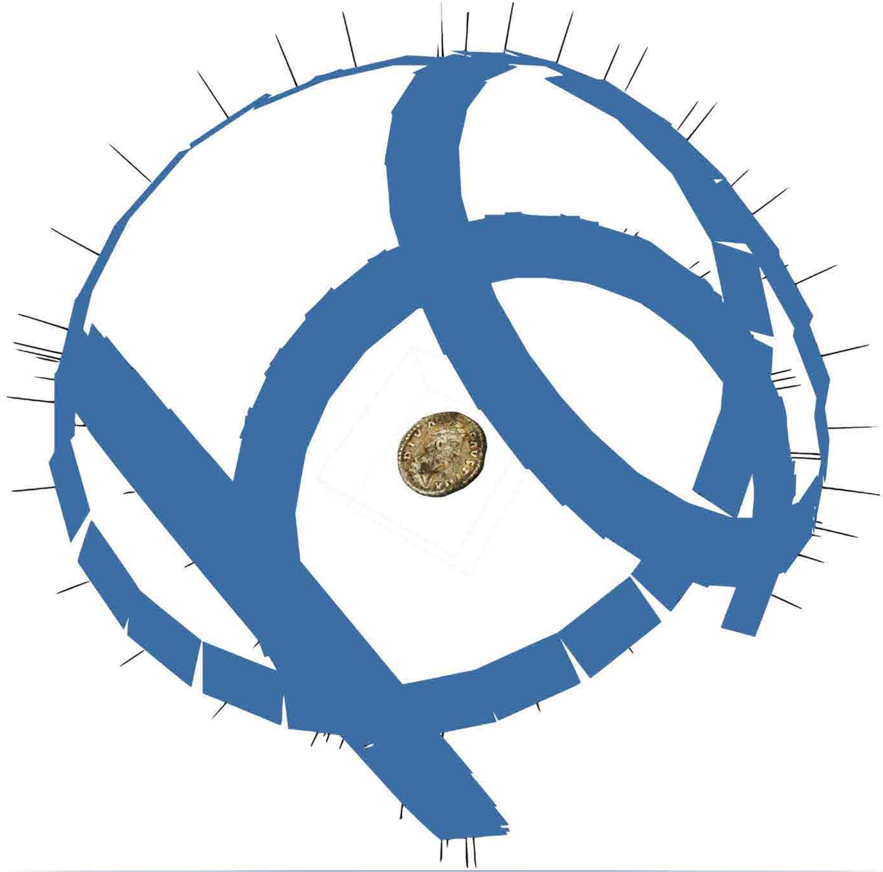

Collection Development, Cultural Heritage, and Digital Humanities

DIGITAL TECHNIQUES FOR DOCUMENTING AND PRESERVING CULTURAL HERITAGE

Edited by ANNA BENTKOWSKA-KAFEL and LINDSAY MacDONALD

ARC HUMANITIES PRESS

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DIGITAL TECHNIQUES FOR DOCUMENTING AND PRESERVING CULTURAL HERITAGE

COLLECTION DEVELOPMENT, CULTURAL HERITAGE, AND DIGITAL HUMANITIES

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Chapter 2

FROM A BURIED FRAGMENT TO THE VIRTUAL ARTEFACT: A CASE STUDY OF GREEK POTTERY

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NATASA MICHAILIDOU, and FOTIS ARNAOUTOGLOU

ABSTRACT

The fragmentary condition of objects is often an issue in the study of material cultural heritage. In archaeology, and in pottery studies in particular, the fragmentary condition of excavated objects impacts on research into their history and presentation. Ceramic vessels and vase fragments are the most numerous archaeological findings and a primary source of information about various aspects of ancient life: private, public, religious, economic and technological, social and artistic. The subject of this chapter is a fragmentary clay drinking cup, kantharos, a vessel attributed to the god Dionysus and a typical drinking vase used at symposia (gatherings). This particular kantharos was unearthed during the excavations at the ancient settlement of Therme, today's Karabournaki near Thessaloniki, Greece. The vase dates to the Archaic period between the seventh and the sixth century BC.

Although the kantharos is preserved to a large extent, its fragmentary condition challenges complete reconstruction. Evidence for reliable reconstruction is insufficient: the lower part that would originally have consisted of a base and foot, is missing. The process of virtual reconstruction through 3D visualization, described in this chapter, has contributed significantly to the study and presentation of the vase. The authors consider the advantages and limitations of technologies used. The process of creating this particular computer model may be applied to other fragmentary vases that come either from the excavation at Karabournaki or any other archaeological site or collection. This research may be of interest to experts in 3D technologies, as well as archaeologists and art historians, both academic scholars and students, museum curators and conservators, educators and other multidisciplinary audiences.

