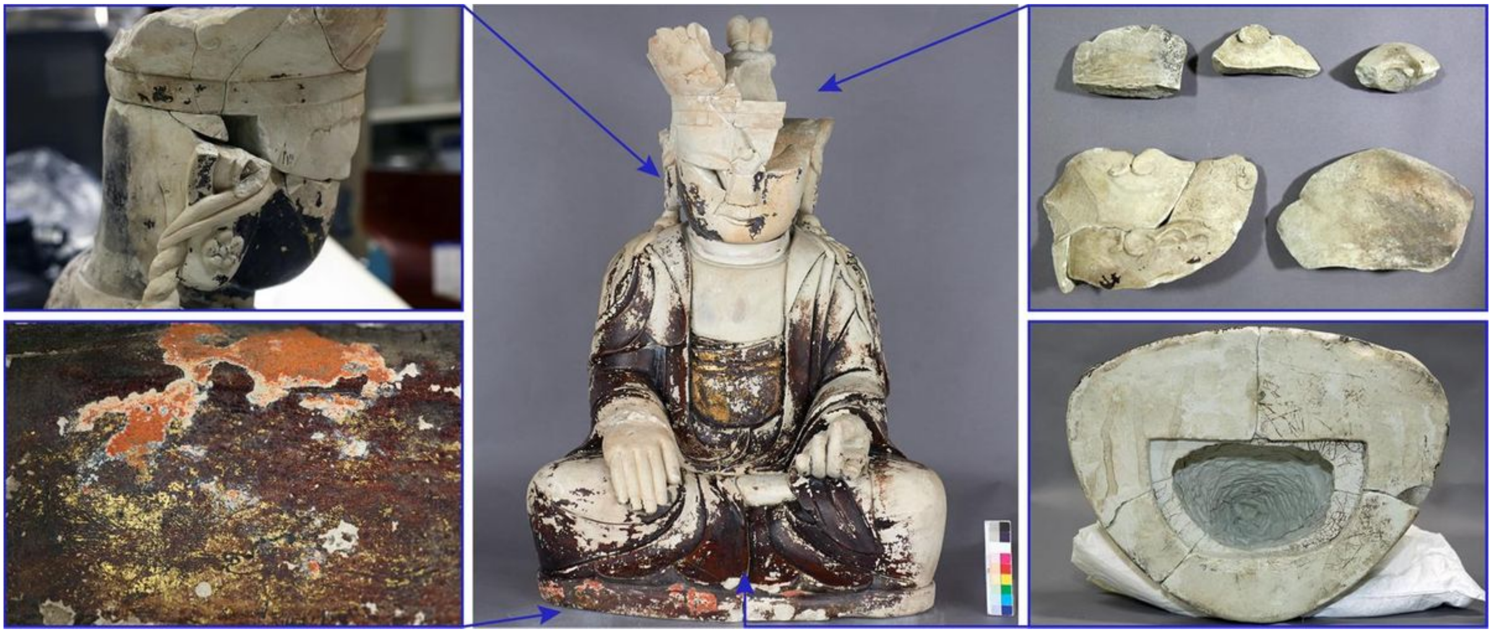

Figure 1

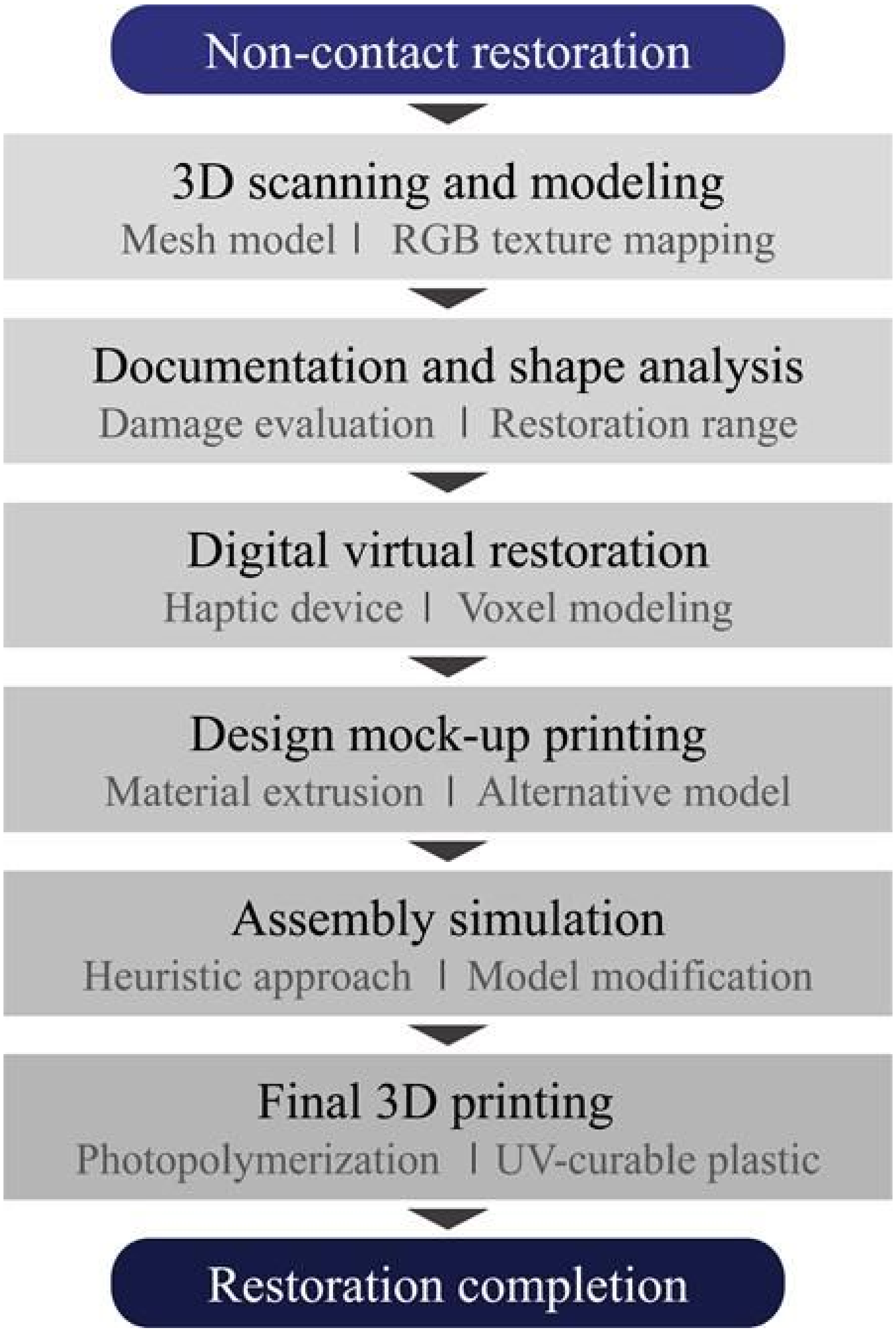
Non-contact restoration
3D scanning and modeling
Mesh model | RGB texture mapping
Documentation and shape analysis
Damage evaluation | Restoration range
Digital virtual restoration
Haptic device | Voxel modeling
Design mock-up printing
Material extrusion | Alternative model
Assembly simulation
Heuristic approach | Model modification
Final 3D printing
Photopolymerization | UV-curable plastic
Restoration completion

