Automated Digital Documentation and Interpretation of Subsurface Cultural Heritage Based on 3D Geometry and AI Inference

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Abstract

This study presents a digital documentation and interpretation methodology for subsurface cultural heritage artifacts based on 3D geometry acquisition and AI inference. A digital solution was developed to automate the conventional manual drawing process of archaeological artifacts, significantly reducing the required time from approximately three hours per artifact to about 23 minutes. Using high-precision 3D scanning and standardized data preprocessing, external contours and cross-sections were automatically extracted, while subjective lines were inferred based on curvature analysis and AI-driven interpretation of accumulated surveyor data. Additionally, visualization data replicating surface patterns and textures were generated through curvature-based shader processing. The proposed approach enhances the objectivity and reliability of artifact documentation by minimizing human error and improving data consistency. It also offers new possibilities for artifact analysis, including the identification of artifacts produced by the same maker through pattern recognition techniques. The results suggest that the developed system can significantly advance digital workflows in archaeological research and heritage conservation, providing a scalable framework for future applications.

1. Introduction

In South Korea, archaeological investigations of subsurface cultural heritage result in the excavation of hundreds of thousands of artifacts annually. According to relevant regulations, selected artifacts must be documented with detailed measured drawings. These drawings serve as fundamental research materials in archaeology and are crucial starting points for academic analysis and interpretation. However, the current documentation process relies heavily on manual methods, requiring an average of more than three hours per artifact. This manual process not only leads to significant inefficiencies but also increases the risk of human error, potentially compromising the reliability and reproducibility of foundational archaeological data. Consequently, concerns have been raised regarding the overall trustworthiness and scalability of research based on such manually produced records. To address these challenges, this study proposes a new methodology for the digital documentation of artifacts based on 3D scanning technology. By automating the drawing process using high-precision 3D data and AI-driven inference models, the method aims to improve both the efficiency and accuracy of artifact documentation. Furthermore, this paper explores advanced interpretation techniques made possible through the accumulation of digital data, offering new perspectives for archaeological research and heritage preservation.

2. Mmethodological Approach

2.1 Selection of Target Artifacts

This study selected the two-tiered mounted dishes (Idantu-changgo-bae), representative artifacts of the Silla Dynasty during the Three Kingdoms period of Korea, as the primary research targets. These artifacts exhibit a standardized form and have been widely excavated from both central and regional burial sites, reflecting a range of regional and chronological variations. Their rotational symmetry, resulting from their manufacturing process as wheel-thrown pottery, makes them particularly suitable for 3D scanning and digital automation. Moreover, since two-tiered mounted dishes are found across various tombs regardless of their scale or type, the accumulated digital data from these artifacts is expected to enable comparative studies on production techniques between regions, chronological analyses, and identification of production sites. Thus, the results of this study could serve as foundational data for the future digital documentation and analytical research of various subsurface cultural heritage artifacts.

2.2 3D Geometry Acquisition

The 3D geometry data used in this study were acquired using the Artec Space Spider II optical scanner manufactured by Artec3D. This scanner is optimized for high-precision scanning of small and complex-shaped artifacts and provides stable, detailed optical data suitable for capturing the intricate surface features typical of subsurface cultural heritage objects. Only scan data achieving a precision level of ±0.05 mm or better were selected as research samples. This strict selection criterion was applied to ensure that even minor deformations or surface irregularities could be accurately recorded, maintaining a consistently high data quality standard essential for subsequent analyses. Additionally, all scanning processes were conducted under controlled lighting conditions, minimizing external interference and environmental variability. This approach ensured uniform data quality across different scanning sessions and contributed to the reliability of the final dataset.

2.3 Data Preparation

The raw point cloud data acquired through 3D scanning were post-processed to create analyzable datasets. Specifically, Artec Studio 18 software developed by Artec3D was used to perform a surface reconstruction process, converting the point cloud into a triangulated mesh format suitable for subsequent analysis.