Keywords: Greek pottery, kantharoi, fragmented objects, archaeological excavation data, virtual reassembly, 3D approximation, visualization, COSCH

Introduction

The focus of this chapter is on how completion of pottery sherds through three-dimensional (3D) digital visualization contributes to archaeological research. Pottery is usually discovered in fragments and in vast numbers. Displayed in museums or deposited in storerooms, the clay sherds play an essential role in reconstructing the past. They are primary sources of information about various aspects of ancient life: private, public, and religious; economic and technological; social and artistic. They are, indirectly, also essential in archaeology for establishing the chronology of the finds under investigation (Biers 1992). For this reason pottery studies are a principal area of archaeological expertise (Orton and Hughes 2013).

It is commonplace, when unearthing pottery, to bring to light vases in a fragmented state. Problems and questions therefore arise as to the study, publication, and exhibition of pottery, especially in light of the vast quantities of excavated sherds (Sparkes 1996).

The application of 3D digitization methodologies to clay sherds can offer significant assistance in dealing with these matters, while the data produced are useful for enhancing archaeological research practice (Tsiafaki and Michailidou 2015; Koutsoudis et al. 2015; Koutsoudis et al. 2009). We discuss the challenges of pottery studies that require the collaboration of different disciplines, including 3D digitization, computer vision, pattern recognition, and computer graphics technologies. The chapter unfolds around a fragmented kantharos (drinking vessel) that has been unearthed in the ancient settlement of Therme, today's Karabournaki in northern Greece. Archaeological and museological questions articulated by scholars studying the vessel are presented and they guided all the stages of research, from the excavation of sherds, through their 3D digitization, to virtual reassembly and completion. The requirements of creating 3D computer models of sherds (in terms of materials, shape, hardware, software etc.) that are necessary for ensuring the adequate quality of data are also considered. To complete 3D digital replicas of the sherds targetless photogrammetric techniques, such as Structure from Motion and Multiple View Stereovision, were applied. The *London Charter for the Computer-based Visualisation of Cultural Heritage* (London Charter 2009) and the *International Principles of Virtual Archaeology* (Seville Principles 2011) were consulted for guidance.

Earlier Research

The application of 3D digitization technologies is considered a common practice in many areas of cultural heritage studies. In archaeology digitization is applied to big excavations and smaller projects (Remondino and Campana 2014). Both

Figure 2.1. Aerial view of the ancient site of Therme, today's Karabournaki near Thessaloniki, Greece. Photo: Karabournaki excavation photo archive, 1996.

archaeological research and its communication to the public are being enhanced by the data produced by such methodologies (Tsiafaki and Michailidou 2015).

For decades research efforts focused on establishing efficient and affordable methods for making 3D digital replicas. Some of these have been applied to pottery studies. The selection of a 3D digitization method depends on budget restrictions, the requirement of high-quality data in terms of geometrical and colour accuracy, as well as safe and efficient procedures of data collection (Breuckmann et al. 2013). Museums and archaeological organizations prioritized the creation of digital 3D repositories of their collections and thus databases with 3D content have become extremely popular. The 3D vase museum of the Perseus Digital Library is a relevant example (Shiaw et al. 2004). High-quality 3D digital replicas of vases enhance documentation (especially typology) and preservation procedures. They enable novel management methods and the remote study over the World Wide Web, simultaneously by a number of users. This is especially useful for studying sherds in storerooms. Restoration procedures, both virtual and actual (through 3D printing technologies) are assisted by the application of 3D shape processing and analysis. Digital 3D replicas play an important role in displays, as well as education and promotion, when used in a virtual museum or in a multimedia educational application.

Basic 3D technologies may generally support research into ancient pottery through:

- visualization of a vase, or fragment, by either range-based or image-based techniques (Willis 2011);
- estimation of a model's volumetric information (Mara and Portl 2012);
- digital reassembly of sherds (Tal 2014);
- an attempt to automatically classify vase types (Koutsoudis et al. 2010; Gregor et al. 2015);
- extraction of vase sections and drawings from 3D models (Hörr et al. 2011);
- digital restoration of fragmented or damaged vases (Hermon et al. 2012);
- use of the digital model in databases or virtual environments (Tucci et al. 2011).

