A Preliminary Study on the Digital Restoration of Ceramics: A Case Study of a Petal-Shaped Bowl from the Hutian Kiln

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Abstract

Ceramics are among the most commonly encountered categories of artifacts in both archaeological excavations and museum collections. Owing to their inherent fragility, however, damage and loss are widespread. Traditional ceramic restoration has relied primarily on manual joining and infilling, a process that places considerable demands on the restorer's experience and also presents certain limitations in morphological reconstruction, process documentation, restoration efficiency, and non-destructive reversibility. With the development of technologies such as 3D scanning, digital modeling, and 3D printing, digital methods have opened up new technical pathways for the restoration of damaged ceramics. Taking a fragmented petal-lobed bowl from the Hutian kiln as a case study, this paper explores the basic workflow of digital ceramic restoration: first, high-precision 3D scanning is used to acquire data from the object itself; next, modeling techniques are employed to digitally reconstruct the missing portions; Boolean operations are then used to generate a model of the replacement component; this model is subsequently transformed into a physical insert through 3D printing; and finally, the insert is installed in a reversible manner. The study shows that digital restoration methods offer clear advantages in data acquisition, morphological inference, virtual reconstruction, improved efficiency, data preservation, and the reuse of results, and can provide a highly practical technical approach for the restoration of ceramic cultural heritage.

Keywords: Ceramic Restoration, 3D Scanning, Digital Modeling, 3D Printing

1 Introduction

Porcelain occupies an important place in the material remains of ancient China. Not only are excavated and transmitted examples vast in number and rich in variety, but they are also distinguished by elegant forms and considerable aesthetic value. Owing to the inherent fragility of porcelain, however, such objects are highly susceptible to damage during long-term preservation and circulation. For a long time, porcelain restoration has relied chiefly on traditional manual methods, yet this approach, with its many evident limitations [1], has become increasingly unable to meet the needs of the current development of digital heritage conservation. In recent years, 3D scanning, computer modeling, and additive manufacturing technologies have developed rapidly and have gradually been applied in fields such as archaeology, cultural heritage conservation, and museum display [2]. Existing studies have shown that digital restoration is no longer confined to virtual presentation, but is increasingly extending toward the fabrication of physical inserts and the practical implementation of restoration [3].

This paper takes a damaged petal-lobed bowl from the Hutian kiln as its object of study and seeks to explore a digital restoration pathway for cultural heritage that is both operationally feasible and procedurally clear. It should be emphasized that the "restoration" discussed here does not aim at a mimetic reconstruction of the artifact as a whole. Rather, it seeks, on the basis of the surviving remains, to use digital technologies to make a reasoned reconstruction of the missing portions and to fabricate replacement components that are both compatible and replaceable, thereby achieving an overall restoration of the vessel's appearance and allowing the beauty of the original object to re-emerge through the encounter between the historical artifact and modern technology.

2 Restoration Object and Condition of Damage

The restoration object discussed in this paper is a damaged petal-lobed bowl from the Hutian kiln. The Hutian kiln was a renowned producer of qingbai ware during the Song dynasty. Its products are noted for their fine body fabric, lustrous glaze, graceful forms, and flowing lines, qualities that accord with the Song aesthetic preference for simplicity and naturalness, and it occupies an important place within the southern qingbai ceramic tradition [4]. As one of the more representative vessel types produced at the Hutian kiln, the petal-lobed bowl is typically characterized by a lobed rim, with corresponding undulating petal ridges extending along the exterior wall of the vessel. The overall form is light and elegant, rich in decorative effect, and combines practical utility with aesthetic appeal [5]. The specimen selected for this study measures approximately 47.7 mm in height, 120.4 mm in rim diameter, and 57.2 mm in foot diameter. Its body is relatively thin, and the entire vessel is covered with a qingbai glaze. Overall, the glaze surface is in fairly good condition, and the piece displays clear morphological characteristics typical of Hutian kiln petal-lobed bowls (Figure 1).

