Application of Three-dimensional Scanning, Haptic Modeling, and Printing Technologies for Restoring Damaged Artifacts

Young Hoon Jo¹ | Seonghyuk Hong

Department of Cultural Heritage Conservation Sciences,
Kongju National University, Gongju, 32588, Korea

¹Corresponding Author: joyh@kongju.ac.kr, +82-41-850-8539

ABSTRACT This study examined the applicability of digital technologies based on three-dimensional(3D) scanning, modeling, and printing to the restoration of damaged artifacts. First, 3D close-range scanning was utilized to make a high-resolution polygon mesh model of a roof-end tile with a missing part, and a 3D virtual restoration of the missing part was conducted using a haptic interface. Furthermore, the virtual restoration model was printed out with a 3D printer using the material extrusion method and a PLA filament. Then, the additive structure of the printed output with a scanning electron microscope was observed and its shape accuracy was analyzed through 3D deviation analysis. It was discovered that the 3D printing output of the missing part has high dimensional accuracy and layer thickness, thus fitting extremely well with the fracture surface of the original roof-end tile. The convergence of digital virtual restoration based on 3D scanning and 3D printing technology has helped in minimizing contact with the artifact and broadening the choice of restoration materials significantly. In the future, if the efficiency of the virtual restoration modeling process is improved and the material stability of the printed output for the purpose of restoration is sufficiently verified, the usability of 3D digital technologies in cultural heritage restoration will increase.

Key Words: Virtual restoration, 3D scanning, 3D printing, Haptic interface, Digital technology

1. INTRODUCTION

Often times, artifacts such as pottery, ceramics, and roof tiles are damaged by artificial and natural factors. As a result, the damaged artifacts need to be repaired and restored for use in exhibitions, research, and education. For repairing and restoring such artifacts, traditionally, natural materials such as egg whites, tree bark, raw lacquer, and bitumen were mainly used(Yang and Seo, 2011); however, since the modern era, various synthetic resins, particularly epoxy resin, has recently been widely applied for the purpose(Hwang and Lee, 2006; Lee *et al.*, 2007; Han *et al.*, 2010; Nam and Jang, 2017).

Generally, restoration using these new materials usually depends on the ability and techniques of a conservator or restorer. However, such manual restoration often leads to secondary damages when the restoration materials come in direct contact with the artifacts, resulting in the materials

being removed from the artifacts owing to inappropriate restoration. Recently, to complement the manual methods, three-dimensional(3D) digital technologies have emerged as new methods for the conservation and restoration of artifacts.

3D digital technologies are state-of-the-art technologies that enable us to record and analyze the shapes of cultural artifacts based on 3D numerical information. In particular, 3D digital data are extremely useful for semi-permanently conserving the current state of the artifacts without being affected by various factors of change. Representative 3D digital technologies applied to cultural artifacts are 3D scanning and printing. In the past, digital technologies were focused mainly on digital documentation through 3D scanning; however, currently, they are being utilized in a wide variety of fields related to cultural heritage such as making technique(Jo and Lee, 2012; Kim and Okada, 2017), shape analysis(Lee *et al.*, 2012; Ahn *et al.*, 2013;

Choi and Ko, 2014), conservation evaluation(Jun *et al.*, 2008; Jo and Lee, 2009; 2016; Soler *et al.*, 2017; Sánchez-Aparicio *et al.*, 2018), monitoring(Kim and Lee, 2017; Wilson *et al.*, 2018), reassembly(Lee and Han, 2015; Zhang *et al.*, 2018), and content creation(Machidon *et al.*, 2018) based on scanned data. In particular, as these digital technologies become integrated with 3D printing technology, their scope of application is becoming wider, extending to cultural heritage restoration, replication, and education(Lee and Wi, 2015; Balletti *et al.*, 2017; Katz, 2017; Xu *et al.*, 2017; Keles and Yaman, 2018; Shin and Hwang, 2018; Ford and Minshall, 2019).

