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VIRTUAL REASSEMBLY AND COMPLETION OF A FRAGMENTARY DRINKING VESSEL

EL REENSAMBLAJE Y LA REPOSICIÓN VIRTUAL DE UN RECIPIENTE DE BEBER FRAGMENTADO

Despoina Tsiafaki*, Anestis Koutsoudis, Fotis Arnaoutoglou, Natasa Michailidou

"Athena" Research and Innovation Centre, Xanthi's Division, PO BOX 159, Xanthi 67100, Greece. tsiafaki@ceti.gr; akoutsou@ceti.gr; fotarny@ceti.gr; amixaili@ceti.gr

Abstract:

A key issue in the study of cultural assets is their often fragmentary condition. This causes serious problems and questions regarding their study and presentation. Pottery fragments are the most numerous findings in every excavation. Furthermore, pottery plays an essential role for the reconstruction of the past, since it provides information for all aspects of life (private, public, religion, death, economy, society, trade, etc.). Therefore, a thorough study and presentation of pottery fragments contribute to a better knowledge of the past. The focus of this work is the visualisation of an ancient Greek drinking vase, a kantharos, which was unearthed during the excavations at the settlement of Karabournaki (ancient Therme) in the area of Thessaloniki (Greece). It dates to the Archaic period (7^{th}-6^{th} c. B.C.) and it was found in fragments among the settlement's architectural remains. The vase is of great archaeological significance due to its peculiarities in terms of shape, decoration and function. Therefore, its digital completion and 3D reconstruction will contribute to its better study and scholarly publication along with a general contribution to the field of pottery studies. We discuss on the 3D digitisation of the kantharos fragments that were based on Structure from Motion/Multiple View Stereovision (SfM/MVS) and a custom automated data collection system. A detailed description of the digitisation pipeline is given along with details related to the quality of the 3D digital replicas of the sherds. Furthermore, we present our manual virtual reassembly and reconstruction pipeline of the kantharos by describing the challenges, issues and ambiguities discovered while analysing the geometrical features of each sherd. A number of photorealistic reconstruction visualisations of the artefact are presented in order to question the applicability of the solution for the actual reconstruction.

Key words: pottery, cultural heritage, digital archaeology, 3D documentation, virtual archaeology, 3D reconstruction

Resumen:

Una cuestión clave en el estudio de los bienes culturales es su condición a menudo fragmentaria. Esta causa problemas y serias dudas en cuanto a su estudio y presentación. Los fragmentos de cerámica son los hallazgos más frecuentes en una excavación. Además, la cerámica juega un papel esencial para la reconstrucción del pasado, ya que proporciona información acerca de todos los aspectos de la vida (privada, pública, la religión, la muerte, la economía, la sociedad, el comercio, etc.). Por lo tanto, un estudio a fondo y la presentación de los fragmentos de cerámica pueden conducir a un mejor conocimiento del pasado. El objetivo de este trabajo es la visualización de un recipiente griego para beber, un Kantharo (recipiente para bebidas) descubierto en las excavaciones del asentamiento de Karabournaki (antigua Therme) en la zona de Tesalónica (Grecia). El vaso se fecha en el periodo arcaico (VII-VI a.C.) y sus fragmentos se encontraron entre los restos arquitectónicos del asentamiento. El recipiente es de gran importancia arqueológica debido a sus peculiaridades en cuanto a la forma, la decoración y su función. Por lo tanto, su acabado digital y la reconstrucción 3D contribuirán a su mejor estudio y a la publicación además de una aportación genérica en el campo de los estudios de cerámica. Se discute sobre la digitalización en 3D de los fragmentos del kantharos, que está basado en Structure from Motion/Multiple View Stereovision (SfM/MVS) y un sistema automatizado de recogida de datos a medida. Se ofrece una descripción detallada del proceso de digitalización junto con los detalles relacionados con la calidad de las réplicas digitales en 3D de los pedazos. Además, presentamos nuestro manual de reensamblaje virtual y el proceso de reconstrucción virtual del kantharos, mediante la descripción de los desafíos, de los problemas y de las ambigüedades descubiertas durante el análisis de las características geométricas de cada fragmento. Se presentan visualizaciones fotorrealistas de la reconstrucción del artefacto con el fin de cuestionar la aplicabilidad de la solución a la reconstrucción real.