Relevant applications of digital technology may range from image-based or range-based recording to virtual 3D modelling. A variety of hardware (less or more complex) and software (commercial or open source) may be used, ranging widely in cost. A 3D digital model may be produced in various formats and sizes, for a range of digital platforms, to be used by diverse users for different purposes.

Recent image-based methodologies offer the option of the digital 3D reconstruction of an object by narrowing the hardware requirements down to a digital camera and a computer system. The Structure from Motion combined with Multiple View Stereovision (SfM-MVS) has become an attractive and popular method. The literature confirms that the photogrammetry community considers this development as significant. SfM is defined as a pipeline of algorithms that are combined in order to create a 3D digital model of a static object, depicted in a set of unordered images, taken from different positions, scales and under varying illumination conditions. Researchers have assessed the quality of the SfM-MVS in relation to its cost, data collection procedures and quality, processing times, as well as human resources and specialist knowledge required. As with any other digitization method, SfM-MVS has its limitations. Nonetheless, a wide range of published results have proved that its applications to the cultural heritage domain are vital.

The authors discussed some aspects of the present study in a conference paper which appeared in the *Virtual Archaeology Review* (Tsiafaki et al. 2016).

COSCH Case Study of Greek Pottery: Description of work

Overview

The virtual reconstruction of the aforementioned kantharos was undertaken as one of the case studies conducted by the Colour and Space in Cultural Heritage (COSCH) network. A primary objective was the interdisciplinary approach to the study in order to contribute to a better interpretation and understanding of this cultural asset.

The Unearthed Fragments

The fragmentary kantharos (drinking cup) was unearthed during the excavations at the settlement of Karabournaki, seen in figure 2.1 (Tiverios et al. 2003a, 2003b). Its archaeological examination looked at (a) the shape of the vase and its typology; (b) the dimensions and state of preservation; (c) the dating of the vase; (d) the clay composition and the production techniques; (e) the decoration, painted or other; (f) the origin and attribution to a workshop; (g) the attributions to a potter and painter; (h) the original and subsequent uses, and (i) the location and context in which it was found.

These research questions are common to an archaeological study of any vase. From an archaeologist's point of view, pottery studies rely on frequent physical handling of the object (vase or sherds) which is necessary to study and fully document it through text, measurements, drawings, analytical results, etc. The sherds may be numerous, not adjacent, and cannot always provide sufficient information for a single and certain 2D reconstruction of the whole vase. Sherds are usually located in remote storerooms. From a museum professional's point of view, a vase or a sherd is one of the thousands found in museum storerooms. Pottery is documented, studied, conserved, and stored there. The conservator examines the museum piece, tries to prevent further damage, and occasionally restores the fragment (Georgaki 2012). If a pottery piece is chosen by curators for display in an exhibition, it means it contributes to the narrative of the show. Archaeological museums display coarseware and fineware, whole vases or sherds. The curators, like archaeologists, believe that pottery conveys important information about a culture of the past. They let the public, whether learned or lay, discover the object through its proper placement, explanatory texts, images, etc. Museum professionals, however, cannot be certain what the visitors, and particularly non-specialists, understand in the end (Einarsson 2014).

The clay fragments of the kantharos vessel (fig. 2.2) found at Karabournaki were studied in its archaeological context. The settlement was established in the late Bronze Age and was still active in the Roman times. Based on the archaeological data, the site flourished during the Geometric (ninth–eighth century BC) and, in particular, Archaic (seventh–sixth century BC) periods. A habitation area on top of a low mound, a cemetery at the foot of this mound, next to a harbour, are what remain of the ancient site (Tiverios et al. 2003a; Tsiafakis 2010). Its military significance and importance for trade was due to its location at the edge of a promontory in the centre of the Thermaic Gulf. The unearthed pottery and other findings came from well-known ancient workshops. This provides further evidence of the importance and far-reaching interaction of Therme (Tsiafakis 2010; Manakidou 2010).

Figure 2.2.
The fragmentary Karabournaki kantharos. Photo: Karabournaki excavation photo archive, 2010.

The vase dates to the Archaic period. It was found amongst the settlement's architectural remains. Kantharos was a popular shape in ancient Greece (Courbin 1953; Villard 1962; Kilinski 2005) especially in Macedonia and Thrace. However, this particular vessel appears to be unique in terms of its profile and its decoration. The primary characteristic of its decoration are four snakes, made from separate pieces of clay, added to the upper part of the vase. The snakes surround the body of the kantharos, with their heads facing the inside of the rim, as if they were about to drink from the vessel. Kantharos is known as a vase of the god Dionysus. It was a typical drinking vessel at symposia, or social gatherings with food and drink. However, this decoration suggests a ritual vase, leading to a hypothesis that might offer significant insights into life in the area. Although the vase presents some similarities to the G 2-3 ware (Ilieva 2013), it cannot satisfactorily be attributed to a particular workshop. Comprehensive findings of archaeological research into the vase will be a subject of an independent study.