This study aims to provide a methodology for utilizing 3D digital technologies in artifact restoration. To this end, the applicability of integrated 3D scanning and printing technologies was examined using a damaged roof-end tile replica. First, the 3D shape of the roof-end tile was obtained through 3D close-range scanning, and a haptic interface was used to conduct virtual restoration modeling based on the data for the original tile. Then, the finished model was printed out with a 3D printer using the material extrusion method and a PLA filament. To verify the dimensional accuracy of the printed output, its additive structure was observed through a scanning electron microscope, and its shape accuracy was determined through 3D deviation analysis and applied to the restoration of the actual object.

2. STUDY TARGET AND METHODS

The study target was a replica of the lotus-patterned roof-end tile dating from the Baekje Dynasty period. Such

roof-end tiles were used to decorate the roofs of major buildings like the royal palace and temples. The lotus pattern is depicted with seven broad lotus petals, and the size of the ovary is big compared to the petals. The ovary contains nine lotus seeds, and the gynostemium is depicted around the ovary. The replica that was used is 64 mm in radius and 9 mm in thickness, with more than one-third of the entire tile missing. However, since it has a symmetric shape centered on the lotus seeds, the missing part can be restored by extrapolation(Figure 1).

The overall study method and process mainly involved 3D scanning of the roof-end tile, digital virtual restoration, 3D printing, and analysis of the layer thickness and shape of the printed output, in that order. First, regarding 3D

Figure 1. Photograph of the roof-end tile replica with the missing part.

Figure 2. Digital technologies used for restoring damaged artifacts. (a) 3D close-range scanning system, (b) Virtual restoration using a haptic interface, (c) 3D printing using the material extrusion method and a PLA filament.

scanning, after considering the size and detailed shape of the roof-end tile, and a close-range scanner(HDI Advance R3X, LMI Technologies, Canada) was used. This scanner relies on the triangulation method using white structured light and two stereo cameras(2.8MP). It can scan at a high speed of 0.88 seconds and has an accuracy of 30-80 μm , depending on the lenses' focal length(16 mm, 25 mm, 30 mm). For this study, 12 mm lenses were used the field-of-view(FOV) was set at 200 mm to scan at an accuracy of 45 μm (Figure 2a). Furthermore, the FlexScan3D software was used for on-site scanning and for registering and merging of the data. The Geomagic Design X was used for editing the data.

Based on the completed scan data, the digital virtual restoration modeling of the missing part of the roof-end tile was conducted using a haptic device(Figure 2b). This haptic device(Geomagic Touch X, 3D Systems, USA) has an accurate 6-degree-of-freedom positional input and a high-fidelity 3-degree-of-freedom force feedback, thus facilitating intuitive modeling by allowing users to feel the objects displayed on screen with their hands. Moreover, this device comes with Freeform Plus, which is the only known modeling software integrated with a haptic device and can

handle robust voxel-based data models. In particular, it not only generates a virtual clay-based model of the original item but also allows modification of the scan data. Thus, it is utilized in a wide variety of domains worldwide including industrial(Abidi and Ahmad, 2015; Rastogi and Srivastava, 2019), medical(Escobar-Castillejos *et al.*, 2016; Wu *et al.*, 2016; Corrêa *et al.*, 2019), and cultural heritage(Park and Kang, 2007; Park, 2008)-related fields.

As for the 3D printing of the virtual restoration model, a 3D printer(Ultimaker 3, Ultimaker B.V., Netherlands) was used based on material extrusion technology along with dedicated filament and software(Figure 2c). This printer has two extruders that can simultaneously print out two materials, which is a great advantage when it comes to models that have a dual or more complex structure. The filaments used for printing were the eco-friendly PLA and the water-soluble PVA. The open-source software Cura was used to convert the data to G-Code for printing and to set up the printing conditions. Furthermore, a scanning electron microscope(MIRA3 LMH, TESKAN, Czech) was used to verify the layer thickness of the printed output, and the Geomagic Control X software for shape analysis.

Figure 3. 3D scanning processes of the roof-end tile. (a) Calibration of the center axis of the turn table, (b) Front and back parts of the automatically scanned roof-end tile, (c) Global registering of the total scan images completed polygon mesh, (d) RGB texture mapping, (e) Models, (f) High resolution mesh data of the detailed patterns.