Palabras clave: cerámica, patrimonio cultural, arqueología digital, documentación 3D, arqueología virtual, reconstrucción 3D

*Corresponding Author: Despoina Tsiafaki, tsiafaki@ipet.gr
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1. Introduction

The fragmentary nature of archaeological finds is a commonplace for archaeologists. The interpretation of these broken and decayed objects and the consequent desired reconstruction of the past are based on the archaeological methodology along with various interdisciplinary tools, some more traditional and some other more advanced technologically (Ercek, Viviers & Warzée, 2010; Maqueda García-Morales, Luque Cortina, Andreu Pintado & Romero Novella, 2015).

This is also the case for pottery discovered in excavations. The partially preserved vases are the most numerous findings in the field and the most numerous items in any archaeological storeroom. Moreover, the clay sherds hold valuable multifarious information for various aspects of ancient life (private, public, religion, death, economy, society, trade, etc.). This is the reason why pottery studies are a principal area of archaeological expertise (Buko, 2008; Orton & Hughes, 2013).

Certain problems or limitations existing in traditional research and presentation methods in pottery and in archaeology in general seem to find ways to be overcome nowadays with the Information and Communications Technologies (ICT) (Tsiafaki & Michailidou, 2015; Tsiafaki, 2012). Modern ICT and especially 3D technologies offer new tools to archaeologists in order to study, interpret and present the human past (and more specifically pottery) to the public in a more complete way than the traditional methods (Dell'Unto, 2014). The 3D recording, visualisation, representation and reconstruction of ancient vases are among these technological trends that have proven to be applicable to archaeology and aim to bring science within this study area (Melero, León & Torres, 2010; Mara & Portl, 2012; Breuckmann, Karl & Trinkl, 2013; Serrano Arnáez, Fernández García & Esquivel Guerrero, 2013).

Recent advances in automated photogrammetric 3D reconstruction methods combined with the continuous evolution of hardware capabilities resulted in a vast increase in the number of applications that are based on 3D digital replicas of artefacts and address specific needs of cultural heritage practitioners such as archaeologists, restorers, museum curators, etc.

Some of the primary research areas in which 3D digital replicas of artefacts play an important role are the virtual restoration, reassembly and completion. There is a wide range of literature focused on algorithms that allow the automated or semi-automated reassembly of sherds that belong to one or more vases. Nonetheless, the reassembly problem is still open and it is considered an active research area (Stamatopoulos & Anagnostopoulos, 2016; Pintus et al., 2015; Rasheed & Nordin, 2015; Willis & Cooper, 2008).

The subject of this paper is an ancient clay vase that was unearthed in fragments (Tiverios, Manakidou & Tsiafakis, 2003a). The archaeologists recognised the shape (kantharos) and reassembled the fragments into their right positions. However, significant parts of the vase, such as the lower part of the vase and its base, were missing. Therefore, the contribution of the 3D technologies was asked in order to proceed with a virtual reconstruction (missing parts geometrical approximation) of the vase and get an aspect of what it had looked like when it was complete.

The virtual reconstruction of the Karabournaki Kantharos took place within the framework of the COST-Action TD 1201 COSCH (Colour and Space in Cultural Heritage) as one of the project's case studies (http://cosch.info/case-studies). The primary scope was the interdisciplinary approach in the study of this cultural asset in order to enhance the cultural knowledge and to contribute to a better interpretation and understanding.

The rest of the paper is organised as follows: In Section 2, we give an archaeological overview of the vase with the primary archaeological and museological research questions. In Section 3 we discuss on the 3D digitisation procedures that resulted in the digital replicas of the vase's sherds and we describe the manual pipeline followed to achieve the virtual reassembly and completion of the vase. In Section 4, we present the evaluation results of the 3D reconstruction process. We conclude, in Section 5, by providing some possible future applications related to the kantharos and its digital representation.

2. The archaeological overview

A fragmentary kantharos (drinking cup) was unearthed during the excavations at the settlement of Karabournaki (ancient Therme) in the area of Thessaloniki, Greece (Tiverios et al., 2003a) (Fig. 1).

Figure 1: Aerial view of the ancient site at Karabournaki, Thessaloniki (Greece).