From a museological point of view, the fragmentary condition of the vase is a major concern. From the collection management perspective and the responsibility for the preservation of objects for future generations, a fragmentary ceramic requires special care.

In order to fulfil its commitment to education, study, and enjoyment, the museum should present the kantharos alongside information that enables the public to understand its original form and use. Learning activities and interpretative displays of tentative reconstruction and plausible restoration (in 2D or 3D, or both) serve as a means to this end.

Creating the Virtual Artefact

Many original fragments of the Karabournaki kantharos have survived. The lower part is missing, which makes the virtual completion of the vessel particularly difficult. The digitization of the sherds in 3D, their virtual reassembly and the completion of missing parts were informed by archaeological evidence and museological practice. Various types of kantharoi were studied by comparison in order to understand the generic shape (Tiverios 1996). The archaeological reconstruction of the upper parts of the vase involved joining fragments. The archaeologists came up with a tentative initial shape.

The creation of the virtual artefact was carried out in two stages: the digitization of the sherds, and the virtual reassembly including 3D approximation of the missing parts. The data set acquired through digitization was used in the second stage. The use of the term "approximation" should be noted. It clarifies that the 3D reconstruction of the complete vessel is an attempt to approximate it. An accurate, full reconstruction is not possible without information about the missing parts.

3D Digitization of the Sherds

The SfM-MVS method was selected for the 3D digitization of the sherds as suitable for dealing with the colours and richness of features on the sherds' surfaces. The choice of this specific method was further justified by the efficiency of the data collection, in relation to the number of sherds, as well as the time restrictions of this project and the team's previous experience of SfM-MVS applications.

A commercial implementation of the SfM-MVS was selected. Agisoft's PhotoScan Professional has been used by the same research team on various digitization experiments that indicated that the tool can be used for photogrammetry projects (Koutsoudis et al. 2015; Koutsoudis et al. 2014; Koutsoudis et al. 2013). For the data collection phase, a pair of mirrorless DSLR cameras (Samsung NX1000) equipped with CMOS sensor (size: 23.5 × 15.7mm, effective resolution: 20.3 megapixels out of 21.6 mega-pixels, pixel pitch: 4.26 μm) were used. The lenses used were 20–50 mm along with 40.5 mm circular polarizing filters. A set of two Elinchrom Mini A studio lights (5500° K), with hooded diffuser softboxes that control light scatter and prevent lens flare, were also used. In order to minimize time and speed up automation of data collection, a computer controlled turntable (Kaidan Magellan Desktop Turntable MDT-19) and a relay-based USB controller for triggering the cameras from distance were used. The cameras were fixed on tripods. An in-house-developed software tool controlled both the turntable's rotation step and the cameras' triggering. This approach allowed the automated generation of closed-loop image sequences and at the same time eliminated any image blurring. The aperture, exposure, white balance, etc., on both cameras, were set manually in

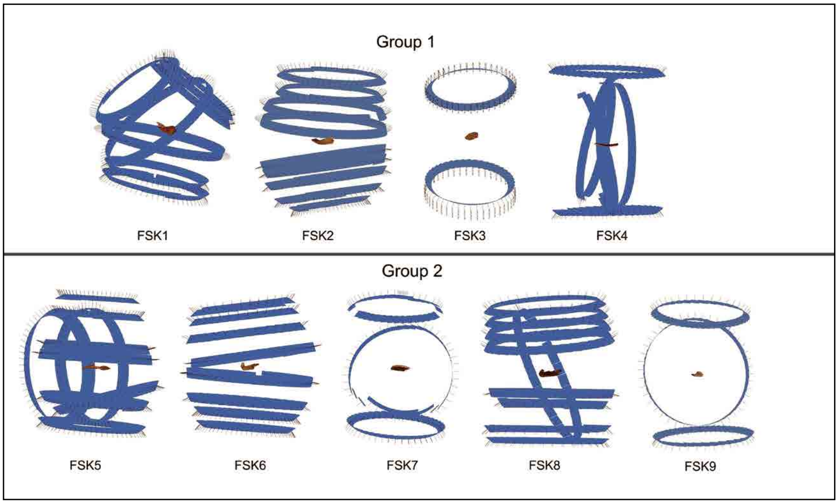

Figure 2.3. Viewpoint spatial distribution of sherds during photoshooting. © Athena Research Center, Xanthi, 2016.