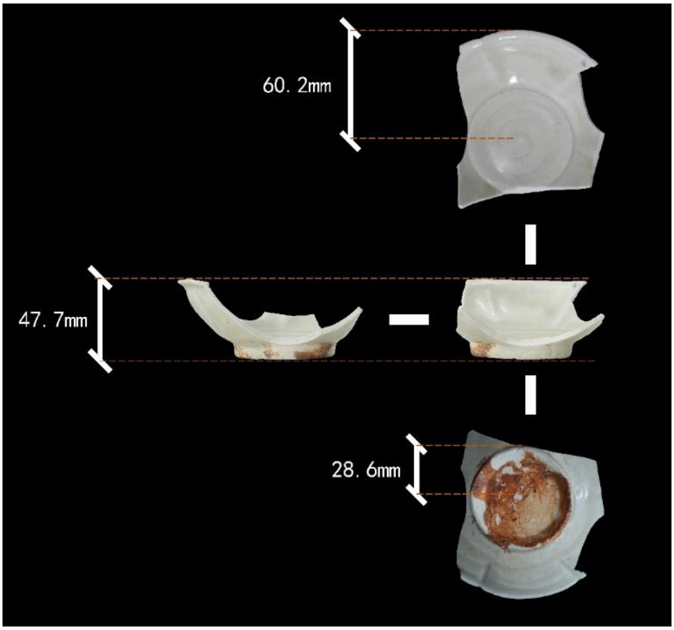

Fig. 1 Dimensional measurements of the petal-lobed bowl specimen

Judging from its state of preservation, the vessel is a damaged object whose principal losses are located along the rim and the belly wall, while the foot ring remains largely intact. The surviving portions still allow the basic outline of the original vessel, the undulating petal-lobed profile, and the curvature of the belly wall to be identified with relative clarity. Owing to the large area of loss, however, the overall form of the vessel is no longer complete. In particular, the missing section at the junction of one side of the rim and the belly wall interrupts the original contour line and affects a holistic reading of the vessel shape. At the same time, the fracture edges of the surviving fragments are comparatively regular, with localized traces of chipping visible in some areas, which to a certain extent increases the difficulty of boundary assessment and fit control in the subsequent infilling process. In its current damaged condition, the vessel is subject to certain limitations in both display and research.

3 Digital Restoration Workflow

The digital restoration approach adopted in this study is structured around the technical workflow of "3D scanning–digital modeling–Boolean operations–3D printing–reversible installation." Each stage of this process is introduced in turn below.

A. Scanning and Model Acquisition

The equipment used in this study for three-dimensional data acquisition was an EinScan Rigil Pro handheld high-precision 3D scanner manufactured by Shining 3D.

Cleaning and preparation. Before scanning, the surface of the object must first be basically cleaned in order to minimize interference from dust, stains, and other factors during data acquisition. Because the surface of the vessel is close to monochrome and lacks distinct feature points, small strips of plasticine may be attached to selected areas to improve scanning performance. The object is then placed on a relatively stable working platform so as to reduce data errors caused by movement during scanning.

Multi-view data acquisition. Given the small size of the petal-lobed bowl, as well as the fine variations in the petal ridges on the exterior wall and the curved surface of the interior wall, the scanning process mainly adopts a multi-angle, sectional acquisition strategy. Key areas, including the exterior wall, interior wall, rim, foot ring, and fractured edges of the missing sections, are scanned progressively so as to ensure the completeness of the model information to the greatest possible extent. Areas with more pronounced local occlusion or greater curvature variation are further refined by adjusting the scanning angle and supplementing the data acquisition.