The site preserves the remains of an ancient settlement placed on the top of a low mound, with its cemeteries at the bottom of the hill and a harbour just next to it (Tiverios, Manakidou & Tsiafakis, 2003b; Tsiafakis, 2010). The site dates from the late Bronze Age down to the Roman times, with its peak to be in Geometric (9^{th}-8^{th} c. B.C.) and particular in Archaic period (7^{th}-6^{th} c. B.C.). Its location at the edge of a promontory in the centre of the Thermaic Gulf makes it very important for trade and military reasons. It is not a coincidence that imports from all over Aegean are unearthed throughout the entire settlement (Fig. 2). Pottery findings are the most common among them and they come from all the most important and known pottery workshops of antiquity (Tsiafakis, 2010; Manakidou, 2010).

Figure 2: The excavation of the ancient settlement at Karabournaki.

The vase (Fig. 3) dates to the Archaic period (7th-6th c. B.C.) and it was found among the settlement's architectural remains. Although the kantharos shape is widespread in ancient Greece (Courbin, 1953; Villard, 1962; Kilinski, 2005) and in particular in the region of ancient Macedonia and Thrace, the specific example is unique in terms of its decoration and for not fitting sufficiently into a particular workshop so far, even though it presents similarities with the category of pottery known as G 2-3 ware (Ilieva, 2013). In the forthcoming scholarly archaeological publication of the vase, there will be all the information related to it.

There are also archaeological issues with its profile that does not follow the typical known examples of its time. Regarding the decoration, it has four (4) added snakes (made by separate pieces of clay) on the upper part of the vase's body. The snakes surround all the body of the kantharos with their heads being inside its rim, as if they are about to drink the liquid inside the vessel. Kantharos is the vase of the god Dionysus and a typical drinking vessel for symposia (social gatherings with food and drink). This decoration points to a ritual vase, however, that might be able to contribute a lot to the knowledge and reconstruction of the life in this area. Its fragmentary condition (although preserved in a large extent) was challenging in its completion and in particular for its lower part (base and foot).

Figure 3: The fragmentary kantharos from Karabournaki.

2.1. Archaeological and museological research questions and needs

The archaeological study of any vase, complete or fragmentary, regards as a rule the following: a) the shape of the vase and its typology; b) its dimensions and condition of preservation; c) the clay composition and the construction techniques; d) its decoration, painted or other; e) the attribution to a potter and painter; f) the original and subsequent uses; g) the location and context in which it was found; h) the dating of the vase; and i) the origin and its attribution to a workshop.

Traditional pottery studies rely to frequent physical handling of the (vase or) sherds in order for the archaeologist to completely document and study them. Moreover, the sherds can be numerous, not adjacent and cannot always provide enough information for one and only secure 2D reconstruction of the whole vase. Last but not least, they are usually located in remote storerooms.

From a museological point of view, a ceramic sherd is again one of the thousands located in museum storerooms. Pottery there is documented, studied, conserved and stored. If it is chosen by curators to be exhibited in a showcase, it means it contributes to the exhibition's narrative (Lord & Piacente, 2014). Archaeological museums especially display coarseware and fineware, whole vases or sherds, usually in large amounts. The curators, as archaeologists, believe that pottery conveys important information about any culture in the past and care to let the public (specialised or not) discover it through proper placement, explanatory texts, relevant images, videos, etc. Museum professionals, though, cannot be fully aware of what the visitors and particularly non-specialists understand at the end (Einarsson, 2014).

Taken into account the way that archaeology and museology work with pottery, we wanted to understand how a 3D model would contribute to these efforts (Bruno et al., 2010) and specifically to the work with the kantharos in the Karabournaki excavation.

On the one hand, our needs and the research questions that our work with the 3D technologies hoped to answer for the archaeological study of the vase related to the aforementioned restrictions of traditional pottery studies. Could a 3D model of this unique fragmentary vase help advance the archaeological study, the handling and documentation of the kantharos? Could the 3D reconstruction offer tentative reconstructions of the vase in its complete form in order to choose the best version of the original kantharos? How would this reconstruction help the archaeological study of the vase, and improved understanding of its initial shape and a better interpretation of its function, too? Moreover, the use of the 3D model and reconstruction for teaching purposes is of vital importance to us, since Karabournaki is a university-led excavation in which many students participate. The demonstration of the model either onsite or online in the excavation's Website, which is being redesigned (Karabournaki, 2016), would contribute to our academic needs.