order to achieve the deepest possible focused field-of-view and a uniform colour sampling for all images. More specifically, white balance was performed manually using ImageWare's colour scanner test target (S2N CSTT-1a) and it was kept constant throughout the data collection phase. However, colour variations (in the visible spectrum) between the fragments are still visible due to variable forms of erosion. An average colour value variance of 5.04% (three primary colour coefficients Red 4.47%, Green 5.65%, Blue 5.01%) was observed between the actual images and the texture maps that measure a total of 76,303 unique colours. These values were calculated on each one of the sherds by averaging the values in areas of 5 × 5 pixels and then compared with similar areas on the actual images.

This semi-automated data collection approach minimized the times a sherd had to be handled. Nevertheless, the repositioning of the digitization equipment for almost every sherd was unavoidable as a similar 3D reconstruction quality was required, in terms of point cloud density and ground sampling distance. The sherds were organized into two groups, based on information provided by the archaeologists. Group 1 consisted of four sherds (FSK1–FSK4) while Group 2 was composed of five (FSK5–FSK9). The grouping was based on the sherds' connectivity. It should be noted that some of the larger sherds (e.g., FSK1, FSK2, and FSK5) were composed of smaller ones that had already been glued together by the conservators and scanned as a single piece.

Figure 2.3 shows the viewpoints in spatial distribution, used to capture each sherd. The number of image sequences corresponds to the geometrical-morpho-

Figure 2.4. Visualization of 3D digital replicas of sherds using Vertex Paint and Smooth Normal Shading visualization approaches. © Athena Research Center, Xanthi, 2016.

logical complexity and size of each sherd. Thus, the more complex the sherd, the more images were required for its complete digitization. A large number of image sequences guaranteed that a 3D reconstruction was solved by the software combining all images into a single network. It is important to avoid partial-scan alignment procedures as they are based on error-minimizing approaches and reduce the geometrical accuracy of the digital replica.

Nine sherds of varying dimensions were reconstructed (fig. 2.4) from 3571 images. Such a number might be considered large. Given the fact that access to the sherds was limited and an accurate 3D reconstruction without partial scan alignment was a prerequisite, this number of images should be considered valid. Detailed information about each digital replica can be found in Table 2.1. The average ground sample distance was 36.73 μm. This level of accuracy is normally required for professional recording of material cultural heritage. For this project, such a resolution might be excessive. Given the fact that the digitization team had one-time access to the sherds, a high resolution was considered best practice. A fixed pixel size (equal distance between the cameras' sensors and the surface of the object) was impossible to achieve. This is depicted as a variance in ground sampling distances (GSDs) and in the average distance between consecutive vertices (considered as high accuracy) of the digital replicas' 3D point cloud (Table 2.1). It should be noted that the total number of images being used (2851) was lower than the total number of images that have been captured (3571). The complete 3D reconstruction of the sherds would have been possible with fewer images. However, as mentioned, access to the sherds was restricted and thus the digitization team worked in a way that enough data were collected and hence additional image sequences were captured.

Virtual Reassembly and 3D Approximation of Missing Parts

A manually implemented pipeline was followed to perform the sherds' virtual reassembly and an approximation of the vessel's missing parts. The pipeline involved the following steps: (1) axis of symmetry detection, (2) spatial distribution and alignment of the two sherds groups based on the axis of symmetry, (3) missing parts generation by using the available data and 3D mesh processing techniques (lathe, 3D mesh Boolean operations and mirroring, etc.), (4) realistic visualization of the vessel using synthetic material (clay) for the approximated parts. The latter were implemented using Matlab and Blender software tools.

The largest sherds were considered best suited for shape analysis and information extraction. The detection of the axis of symmetry was a prerequisite for aligning the scattered sherds within 3D space and an important parameter for the approximation of the missing parts. Using Blender, several *plane-to-3D mesh* intersections were computed. The horizontal and vertical intersections were calculated on the least damaged areas of the selected sherds (FSK2, FSK5) in an attempt to extract the most accurate data. The resulting point sets lay on horizontal and vertical planes and describe different parts of the sherds' profile (fig. 2.5). The point

Table 2.1. Data collection details of each 3D digital replica sherd.