3. RESULTS

3.1. Three-dimensional scanning result

3D scanning refers to the technique of obtaining the 3D shape of a cultural asset in point cloud or mesh form using the interference or reflection data of a light source projected on an object's surface. This scanning process involves two steps, namely, a 3D scan to measure the shape of a cultural artifact and convert it into a structured point cloud using a physical scanner, and data processing to construct a 3D shape from the point cloud. Thus, 3D scanning can be explained in terms of shape reverse engineering, as it makes a digital model or an actual object with the same shape through data processing based on the measurement data for the original artifact.

The 3D modeling of the roof-end tile through 3D scanning mainly involved three steps, namely, task planning, 3D scan, and data processing. Generally, a complete model of the target object cannot be made from a single scan; therefore, it is necessary to perform scores or hundreds of scans from various directions. For 3D scanning the roof-end tile, the automatic rotation method was used by means of a rotary table. To this end, first, the center axis of the rotary table was calibrated and the roof-end tile was placed on the table(Figure 3a). In total, 36 scan images were obtained 18 each from the front and back, while turning the table by 20° for each scan. This method has the advantage of facilitating the data processing because it enables the automatic completion of the initial registering data for each measured side at the scan site.

As shown in Figure 3b, the on-site scan results comprise data on specific parts of the scanned object and hence it is necessary to combine them into one coordinate system through post-processing(Figure 3b). This work of converting to one coordinate system is called “aligning” or “registering”. The coordinates of the two mesh datasets were aligned on the front and the back of the roof-end tile through manual registering(Figure 3c). Moreover, a 3D model of the roof-end tile was produced through “merging”, which is the task of combining the scan datasets into one dataset(Figure 3d). Lastly, RGB texture mapping was applied to the 3D polygon mesh model to enhance its realism(Figure 3e). The completed 3D model of the roof-end tile comprised a total of 3,779,012 polygons and thus had a considerably high resolution that enabled us to clearly identify the patterns, fracture surface, and traces left by pressing(Figure 3f).

3.2. Virtual restoration modeling based on haptic interface

In this study, the digital virtual restoration of the missing part of the roof-end tile was conducted based on the 3D scanning results of the tile, and a haptic interface was used for modeling. In this context, “haptic interface” in the broad sense, refers to the entire system that transmits tactile sensations to the user. This system comprises a haptic device, a hardware device that generates tactile sensations by transmitting physical force to the user who is directly in contact with it; a teleaction environment or a virtual environment consisting of computer graphics and physical property values; and a controller that conveys the

Figure 4. 3D virtual restoration processes of the roof-end tile using the haptic interface. (a) Selection of the reference model from the original object, (b) Insertion of the reference model into the missing part, (c) Revision and transformation of the virtual model based on Boolean operation, (d) Completion of the virtual restoration model.

movements of the haptic device to the virtual environment and transmits the contact force of objects in the virtual environment to the haptic device. The main purpose of this haptic interface is to allow the user to feel the physical properties of the modeled virtual environment or actual environment through the haptic device(Kyung and Park, 2006).

The information cognized through this haptic interface is mainly composed of three types, namely, information related to kinesthetic sense, tactile sense, and proprioceptive sense. For the virtual restoration modeling of the missing part of the roof-end tile, a kinesthetic haptic interface was used. This type of interface allows the user to cognize impact and interference between the haptic device and the data through vibrations. It also provides a more efficient solution for designing free and complex shapes compared to the traditional kind of modeling using a mouse, and it is widely used in medical, mechanical, and cultural artifact-related fields worldwide.

The virtual restoration modeling of the missing part of the roof-end tile was conducted. First, the reference model of the original roof-end tile was selected(Figure 4a), copied, and inserted into the missing parts(Figure 4b). However, the inserted reference model did not completely match the missing area. Thus, the completion level of the virtual restoration of the missing part was improved by revising and transforming the virtual model based on Boolean operation(Figure 4c). Through this virtual restoration modeling, the missing part's volume was calculated to be $47,913 \text{ mm}^3$, which amounts to 38.4% of the roof-end tile's total volume(Figure 4d).