Surface reconstruction is a critical step for ensuring the connectivity of the scanned data and for consistently representing the surface geometry of artifacts. During the post-processing phase, default software settings were applied to standardize the processing conditions and maintain uniform data quality across all samples. Basic refinement operations, such as denoising and hole filling, were performed to remove scanning noise and fill minor gaps, but no modifications were made that could alter the original geometry of the artifacts. This approach was adopted to preserve the objectivity and authenticity of the digital documentation. As shown in Figure 1, the image provides examples of the selected artifacts (two-tiered mounted dishes) captured through 3D scanning. The numeric labels are merely used to distinguish between individual specimens and do not represent measurement or resolution values.

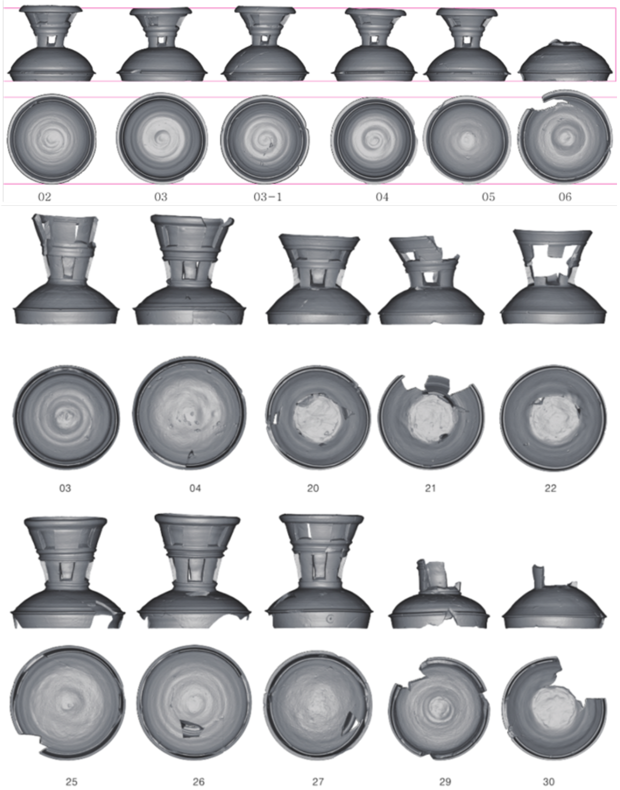

Figure 1. 3D scan data of the artifact.

2.4 AI Design Assumptions

The software developed in this study was designed with three primary objectives: visualization, drawing, and automation of archaeological measured drawings. To support high-volume 3D data processing and stable real-time visualization, a robust technical architecture was established. The programming language C++ was adopted to ensure efficient memory management and high processing speed, essential for handling complex 3D artifact models. For 3D visualization, the Visualization Toolkit (VTK), an industry-standard library specialized in scientific data rendering, was integrated to enable efficient and detailed representation of intricate artifact geometries. The software was developed as a standalone desktop application, independent of network environments, to allow for stable operation and real-time data processing even in fieldwork conditions. To design the AI inference model, a large volume of manually generated measured drawings was collected. A statistical approach was applied to model the subjective judgment criteria used by researchers when creating drawings, accounting for individual variability. This modeling aimed to minimize subjective errors and improve the reliability and reproducibility of automated measured drawings.

3. Implementation

3.1 Analysis of Drawing Components

The digital measured drawings in this study are composed of four major elements: section lines, outlines, subjective lines, and visualization data. Section lines and outlines are objective representations of the actual shapes of artifacts, playing a crucial role in understanding and categorizing their structural characteristics. The outline depicts the overall external contour of an artifact, while the section line simplifies and highlights its internal structure. In contrast, subjective lines are based on the researcher's interpretation, intended to reflect the maker's original intent or functional aspects of the artifact. These lines are drawn through the observation of fine surface details, manufacturing marks, or usage traces, and may vary depending on the researcher’s perspective. Visualization data (frottage) captures detailed surface features such as patterns, textures, and subtle topographical variations. By documenting both structural and surface characteristics, the visualization data contributes significantly to the comprehensive analysis and interpretation of artifacts. Each of these components was considered individually in the system design, enabling independent automation of their generation. In addition to these, pattern lines were identified as a distinct visual element used to represent decorative surface features, and were included in the system to support typological interpretation. This approach enhances the objectivity and reproducibility of the measured drawings and provides a scalable foundation for extending digital documentation across diverse archaeological artifacts. Figure 2 illustrates the four key components of the digital measured drawings: section lines, outlines, subjective lines, and visualization data.