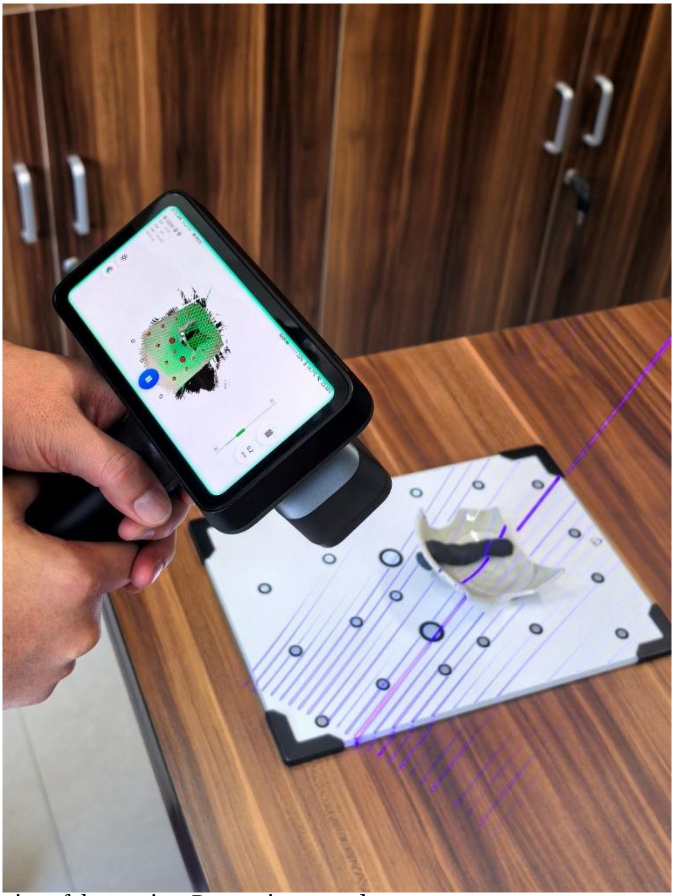

Fig. 2 Illustration of the on-site 3D scanning procedure

Generation of the 3D model. After the raw data acquisition is completed, the resulting point-cloud data are imported into the scanner’s client software for post-processing, which mainly includes data alignment, noise removal, local hole filling, and surface optimization[0]. Through this procedure, the raw scan data can be converted into a clear and complete 3D model.

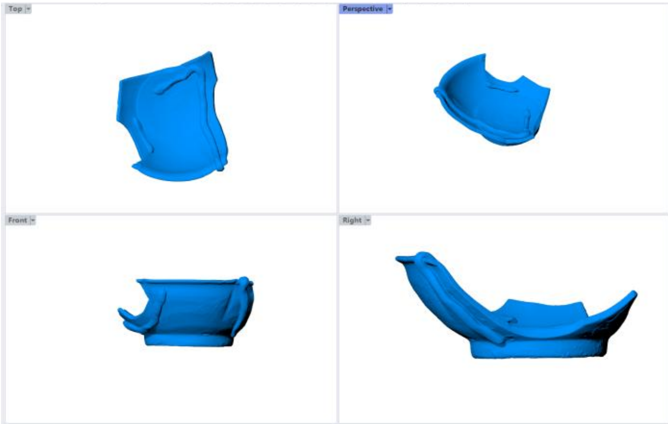

Fig. 3 Multi-view images of the 3D model of the petal-lobed bowl

B. Digital Modeling

Extraction of the contour lines of the surviving fragments. The first step is to conduct a careful observation and analysis of the overall structure and contour curves of the surviving fragments of the petal-lobed bowl. Relatively well-preserved portions are then selected and sectioned both vertically and horizontally in order to obtain information on the vessel's internal structure. On the basis of these sectional views, the contour lines of the petal-lobed bowl can then be extracted. The quality of this step directly affects the subsequent modeling results and, indeed, the success of the restoration process as a whole. It therefore requires repeated adjustment and refinement, with particular attention paid to such details as the trajectory of the rim, the curvature of the belly wall, the undulating relationships among the petal units, and variations in wall thickness.

Morphological inference and generation of a complete reconstructed model. On the basis of the formal characteristics and structural curves of the petal-lobed bowl, the missing portions can be subjected to geometric inference and digital reconstruction. For missing areas showing clear correspondences, reconstruction may be carried out by mirroring or positional alignment with reference to the better-preserved side. For areas in which the curved surface remains generally continuous but is locally interrupted, the missing portion may be reconstructed by extending the adjacent surviving surfaces and smoothing the transition. For areas where the boundaries of individual petal units remain relatively clear, the missing portions may be partially replicated and adjusted on the basis of the preserved petal structure. Through these procedures, a complete digital model of the petal-lobed bowl can be generated that conforms to the original rhythmic formal order and vessel characteristics.