Sherd name	Number of images used for the 3D reconstruction	Ground sample distance (μm)	Number of image closed loops	Number of vertices	Average distance between two consecutive vertices
GROUP 1 – FSK 1	437	47.16	7	5,956,000	~110 μm
GROUP 1 – FSK 2	547	48.54	9	7,827,421	~82 μm
GROUP 1 – FSK 3	94	32.84	2	1,716,631	~55 μm
GROUP 1 – FSK 4	209	31.34	4	2,204,425	~50 μm
GROUP 2 – FSK 5	526	39.92	9	6,908,370	~80 μm
GROUP 2 – FSK 6	414	27.28	8	3,996,016	~48 μm
GROUP 2 – FSK 7	150	30.38	3	3,220,855	~61 μm
GROUP 2 – FSK 8	333	36.16	9	5,335,942	~70 μm
GROUP 2 – FSK 9	141	37.02	3	2,401,313	~57 μm
Totals / Averages	**2,851 / –**	**– / 36.73μm**	**– / 6**	**39,566,973 / –**	**– / 68 μm**

sets coordinates of the horizontal intersections were processed in Matlab and by using the best-circle fit function a range of circle equations were identified. These equations define the averaged interior and exterior boundaries of the vessel's main body. Additionally, the projections of the normal vectors of the facets that belong to the horizontal intersections were used to identify the axis of symmetry. The detection of a mathematically expressed unique axis was impossible. This was due to the fact that a vessel made by a human hand, although on the potter's wheel, could

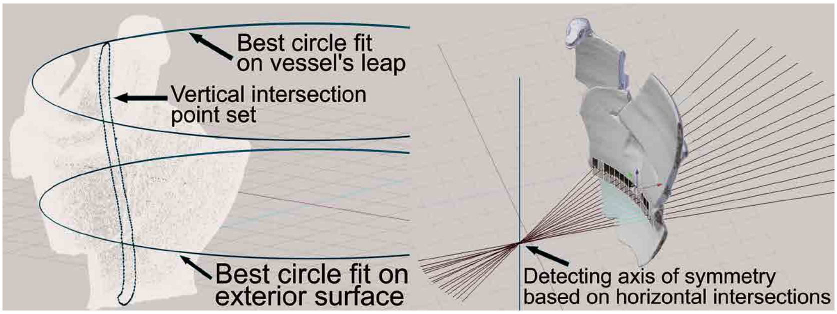

Figure 2.5. Extracting profile data using horizontal and vertical intersections of a sherd. © Athena Research Center, Xanthi, 2016.

not be symmetrically perfect. Furthermore, this was also an indication that sherds have been abstractly deformed through the centuries. Nevertheless, the averaged normal vectors intersection point's coordinates of the facets were calculated in Matlab and used to detect an optimum axis of symmetry (fig. 2.5).

The axis of symmetry was then used to position and align the sherds in 3D space. The connectivity between the different sherds of each group was provided by the archaeologists and performed within Blender. Colour information from the sherds' surface and various 3D modelling tools provided by Blender proved to be very useful for the manual alignment of the sherds. More specifically, the vertex-based snapping tool provided a means of detecting collision between the 3D digital replicas. It should be noted that when aligning partial scans with overlapping areas there are algorithms (e.g., ICP) that take under consideration both surface and colour information. In this case, this was not applicable as there were no overlapping parts between the sherds. The digitization team used the colour

Figure 2.6. The nine sherds aligned and organized into two groups. Spatial distribution of Group 1 sherds (left) and Group 2 sherds (right). Colour encoding indicates a different sherd. © Athena Research Center, Xanthi, 2016.

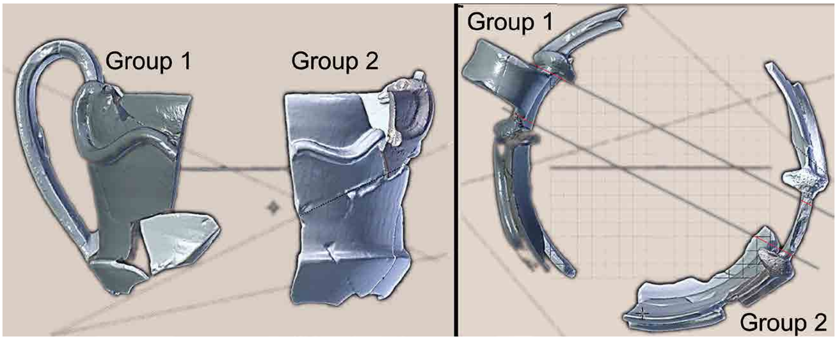

Figure 2.7. Spatial alignment of the two groups of sherds. Positioning of the two groups around the axis of symmetry (left). Position refinement using handle positions as reference (right). © Athena Research Center, Xanthi, 2016.