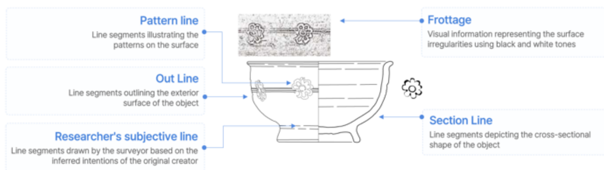

Figure 2. Components of the measured drawing.

Figure 3 presents the process of generating the digital measured drawing from 3D geometry.

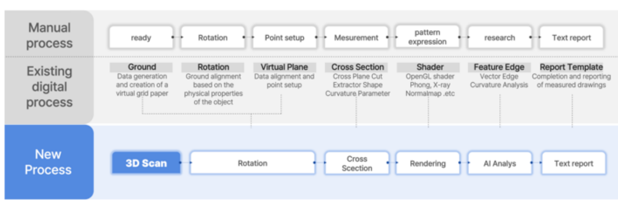

Figure 3. Measured drawing generation process.

3.2 Data generation method

3.2.1 Generation of Outlines and Section Lines

To objectively extract the fundamental geometric information of artifacts, external contours and cross sections were automatically generated from the 3D scan data. Cross sections were obtained by calculating the intersection between the 3D mesh data and vertically aligned planes, providing a simplified view of the internal structure of the artifacts. External contours were extracted by identifying the outer boundary of the scanned data, accurately representing the overall shape of each artifact. An Axis-Aligned Bounding Box (AABB) is a rectangular bounding volume aligned with the coordinate axes that encapsulates the entire 3D object. In this context, the geometric center of the AABB was used as a reference point to align and merge the section lines and outlines. Based on this center, the section and outline data were matched and integrated, ensuring that the vertical cross-section and external contour were consistently aligned. This approach effectively prevents potential errors such as axis distortion or misalignment, which often occur in manual drafting processes. As a result, the system ensures higher consistency and accuracy in the generation of digital measured drawings. As shown in Figure 4, the digital frottage method replicates surface details more consistently compared to manual drawings.

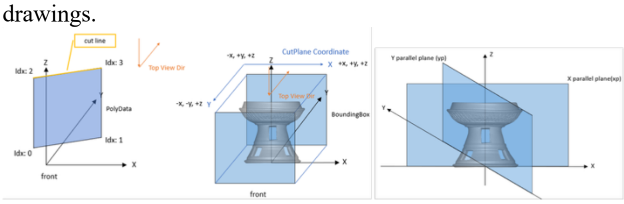

Figure 4. Comparison of digital frottage results and traditional visual inspection techniques.