Figure 2

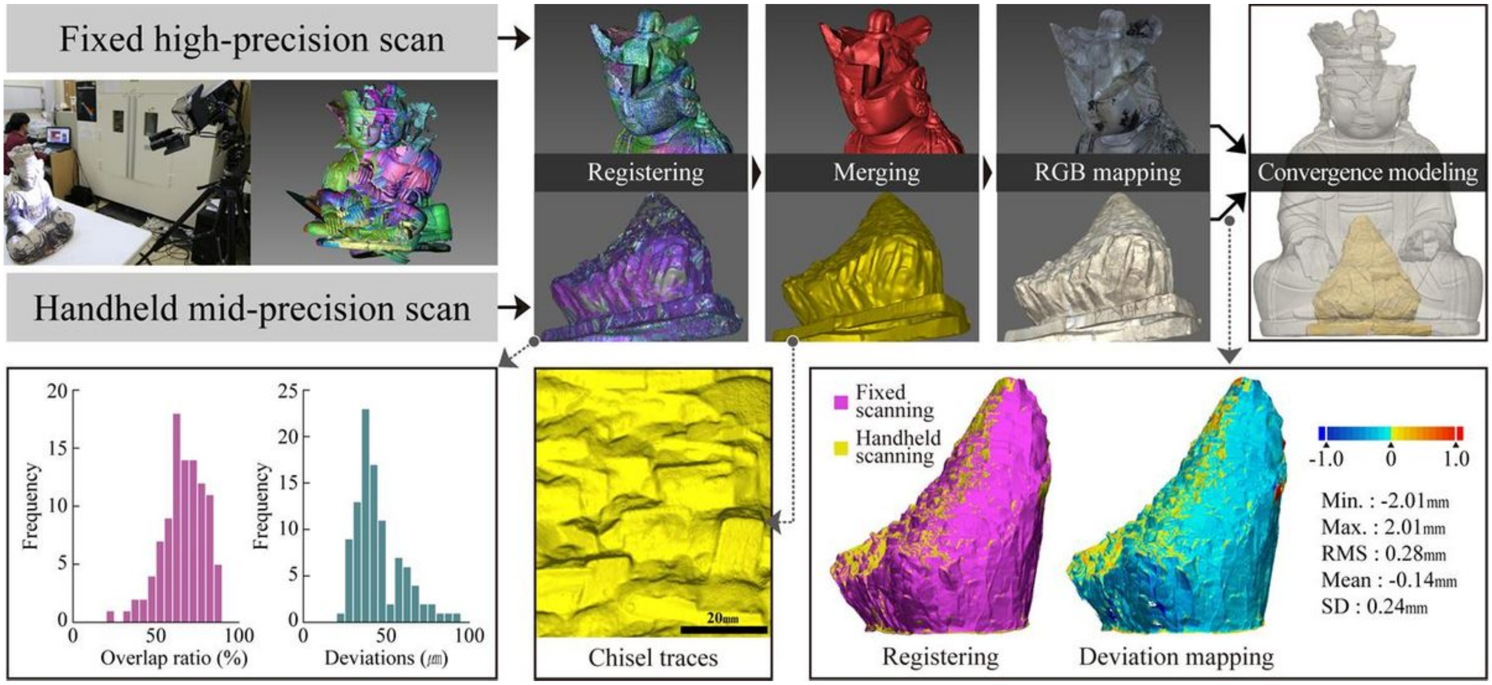

Figure 3

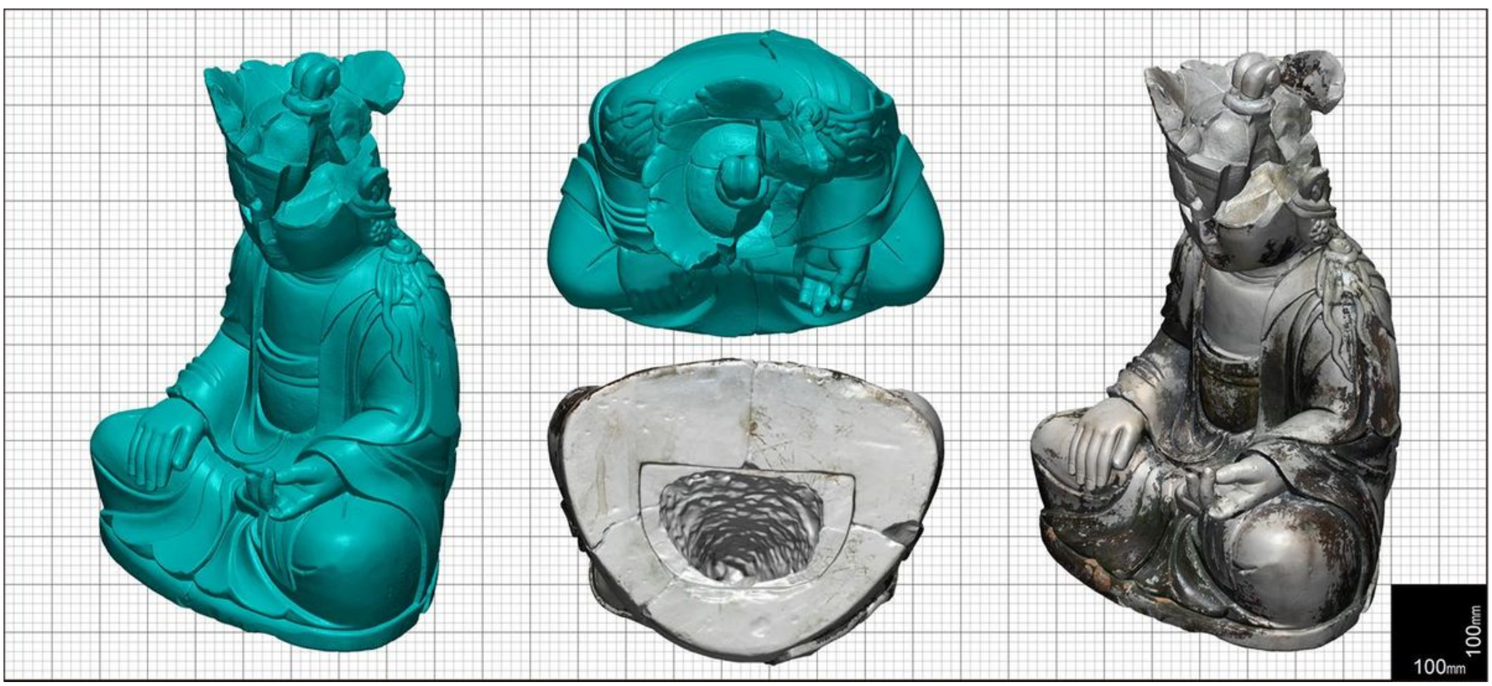