and decoration information provided for reference only. Blender software does not provide computer supported alignment mechanisms of partial scans. Once the two groups were completed (fig. 2.6) they were positioned into 3D space according to the interior and exterior limits introduced by the previously computed interior and exterior boundaries. They were then rotated around the axis of symmetry in order to be placed one opposite the other (fig. 2.7). This was based on the assumed symmetric positioning of the handles. Again, the alignment was performed manually within Blender. The process required an experienced user

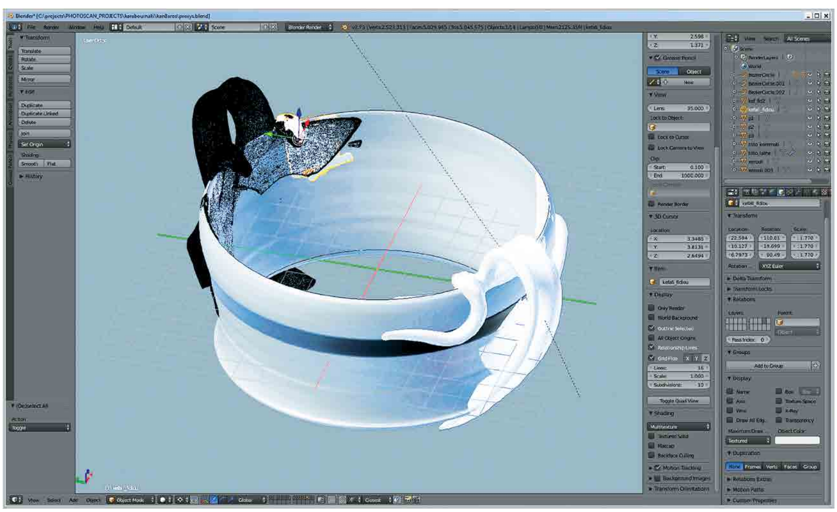

Figure 2.8. Using lathe to create an approximation of the vessel's main body. © Athena Research Center, Xanthi, 2016.

Figure 2.9. Visualization of the approximated body, with and without the sherds digitized in 3D, after applying the Boolean 3D mesh operations. © Athena Research Center, Xanthi, 2016.

Figure 2.10. Different viewpoint renderings of the virtually reconstructed kantharos. © Athena Research Center, Xanthi, 2016.

with a good understanding of a range of operations related to 3D rotation around a given centre of rotation and translation.

The 3D lathe technique was used to create the vessel's main body (fig. 2.8). The vase's body was composed by rotated instances of the vertical intersection point set in a 3D Cartesian coordinate system. As the 2D point set is rotated about a coplanar axis, an azimuthal symmetry is achieved. A vertical intersection point set representing the maximum available profile, was used to form the approximated body. The complete profile of the vessel could not be extracted from the available sherds. The vessel's base was missing and thus its approximation was based on design principles found in the literature. The archaeologists' contribution was of great importance for agreeing on a highly plausible base. Moreover and in order to provide a complete virtual vase, we performed the duplication and mirroring of the existing handle in order to produce the missing one (fig. 2.9).

Furthermore, a number of 3D mesh Boolean operations were performed between the synthetically reconstructed body and the digitized sherds. This resulted in a 3D mesh-based approximated representation of the vessel's missing parts (fig. 2.9). The final step was the generation of photorealistic visualizations of the vessel. Digital clay material was selected because it provided clean visual lines between the digitized and synthetic parts of the kantharos (fig. 2.10). The 3D technology was therefore used here in order to contribute to the pottery study, along with a desire to comply with the London Charter and the Seville Principles of visual transparency in historic visualization.

Critical Discussion and Evaluation of the Research

The choices made helped to achieve the principal aims, namely to assist with the archaeological study of the vessel, as well as to provide means for the communication of a fragmented vase to the general public.

Most importantly, both the expert pottery excavator and the 3D technology expert played leading roles within the 3D digitization and reconstruction team. They ensured that all the available research sources (pottery and archaeological data) and the latest advances in 3D technologies and techniques were taken into consideration.

The documentation of the case study, at all its stages, was thorough enough to clearly convey to all potential users its aims, methodology, and output. The commitment to include this work in the forthcoming website, newly designed for the Karabournaki excavation, will ensure the sustainable dissemination of information, including all the parameters of the 3D digitization and reconstruction of the kantharos, to the public.

Digital preservation of the computer-based visualization data has been secured through rigorous digital archiving. A 3D model of the reconstructed vase will be printed, in order to create a physical 3D record of the work. Archaeological work may be aided by placing the extant fragments on top of the reconstruction. The excavators, working in academic and research institutions, will disseminate the work and its outputs in presentations and educational sessions.