3.2.2 Generation of Researcher's Subjective Lines

Subjective lines in measured drawings are determined based on the researcher's observational judgment and do not follow a standardized rule, reflecting the nonuniform characteristics of artifact interpretation. Depending on the researcher's perspective, the criteria for identifying significant features may vary, potentially affecting the consistency of documentation. Two major heuristics were applied to infer where subjective lines should be drawn. First, regions where the curvature of the artifact's surface changes sharply, as observed in cross-sectional profiles, were prioritized. Although no strict mathematical threshold for curvature strength exists, areas exhibiting pronounced curvature were intuitively judged as significant. Second, even in regions with high curvature, a distinction was made to exclude irregularities caused by material properties or unintentional deformations, again based on empirical judgment. To address these inherent subjectivities, a large dataset of manually drawn measured drawings was collected, totaling 3,024 examples of the same artifact type. To infer the researcher's subjective judgment in the placement of interpretive lines, a generative adversarial network (GAN) architecture based on the Pix2Pix model was adopted. This approach allows the system to learn implicit heuristics embedded in expert-made drawings. A total of 3,710 high-quality measured drawings, manually created and qualitatively evaluated by domain experts, were selected as training data. The image transformation network learns to generate line suggestions from 3D geometry inputs, while the discriminator distinguishes between machine-generated and ground truth drawings based on adversarial loss. Post-processing procedures, including a thinning algorithm and linear fitting, were applied to produce geometrically consistent line outputs. This hybrid model enables the automated suggestion of line placements that emulate the stylistic and interpretive decisions of experienced archaeological illustrators.

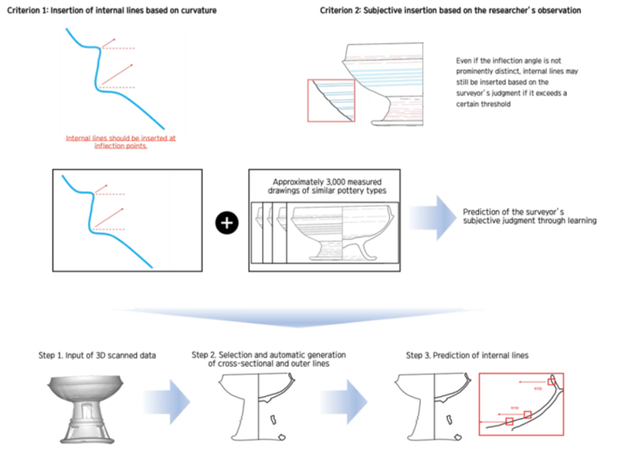

Figure 5. AI-based prediction of researcher's subjective line insertion based on curvature analysis.

Analysis of the distribution showed that most subjective lines corresponded to strength scores between approximately 3.2 and 7.5. Using this information, candidate points for subjective lines were automatically suggested based on the initially generated section lines and outlines, while allowing researchers to make final judgments. This hybrid approach leverages data-driven modeling to assist human interpretation while preserving the expert's role in the final documentation process.

3.2.3 Visualization Data Generation

To visualize the surface features of artifacts based on 3D scan data, a structured process was designed to analyze and represent shape information. In the first stage, a shader program was used to calculate the normal vectors of the surface mesh based on the view direction. Using these normal vectors, a gradient map was generated, which quantified the rate of surface slope changes. The first derivative of the gradient map was then computed to obtain a Hessian matrix, enabling the calculation of surface curvature. The resulting values, ranging from -1 to 1, were normalized into a gray map, visually differentiating convex and concave regions. Finally, an image post-processing step was applied to emulate the appearance of traditional frottage, enhancing the readability of subtle surface details. Figure 6 illustrates the curvature-based shading process for generating digital frottage from 3D scan data. As shown in Figure 7, the resulting digital frottage closely resembles traditional ink rubbings while preserving higher geometric fidelity.

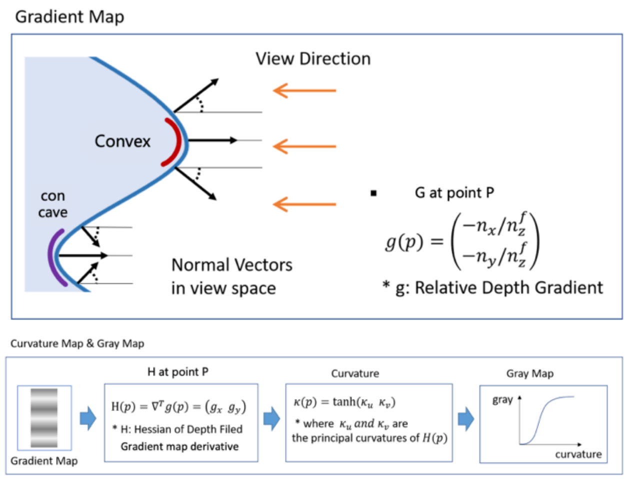

Figure 6. Visualization Data Generation.