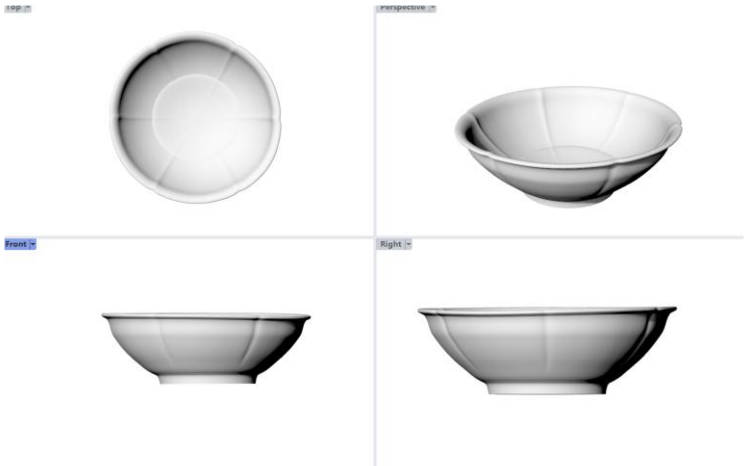

Fig. 4 Complete reconstructed model

Model optimization. After the preliminary reconstruction has been completed, the model must undergo further optimization. This includes adjusting the fit of the boundaries, refining the junctions between curved surfaces, and correcting locally unnatural transitions, so that the digitally reconstructed result not only conforms as closely as possible to the overall morphological logic of the original vessel, but also possesses the compatibility required for subsequent printing and installation.

C. Boolean Operations and Generation of the Replacement-Component Model.

The 3D scanned model of the surviving fragments of the petal-lobed bowl was superimposed on the complete reconstructed model within the same coordinate system to ensure consistent spatial alignment between the two. A Boolean difference operation was then applied to directly obtain the required replacement-component model, as shown in Figure 5.

Fig. 5 Schematic illustration of the Boolean operation

D. Printing of the Replacement Component

Model optimization. After the replacement-component model has been extracted, it must be further adjusted in accordance with the practical requirements of 3D printing. This includes checking whether the model is watertight, whether its boundaries are clearly defined, whether any local areas are excessively thin, and whether sharp corners or suspended structures that might affect printing stability are present. For edge areas intended to come into direct contact with the original vessel, the fitting surfaces should also be appropriately refined so as to avoid excessive tightness, looseness, or local misalignment during subsequent installation. Once these procedures have been completed, the replacement-component model can be exported and moved to the printing stage.

Selection of printing materials. Given that porcelain restoration requires the replacement component to possess a certain degree of morphological precision while also taking into account weight, visual effect, and the convenience of subsequent finishing, this study employed two different colors of photosensitive resin for the printing of the replacement parts.

Surface finishing. After printing, the model must undergo support removal, surface finishing, and localized polishing, after which it is trial-fitted with the original vessel. If the trial assembly demonstrates a satisfactory fit, the process may proceed to the next stage of installation and joining.

E. Reversible Installation

Reversible installation refers to the use of different mounting or joining methods according to the material properties of the object and the requirements of display, so as to ensure that the restored parts can be repeatedly removed and reinstalled while minimizing the risk of contact-related damage. Such methods may include bonding with non-damaging adhesives, magnetic attachment, and snap-fit assembly. In the present case, the petal-lobed bowl was restored by joining the polished replacement component to the original object using a reversible conservation adhesive. The advantage of this reversible approach is that if material aging occurs in the future, if new materials become available, if technological advances are made, or if the restoration scheme requires adjustment and refinement as research progresses, the printed replacement component can be removed and replaced with relative ease, causing little to no secondary damage to the artifact itself.

4 Restoration Results and Methodological Reflections

A. Analysis of the Restoration Results

Following the restoration procedures outlined above, the final outcome shows that the printed replacement component forms a relatively natural integration with the surviving fragments of the original vessel in terms of overall contour, surface curvature, and boundary fit. It effectively restores the original rim profile, the curvature of the belly wall, and the rhythmic undulation of the petal lobes. Compared with its condition prior to restoration, the petal-lobed bowl has been significantly improved in terms of overall morphological readability, the presentation of details, and aesthetic appreciation, as shown in Figure 6.