Following the completion of the work an evaluation took place to examine the approach adopted for the study and its results. A group of COSCH members, among others, viewed and examined the 3D model. They were primarily archaeologists, museologists, and technology experts. They were already familiar with the study and had been kept informed on its progress through presentations given at COSCH meetings. All of them were present at the final presentation of the case study, raised various issues, and asked relevant questions. Their comments were recorded in a structured questionnaire consisting of six closed questions concerning (1) the adopted methodology, (2) the study's outputs, (3) the digitization approach, (4) the procedures followed, (5) the contribution to archaeology and museology, and (6) the communication of the vase to the public. At the end, any additional comment was recorded in an open-ended question.

The evaluation offered ideas regarding the 3D model and its use within the archaeological and museological fields, for both expert researchers and the general public. The appropriateness of the methodology undertaken and the relevance to the stakeholders' requirements was highlighted by all participants. They judged that the 3D model offered a significant improvement on the traditional graphic archaeological documentation system, since it provides high image quality and a digital copy of the vessel in real dimensions. It was noted that the model strongly contributes to the digital preservation of the material characteristics of the vase and is especially useful in the field of digital visualization.

The need for 3D models to become even more effective research tools was also stressed. This work on a unique type of vase—fragmentary and with specific features—was considered a base for further research. For example, the use of automatic methods could be considered in collaboration with other relevant projects. Manual processing should be avoided, as much as possible, to reduce the time and cost of such work. Automation could be applied to the reconstruction and creation of sections and other views of the vessel. Generally, the need to study the feasibility of the whole process, from a material and financial point of view, was underlined.

All the evaluators considered the 3D computer model a surrogate for the real artefact, that is, an authentic find that should be promoted alongside the archaeological knowledge that it represents. This knowledge could be better communicated through the addition of digital storytelling (Roussou et al. 2015).

From an aesthetic as well as technical points of view, the reconstruction of the original colours of the vase would help to create a visually more attractive 3D model. The application of SfM-MVS to 3D digitization proved adequate for the generation of high-quality 3D data. The semi-automated procedure enabled the generation of 3D digital replicas without the need to apply partial scan alignment procedures. The digitized sherds were aligned into groups with the help of 3D modelling tools available in Blender. The vertex-based mesh snapping is such an example. The produced virtual reconstruction is visually adequate but the exploitation of an algorithm that is able to quantify the matching error between two surfaces could be used along with the snapping tool, in order to achieve a more objective alignment of the sherds. From a more practical point of view, such accuracy would be more important for cases where matching surfaces are not degraded to such an extent or when the available sherds represent a larger proportion of the original object.

Future Research and Conclusion

The study of this unique vessel is of great importance to archaeologists. Its fragmentary condition set limitations to 3D reconstruction. Although an experienced archaeologist and a pottery specialist can recognize, classify, and date the pieces with ease, this is not always possible for less experienced researchers and the general public. Neither archaeologists nor the general public can have a complete picture of the kantharos in question, but its 3D model can assist in dealing with the research needs of both archaeology and museology. A 3D computer model can be made accessible whenever wanted, from everywhere, to be looked at from every side and as close as needed. The accurate 3D visualization can be used to study the shape and decoration of the vase. The model can provide a better sense of the vase than the 2D photos of individual sherds; while different versions of the 3D reconstruction model can assist with the restoration of the object without disturbing the fragments. The 3D model can be used in teaching about pottery, rituals, and in other courses. The excavation at Karabournaki is led by academics who are likely to benefit from this resource. A low-resolution model will be made available in the digital collection on the Karabournaki website for education.

A high-quality 3D model can be used in conservation to monitor the condition of the actual vessel, to assess any possible changes, and assist in taking decisions concerning its preservation. The model and the hypothetical reconstruction can be used by a museum for remote study, in virtual exhibitions (and also at their planning stages). It can be displayed next to the real artefact in an actual exhibition space, to allow the public to get a better sense of the ancient vase. To increase the realism, texture mapping can be applied to the approximated parts of the vessels, using the available sherds as the primary source of the colour information. It will take time for the actual vase to be thoroughly studied and exhibited. While it is kept in a storeroom, awaiting its full archaeological publication, this virtual demonstration may be very important. In an actual future exhibition space a 3D-printed base may be used to hold the actual sherds. Thus, the 3D model, digital or printed, will contribute to the enhancement of archaeological research and knowledge.