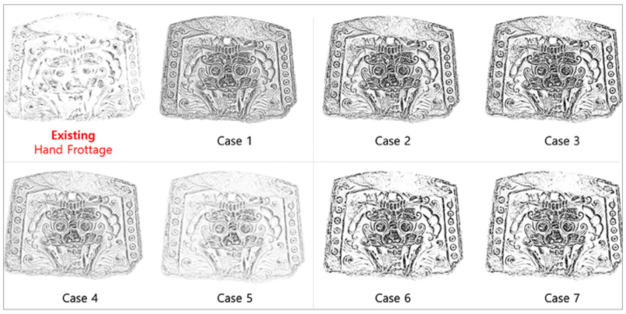

Figure 7. Comparison of digital frottage.

3.3 Evaluation Approach

Performance testing and validation of the developed system were conducted through the Korean Agency for Technology and Standards (KATS), the official national body overseeing technical standardization and certification in Korea. The evaluation included structured testing procedures such as time measurements for processing efficiency, accuracy assessments of generated drawings, and reliability tests across different artifact types. In addition to formal testing, third-party evaluations involving cultural heritage experts were carried out to assess the archaeological validity and practical usability of the automatically generated drawings. Experts compared the automated outputs with traditional manually drawn measured drawings, focusing on factors such as line accuracy, completeness of detail, and representational fidelity. The combined evaluation results showed that the developed system achieved a processing speed approximately eight times faster than conventional manual methods, drastically reducing the time required for documentation without compromising quality.

To evaluate the performance of the proposed system, two complementary methods were employed. First, a formal certification process was conducted under the supervision of the Korea Agency for Technology and Standards (KATS) and the Ministry of Trade, Industry and Energy. A total of 50 trials were carried out using artifacts of the same typology to assess whether the AI-based output effectively followed the interpretive patterns typically applied by expert illustrators. Instead of accuracy per se, processing time was used as the primary performance metric. As a result, the average time per artifact was evaluated at 23 minutes through this standardized benchmarking process. Second, a qualitative evaluation was conducted through a third-party panel consisting of experienced researchers affiliated with a university museum. Given the interpretive nature of archaeological drawings, the panel assessed whether the AI model appropriately emulated human decision-making in line placement. The expert panel concluded that the model's output adequately reflects expert-level reasoning and interpretive patterns. However, they also noted that some outputs were clearly suboptimal, emphasizing that the model should be treated as a decision-support system—offering multiple candidates from which skilled users must ultimately select the most appropriate result.

Furthermore, the quality of the automated measured drawings was evaluated to be at a level equivalent to or slightly better than that of traditional manual drawings in terms of both geometric accuracy and interpretive reliability. These findings strongly indicate that the proposed digital documentation solution not only enhances efficiency but also upholds the academic rigor, precision, and interpretive standards essential for archaeological research and cultural heritage preservation.

4. Analytical Interpretation

4.1 Reduction of Manual Measurement Errors

Traditional manual measurement methods in archaeology are susceptible to various forms of human error, including subjective judgment in measurement, distortions arising from the scaling, reproduction, and documentation processes, and deformations inherent to the artifacts themselves. These issues are particularly pronounced when dealing with rotational artifacts such as ancient pottery, where slight variations in the positioning of cross-sectional measurements can lead to significant discrepancies in recorded dimensions, ultimately affecting the reliability of the data. Recent studies have reported that even in wheel-thrown pottery from the ancient Silla Dynasty, differences of approximately 2 millimeters between the maximum and minimum widths are common due to inherent manufacturing variations and post-firing deformations. Although seemingly minor, such dimensional discrepancies can critically affect the results of typological classification, regional comparisons, and technological studies that depend on precise morphological data. The adoption of 3D scanning-based digital measurement technology fundamentally eliminates these sources of error by capturing the complete geometry of the artifact rather than relying on selected cross-sectional planes. By analyzing the entire 3D surface, the system identifies representative sections that best reflect the original shape, allowing for more objective, accurate, and reproducible documentation. This approach enables a more reliable determination of representative dimensions, improves comparability across datasets generated from different artifacts or excavation sites, and systematically addresses the inherent limitations of conventional manual documentation methods. To further clarify the structure and visual roles of each line element,