Figure 4

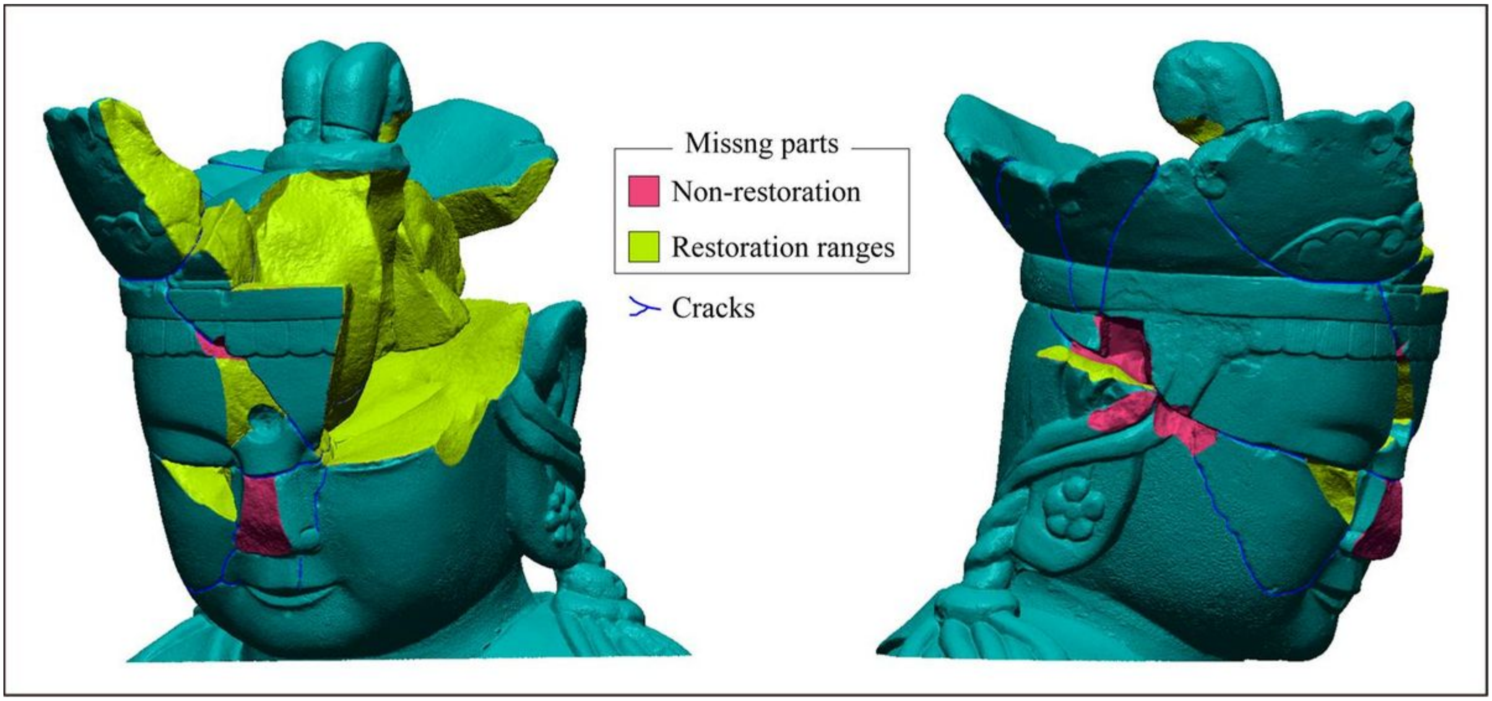

Figure 5