On the other hand, within the context of museology and the purpose of museums ("Education, study and enjoyment", ICOM, 2016) how would both the curators and the visitors (i.e. of a web exhibition of the Karabournaki pottery) use and benefit from a 3D model and reconstruction of the fragmentary kantharos? Our research would need to cover the main areas of museum studies that are management and preservation of collections for future generations, interpretation and presentation to the public through exhibitions and various education activities with the use of ICT (Tucci, Cini & Nobile, 2011). To what extent would the 3D model overcome limitations in the understanding of the vase by the public due to its fragmentary status? How would it contribute to the comprehension by non-specialists of the kantharos' original shape and function?

And more importantly, in terms of both archaeology and museology what drawbacks would there be regarding the 3D digitisation and reconstruction of the kantharos and how could they be limited? For example, data accuracy and image quality were areas of interest very important to the archaeologists' team, since there is the essential need to be able to work on an average computer, with basic computer skills, with a high resolution model, virtually handle it and extract information that one would extract having the real artefact in hand.

3. 3D digitisation and virtual reassembly

Taken under consideration the archaeological information in combination with the archaeological and museological research questions and perspectives, we proceeded with the 3D digitisation of the kantharos sherds and its virtual reassembly and missing parts completion. Various examples of different types of kantharos were used in order to understand the general shape (BAPD, 2014; Tiverios, 1996). Moreover an archaeological reconstruction of the vase took place, by putting together the joining fragments and providing its tentative shape with the exception of the lower part and the base, which are completely missing.

The technique and methodology chosen were adopted for this case study among others (laser scanning, photogrammetry, other techniques using digital photography) due to previous related work as well as the limited time and budget we had.

3.1. Data collection phase

In order to create the 3D digital replicas of the kantharos' sherds, we have used the SfM/MVS approach. A commercial implementation of the algorithm (AgisoftPhotoscan Professional) was selected, based on the results of previous published works that involved the extensive evaluation of the produced 3D data (Koutsoudis, Ioannakis, Vidmar, Arnaoutoglou & Chamzas, 2015; Koutsoudis, Vidmar & Arnaoutoglou, 2013; Koutsoudis et al., 2013).

The data collection phase involved the use of a high accuracy turntable controlled by a computer (Kaidan Magellan Desktop Turntable MDT-19) and a pair of mirrorless DSLR cameras (Samsung NX1000) with 20-50 mm lens along with 40.5 mm circular polarising filters. The camera's sensor size was 23.5 x 15.7 mm with a 4.26 μm pixel pitch and resolution of 21.6 MP. For the automation of each sherd's photoshooting, we implemented a software tool that is able to control the turntable using the EMCee protocol while triggering the digital cameras through a relay-based USB controller.

Such an approach reduced dramatically the duration of the data collection phase and at the same time played an important role in minimising the total number of times the sherds had to be touched by the digitization team. It should be noted that some of the large sherds were composed by smaller parts, which had already being glued together by the conservators. These had been scanned as a single sherd.

For the accurate scaling of the 3D digital replicas, we used the encoded photogrammetric targets offered by Photoscan. They were placed around each sherd during the data acquisition phase and distances between their centres were measured. It should be noted that the software detects targets automatically, while the real world dimensions are used within the 3D reconstruction algorithm.

Furthermore, a number of support materials were used to ensure sherds' stable positioning on the turntable. Despite the automation, capturing all sherds' concavities was a challenging procedure. Multiple image sequences depicting each sherd from different viewpoints were captured, in order to ensure that a single image network can be produced under a single bundle adjustment and thus provide the base of a complete 3D reconstruction of each sherd without the need of aligning partial scans. A total of 2851 images were used for the 3D reconstruction of nine different sherds (Fig. 4). The average ground sample distance was 36.73 μm, resulting that 1cm in the real world was represented by 544 pixels.

The repositioning of the digitisation equipment for almost each of the sherds was necessary in order to provide a similar 3D reconstruction data quality. A fixed pixel size (equal distance from the camera's sensors) for all sherds was not possible and thus the existence of a variance in GSD and in the average distance between consecutive vertices (Table 1). The different number of image sequences (closed loops) shown in Table 1 depicts the variable morphological complexity of each one of the sherds.