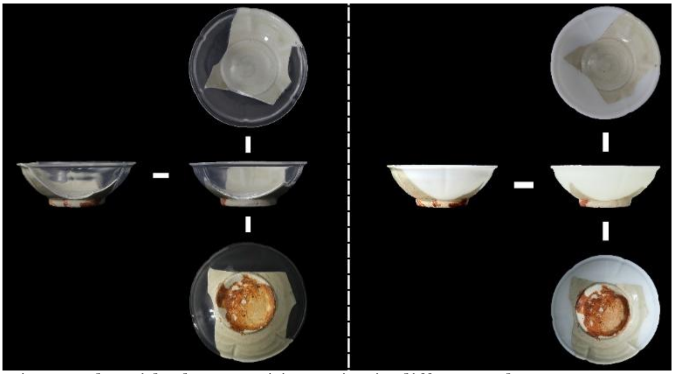

Fig. 6 Restoration results with photosensitive resins in different colors

B. Advantages of Digital Restoration

Judging from the results of this case study, digital restoration demonstrates the following advantages over traditional restoration methods.

More precise information acquisition.3D scanning technology can achieve a measurement precision of up to 4 μm, effectively reducing the subjective errors of visual observation and the limitations of manual measuring tools. Moreover, it can accurately capture complex structures such as curved surfaces, grooves, and narrow gaps [7], offering strong capability in the reproduction of fine details and addressing blind spots that are difficult to reach through manual measurement.

A visible and traceable restoration process. Whether in the form of 3D scanning data, reconstructed models, or the processes of parameter adjustment and scheme comparison, all stages of the workflow can be preserved as digital resources for exhibition, research, and teaching [8]. This means that cultural heritage restoration is no longer merely a one-time practical operation, but instead becomes a digital process that can be documented, traced, and continuously reused.

Greatly improved restoration efficiency. Traditional restoration often relies on manual joining and shaping [9], and is therefore relatively time-consuming. By contrast, digital restoration, through the use of 3D scanning, digital modeling, and 3D printing technologies [10], can complete morphological reconstruction and the fabrication of replacement components within a comparatively short period of time. At the same time, the digital data already acquired can provide references for the restoration of similar objects, thereby reducing the costs of repeated data acquisition and trial-and-error experimentation.

Non-contact and reversible operations can reduce the risk of secondary damage to the artifact. Traditional manual restoration generally requires repeated shaping and trial fitting, and once a physical fill has been formed, it is difficult to make substantial modifications. Digital restoration, by contrast, makes it possible to carry out repeated adjustment and optimization in virtual space, thereby avoiding damage caused by direct intervention on the physical object. Reversible installation further minimizes physical intervention, making possible an essentially non-destructive upgrading of restoration practice and its sustainable continuation.

C. Problems and Limitations of Digital Restoration

Although digital restoration has clear advantages, several issues still deserve attention at the present stage.

Strong dependence on the quality of preliminary data acquisition. If occlusion, missed scans, or insufficient precision occur during the scanning process, the subsequent digital reconstruction may lose its reliable basis, thereby affecting the accuracy of the replacement component. This is especially true for objects with thin walls, pronounced reflectivity, or relatively complex local damage, for which the quality of scanning often directly determines the upper limit of what digital restoration can achieve.

Although digital reconstruction can infer missing parts on the basis of extant morphology, it cannot be entirely separated from the researcher's judgment. In the case of this petal-lobed bowl, digital inference is relatively straightforward because the formal logic of the vessel is clear and the petal units display a certain degree of repetition. However, when dealing with objects of irregular form, severe deformation, or excessively high levels of damage, digital modeling alone may not necessarily yield a sufficiently reliable reconstruction.

Although 3D-printing materials offer advantages in lightness, plasticity, and ease of post-processing, they still cannot fully match the original artifact in terms of color, gloss, tactile quality, and durability [11]. Accordingly, printed replacement components are better understood as auxiliary and replaceable restoration materials, rather than as a true recreation of the material properties of the original object.

5 Conclusion

Taking a damaged petal-lobed bowl from the Hutian kiln as a case study, this paper offers a preliminary exploration of the basic workflow of digital ceramic restoration through the technical sequence of “3D scanning–digital modeling–Boolean operations–3D printing–reversible installation.” Practice shows that this method possesses significant advantages in data acquisition, morphological inference, virtual reconstruction, improved efficiency, data preservation, and the reuse of results, and that its restoration outcomes and operational stability can be well assured. At the same time, however, there remains room for further improvement in such areas as its adaptability to complex objects, material selection, and evaluative decision-making. Overall, digital restoration provides a new technical pathway for cultural heritage conservation practice that is procedurally clear and highly operable. Moreover, with the continuing updating and iteration of digital technologies, the restoration and conservation of cultural heritage will undergo profound transformation [12].

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