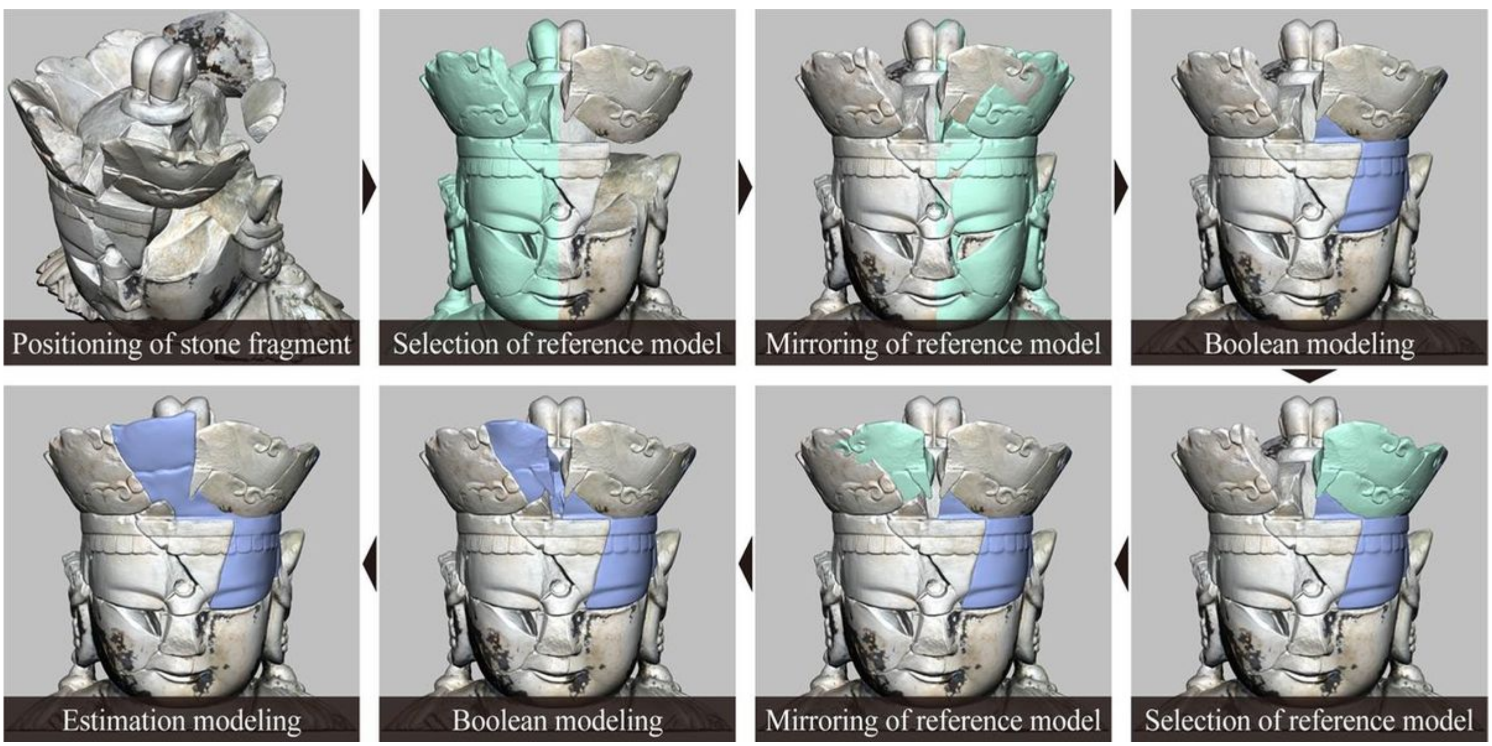

Figure 6

Figure 7

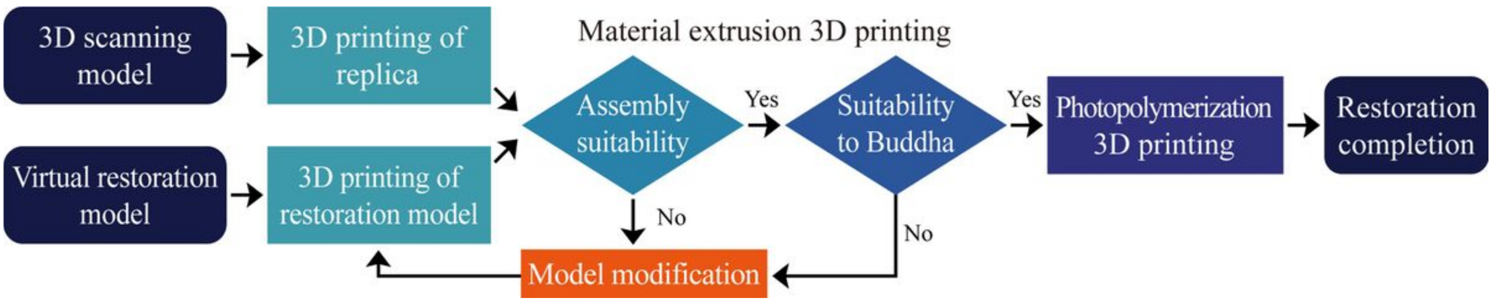