Figure 8 presents the classification criteria used in digital measured drawings.

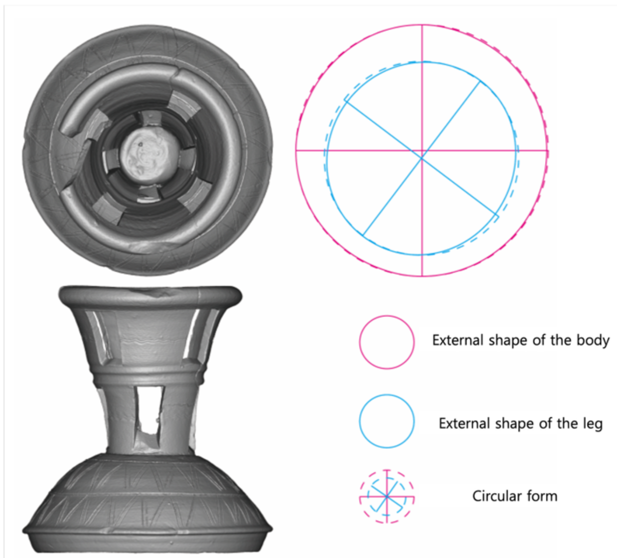

Figure 8. Classification criteria for the target pottery types.

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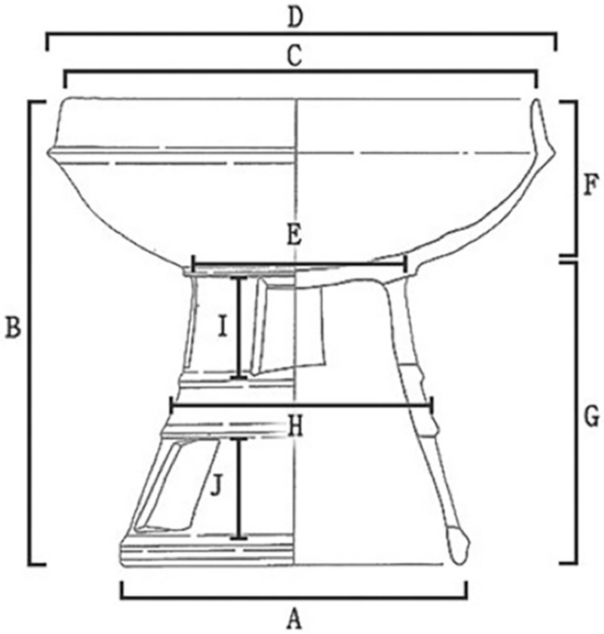

Figure 9. Original 3D geometry of the scanned artifact, serving as a reference model for validating measurement accuracy.

In doing so, digital measurement significantly enhances the scientific rigor of archaeological documentation and contributes to higher standards of precision, reproducibility, and interpretive reliability in heritage research and preservation activities.

4.2 Analysis of Artifacts from the Same Producer

The accumulation of digital measured drawings has opened new possibilities for analyzing artifacts produced by the same maker. Traditionally, identification of artifacts crafted by the same individual or workshop relied heavily on visual comparisons using photographs or frottage images. However, such methods are often limited by inconsistencies in photography angles, scaling errors, inaccuracies in rubbings, and surface contamination, leading to challenges in achieving reliable comparisons. Moreover, physical deformations caused by material shrinkage during the manufacturing or firing process further complicate direct visual comparison, introducing unintended variations that obscure true production characteristics. To overcome these limitations, this study applied a pattern recognition approach similar to methods used in fingerprint and facial recognition technologies. Figure 10 illustrates the similarity analysis of digital measured drawings, demonstrating how geometric patterns can be used to infer common production origins among artifacts.