Table 1: Details for each of the sherds digital replica data.

Sherd Name	*No. of images used*	*GSD (μm)*	*No. of image closed loops*	*No. of vertices in millions*	*Average distance between conse-cutive vertices (μm)*
FSK 1	437	47.16	7	5.95	110
FSK 2	547	48.54	9	7.82	82
FSK 3	94	32.84	2	1.71	55
FSK 4	209	31.34	4	2.20	50
FSK 5	526	39.92	9	6.90	80
FSK 6	414	27.28	8	3.99	48
FSK 7	150	30.38	3	3.22	61
FSK 8	333	36.16	9	5.33	70
FSK 9	141	37.02	3	2.40	57

Figure 4: The 3D digital replicas (vertex paint) of the nine sherds organised into two groups based on their contiguity.

3.2. Reassembly and completion

As mentioned in the introduction, a manually implemented pipeline was followed to perform the reassembly and virtual completion of the vase. This was due to several reasons. Our previous implementation of a published pair-based matching algorithm that exploits the coarseness on the broken boundaries did not succeed probably because of the sherds degradation and/or deformation on the matching surfaces. Additionally, the limited funding resources along with the time allocation and the fact that it was a one-case scenario lead to the implementation of the following pipeline.

The initial step of the applied processing pipeline was the detection of the axis of symmetry of the vase based on sherds shape analysis. We considered the largest sherds as the optimum source for extracting such geometrical property. A number of plane-to-3Dmesh intersections were performed using Blender (2016) in order to extract both vertical and horizontal point sets (profiles that lay on a plane in 3D space). The intersections were performed on the least damaged (erosion) areas in an attempt to extract the best possible measurements.

The extracted point sets were processed in Matlab (2006). More specifically, a range of circle equations were identified using the best circle fit function on the horizontal intersection point sets. These equations were used to identify the interior and exterior boundaries of the vase's main body. These were considered as the averaged limits of the vase's main body. In addition, the projections of the normal vectors of the facets that belong to the horizontal intersection points were used to identify the vase's axis of symmetry. Unfortunately, the detection of a unique (mathematically expressed) axis was impossible. Apart from the fact that a hand-made vase is not symmetrically perfect, this was also an indication that sherds have been abstractly deformed through the years. Nevertheless, an axis of symmetry is a prerequisite for placing the sherds correctly into the 3D space and also for the generation (3D lathe) of the synthetic parts of the main body that will complete the vase. The averaged normal vectors intersection point's coordinates were used to detect the 'optimum' axis of symmetry (Fig. 5).

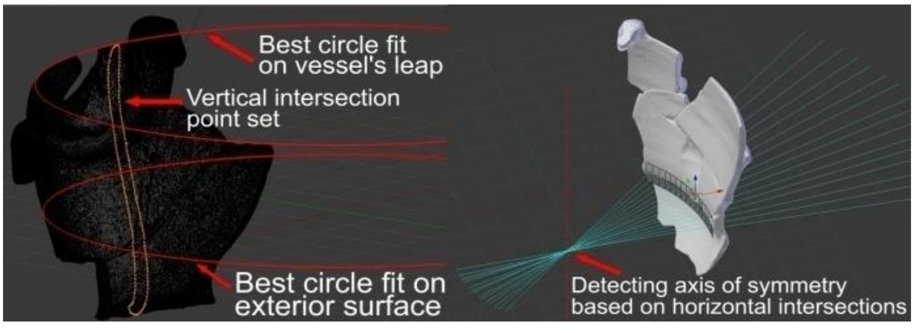


Figure 5: Performing shape analysis using horizontal and vertical Intersections on the sherds.

Once the axis of symmetry was identified, the second step was to organise the sherds into two groups and manually align them (Fig. 6). It was a process that was based on the information provided by the archaeologists about the grouping of the sherds and their spatial distribution. This was performed using the previously defined internal and external boundaries, the vertex-based snapping tool that Blender offers along with the texture information (vase's decoration). The two groups have no complementary parts and their positioning around the axis of symmetry was based only on the location of the handles.

In group 1 the handle is complete (Fig. 6a), while in the second group (Fig. 6b) one can see only a part of where the handle begins to evolve (FSK 7). The two sherd groups were placed one against each other using the handle as a strong symmetry indicator, while all sherds were positioned within the interior and exterior boundaries (Fig. 7). The whole alignment process was performed manually within Blender.