Figure 8

Figure 9

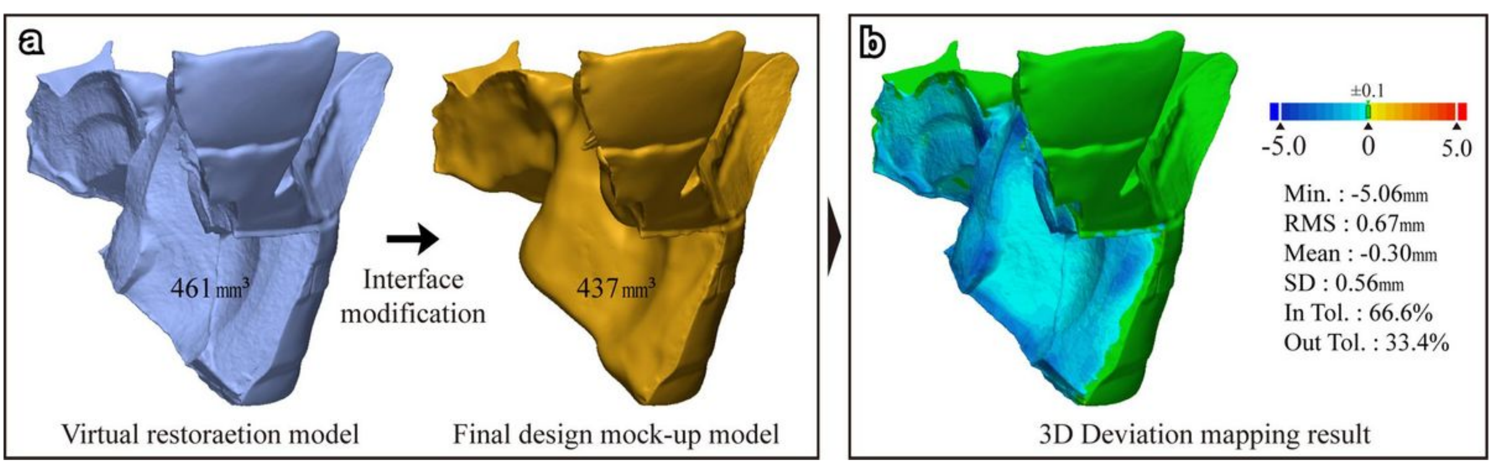

Figure 10