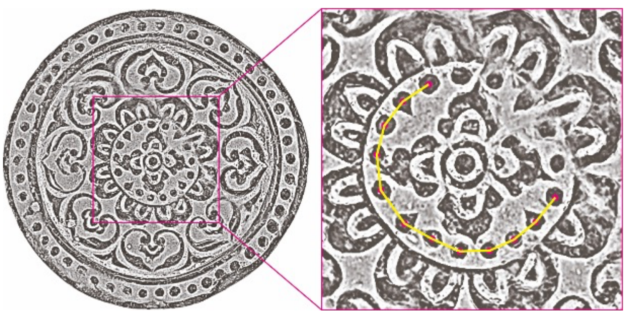

Figure 10. Similarity analysis of artifacts attributed to the same producer.

By leveraging large-scale accumulated 3D data, specific regions of the artifacts were quantitatively compared in terms of dimensional ratios and curvature patterns. Particularly for artifacts such as roof-end tiles, which were often mass-produced using molds, this method allows for the detection of highly similar patterns indicative of common production origins. The application of pattern-based comparative analysis provides a more objective, scalable, and precise framework for investigating production techniques, estimating provenance, and supporting typological and chronological studies in archaeology.

5. Conclusions

5.1 Summary and Implications

This study aimed to develop and apply a digital documentation technology for artifacts excavated from subsurface cultural heritage sites. Through the use of high-precision 3D scanning and AI-driven inference techniques, the documentation process was significantly improved, reducing the average time required per artifact from approximately three hours to about 23 minutes. In addition, the visualization outcomes achieved a quality level comparable to traditional frottage methods, thereby demonstrating the potential for substituting manual documentation processes. Analysis of the accumulated digital data revealed an average measurement deviation of approximately 1.4 centimeters compared to manual drawings. This deviation, while minor, highlights the degree of error inherent in conventional manual measurements and confirms the improved reliability and consistency achievable through digital methods. Moreover, the accumulation of high-quality digital measured drawings has opened pathways for expanded research, including the automated typological classification of artifacts and the identification of artifacts produced by the same maker. These findings underscore the broader potential of digital documentation technologies to transform archaeological research methodologies and support the preservation and interpretation of cultural heritage in more robust and scalable ways.

5.2 Limitations and Future Work

While the present study successfully demonstrated the efficiency and reliability of the proposed digital documentation approach, several limitations remain. As 3D scanning devices and software technologies continue to evolve, discrepancies between datasets produced by different generations of equipment may arise, potentially affecting the long-term consistency and comparability of accumulated data. To address this issue, future research should focus on the development of standardization protocols for 3D data acquisition and processing, ensuring interoperability across different scanning platforms and temporal datasets. Additionally, further studies are needed to refine automated comparative analysis techniques for artifacts from various production periods, enhancing the capability of digital documentation to support chronological classification and provenance studies. Through continuous advancement of data compatibility technologies and analytical methodologies, it is anticipated that digital measurement solutions will become an integral component of archaeological research, contributing to more accurate, scalable, and sustainable heritage documentation practices.

While the current system is optimized for rotationally symmetrical pottery types, its applicability to asymmetrical or fragmented artifacts remains limited. Future work should investigate methods such as adaptive mesh segmentation, local curvature field analysis, and region-based classification to extend the system's usability to a wider range of cultural heritage

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materials, including stone tools, architectural fragments, and hybrid-form objects.
Additionally, future research should explore the development of cross-institutional protocols and open standards to ensure interoperability among different scanning and documentation platforms. International collaboration will be essential in establishing a globally accepted framework for digital heritage documentation.

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