3.3. Three-dimensional printing result

Additive manufacturing is a technology that was first referred to as “rapid prototyping”(RP), however with its recent popularization, it eventually came to be known as “3D printing”. The former name highlights the technology’s capability of making prototypes at high speeds, while the latter name highlights the process of slicing a 3D model into two-dimensional cross sections(differential) that are sequentially reconstructed, which are then used to manufacture a given material additively one layer at a time(integral). In other words, just as an inkjet printer recreates inputted photographs or documents by spraying ink, 3D printing is a cutting-edge manufacturing process that forms some material(polymer, metal, paper, wood, etc.) into a particular shape layer by layer, using various types of 3D printers (photo polymerization, extrusion, jetting, fusion, etc.) based on a 3D model created through scanning and computer graphics.

3D printing methods are classified according to principle and material by various institutions and researchers. Among them, the classification method provided by the technical committee of ISO/TC additive manufacturing is the most widely used. As defined in ISO/ASTM52900(2015), primarily, there are seven representative 3D printing techniques based on associated criteria: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. In this study, the material extrusion method was chosen to print the result of the 3D virtual restoration of the roof-end tile’s missing part. Furthermore, for the output material, the

Figure 5. 3D printing processes of the roof-end tile. (a) Positioning of the virtual restoration model. 3D printing output before (b) and after (c) removing the PVA supporter.

biodegradable polymer PLA was chosen, and the water-soluble polymeric compound PVA was used as the support material.

The 3D printing of the virtual restoration model was conducted in seven stages. First, the 3D modeling data were converted to STL files suitable for printing, and a zero-defect test was performed to check for any problems in the polygon mesh. Moreover, the virtual restoration model was positioned at an inclined angle of 30° so that additive patterns would not appear on the surface of the printed output(Figure 5a), and dedicated software was used to set layer thickness($60\text{ }\mu\text{m}$), nozzle temperature(210°C), bed temperature(80°C), and printing speed(70 mm/s). Based on these settings, the movement path of the 3D printer nozzle was quantified by generating a G-Code. Lastly, a check was conducted to ensure that the printer bed was level and the bed and the nozzle were preheated, and then the G-Code was fed into the 3D printer to generate the printout. Figures 5b and 5c show the 3D printing result of the virtual restoration model.

3.4. Accuracy assessment

To determine the resolution of the 3D printing output and verify the accuracy of its layer thickness, a 10 mm^3 square model was observed through with a scanning electron microscope(Figure 6a). It was found that the filament extruded from the nozzle is not homogenous in terms of having uniform thickness for each layer(Figure 6b). The layers had a mean thickness of about $60\text{ }\mu\text{m}$ with an error range of $\pm 10\text{ }\mu\text{m}$. In particular, measurement of the layer thickness of an arbitrary set of ten consecutive layers yielded a mean thickness of $61.51\text{ }\mu\text{m}$, with a range of minimum thickness at $52.17\text{ }\mu\text{m}$ and maximum thickness at $72.36\text{ }\mu\text{m}$ (Figure 6c). Since these values are quite similar to the value($60\text{ }\mu\text{m}$) set under the additive layer conditions for printing, it was determined that the overall layer thickness accuracy is high.

Next, to verify the shape accuracy of the 3D printing output, 3D close-range scanning was performed on the printed output(Figure 7a). The overall scan conditions and

Figure 6. Scanning electron microscope results. (a) 10 mm^3 cubic sample for observing layer thickness, (b) Measurement of the layer thickness of an arbitrary set of ten consecutive layer, (c) Detailed additive layer conditions.

Figure 7. Accuracy analysis of the printed shape. (a) Virtual restoration and 3D printing output models, (b) Registering the 3D scanning model of the printed output based on the virtual restoration model, (c) 3D deviation analysis results between two models.