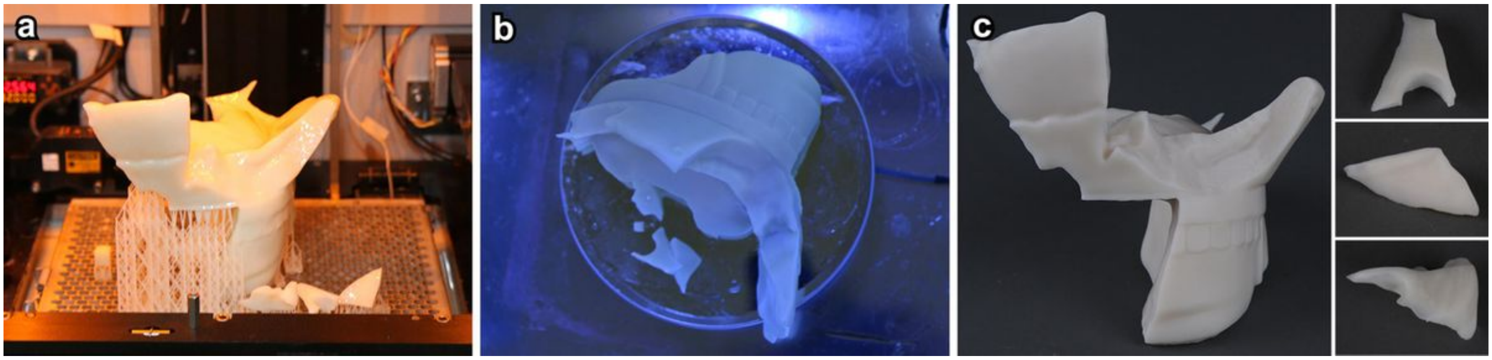

Figure 11

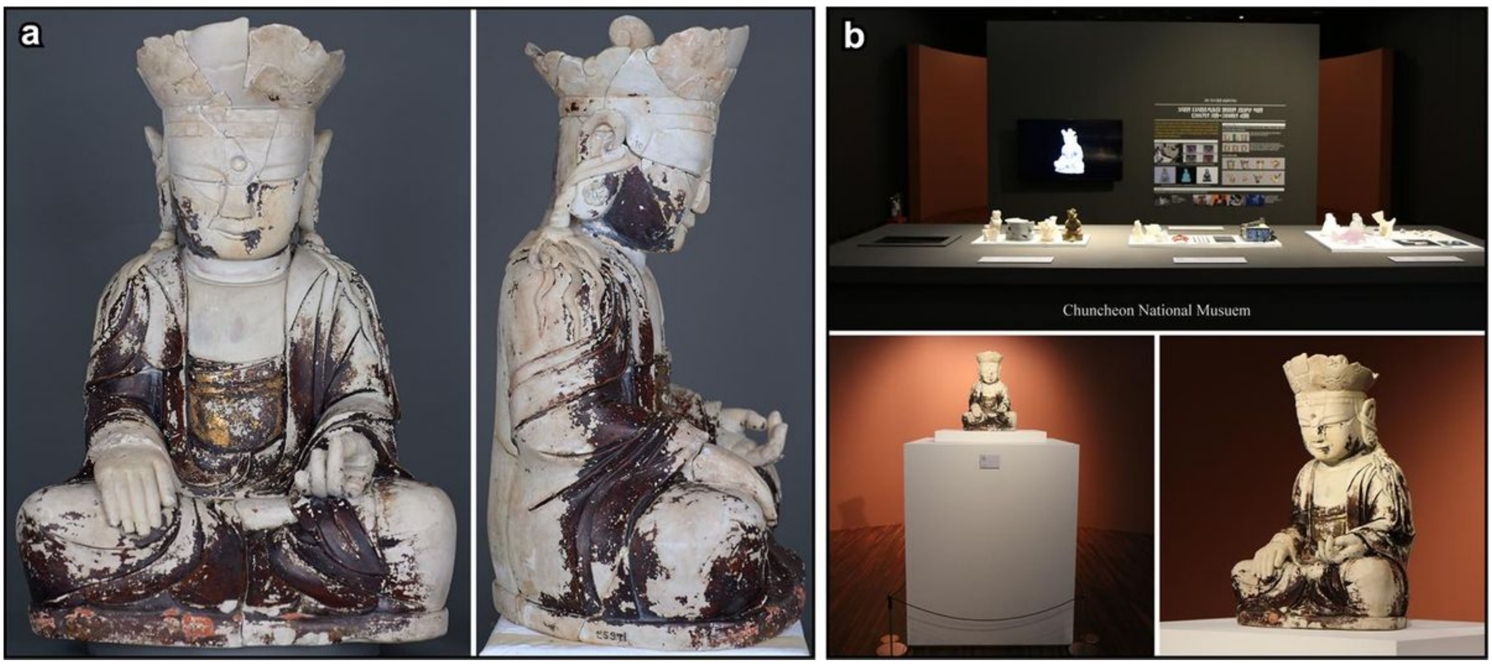

Figure 12