Figure 8. Restoration results using the 3D printing output.

data processing were set in a manner similar to the original roof-end tile. Deviation analysis was performed on the 3D scanning model of the printed output on the basis of the virtual restoration model(Figure 7b), and this was used to calculate the minimum, maximum, mean, and root-mean-square(RMS) deviation.

As a result, the two models were shown to have a mean deviation of 0.019 mm, ranging from a minimum of -0.283 mm and maximum of 0.286 mm, and an RMS of 0.060 mm (Figure 7c). Considering that the accuracy of the 3D scanner is 0.045 mm, it can be determined that the 3D printing output has an error of about 0.015 mm. However, most of the error appears at the beginning portion of the printed output and in the additive direction rather than on the fracture surface. Furthermore, when we examine the restoration results involving the 3D printing output and the original roof-end tile, it was revealed that the joined surfaces and the patterns fit together exquisitely, thus indicating that no post-processing is required(Figure 8).

4. DISCUSSION AND CONCLUSION

Generally, the restoration of damaged artifacts is manually conducted by conservators. However, the manual restoration depends on the ability of the restorers or conservators, making it impossible to conduct preliminary checks through simulation and difficult to predict the restoration result. Moreover, the use of irreversible synthetic resins for the restoration material may cause secondary damage to the artifacts. Therefore, in this study, the applicability of integrated 3D scanning, virtual restoration modeling, and printing technologies with regard to a damaged roof-end

tile replica was examined. In addition, a study methodology for utilizing these technologies in artifact restoration was provided.

First, a 3D model of the roof-end tile was produced through 3D close-range scanning, data processing such as registering, merging, and editing, and RGB texture mapping. Then, regarding the digital virtual restoration model that is based on a haptic interface, the reference polygon mesh was copied and inserted into the missing part, and the model was completed after it was revised and transformed to match the original tile based on Boolean modeling. Last, for printing out the virtual restoration model, a 3D printer employing the material extrusion method and PLA filament(with PVA as the support material) was used. In particular, the overall 3D printing process involved conversion to the STL file extension, zero-defect testing, positioning of the model, inputting the printing conditions, G-Code generation, printer setting, G-Code input, and printing, in that order.

In addition, the printed output was observed through a scanning electron microscope and 3D deviation analysis was conducted to determine the shape accuracy of the final output. Consequently, it was discovered that the 3D printing output has dimensional accuracy and consistent layer thickness, thus fitting extremely well with the fracture surface of the original roof-end tile. However, precision joining of fractured surfaces may lead to nonconformity when an adhesive is used on the fractured surface. Therefore, it seems that three-dimensional modeling and printing considering adhesive application are required in the future. Previous research using 3D printing did not discuss on the accuracy of the printed output because they mainly focused on the restoration processes of the artifacts(Lee and Wi, 2015; Shin and Hwang, 2018). However, in the overall study procedure described above, the use of the haptic interface for virtual restoration and the accuracy assessment of the 3D printing output were significant in enhancing the quality of the restoration of the missing part.

Conservation treatment and restoration of the artifact and monuments primarily depend on the manual technique (Lee *et al.*, 2010a; Lee *et al.*, 2010b). However, such a method involves unavoidable direct contact with the artifacts and

monuments and often causes secondary damage. However, the convergence of virtual restoration based on 3D scanning and 3D printing technology helped in minimizing contact with the artifact and in expanding the diversity of the restoration materials. In the future, if the efficiency of the virtual restoration modeling process is increased and the material stability of the restoration printing results is sufficiently verified, 3D digital technologies can be widely utilized in the restoration of similar cultural artifacts.

Presently, with the rapid advancement of hardware and software technologies 3D digital technologies are likely to develop continuously. In the field of conservation science, specifically, preserving the original state of cultural artifacts and documenting the conservation process are extremely crucial, and thus it is essential to use digital documentation through 3D scanning for these purposes. Moreover, 3D printing can be applied in a variety of ways including cultural artifact conservation, restoration, and replication. Therefore, it is probable to refer to 3D digital technologies as “the future technologies of cultural heritage conservation science”.

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