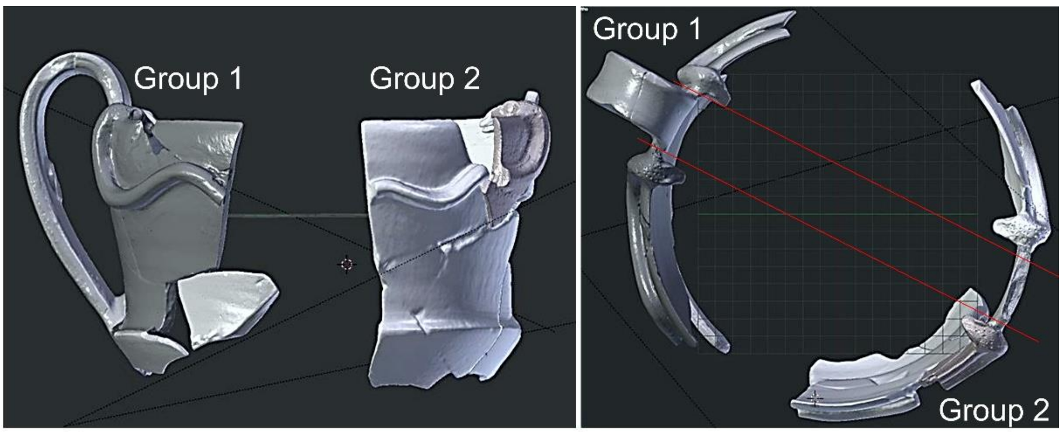
Furthermore, the generation of the vase's main body was based on the lathe 3D modelling technique. The synthetic main body was produced by a vertical intersection point set that represents the maximum available (based on the sherds) profile of the vessel. The vase's body is composed by rotated instances of the vertical intersection point set in a 3D Cartesian coordinate system. As the two-dimensional point set is rotated about a coplanar axis, an azimuthal symmetry is achieved.

Once the synthetic body was created, a number of 3D mesh Boolean operations (intersections) were performed between the synthetic body and the digital replicas of the sherds. This had as a result a mesh, where all overlapping areas (common areas between the sherds and the synthetic main body) were accurately removed (Fig. 8). This resulted a visualisation of the vase's main body missing parts. In addition, a digital replica of the preserved handle was produced and mirrored in order to virtually complete the vase. The profile of the vase's base was missing (cannot be extracted by the given sets of sherds). Thus, in order to produce a complete virtual reconstruction, we 3D modelled the base by following design principles of the specific vase type found in the literature (Fig. 8). We have made several versions of the model, mainly according to various Kantharoi's bases, and the archaeologists' team decided which fitted closer to the potential initial state of the vase.

The last step of the reconstruction pipeline was the texture mapping of the synthetic (computer generated) parts of the vase. A clay material was selected as it offered a realistic visualisation and clean visual lines between the digitised and synthetic (modelled) parts of the vessel. Figure 9 depicts four different viewpoints of the reconstructed vase made in Blender. Note that the mirrored handle is also depicted using the clay material and not the original colours preserved in the sherd.

(a) (b)

Figure 6: Spatial distribution of sherds: a) Group 1; b) Group 2.



(a) (b)

Figure 7: Spatial alignment of the two groups of sherds: a) Positioning of the two groups around the axis of symmetry; b) Position refinement using handle positions as a strong indicator.

(a) (b)

Figure 8: Visualisation of the synthetic part of the vessel's body: a) Aligned with the two groups of sherds; b) After the application of the Boolean 3D mesh operations.

Figure 9: Different viewpoint renderings of the virtually completed kantharos.

4. Evaluation

After the completion of the 3D digitisation and reconstruction an evaluation took place, in order to examine our approach and its results. As a COSCH case study, COSCH members viewed and examined the 3D model. They come from all the involved disciplines being primarily archaeologists, museologists and technology experts. They were already informed on the study's stages after multiple presentations within the context of the COSCH project. After the final presentation, they posed relevant questions and offered their remarks and notes in a structured questionnaire. The latter had six (6) close-ended questions regarding the evaluation of 1) the methodology undertaken, 2) the study's output, 3) the digitisation approach, 4) the procedures followed, 5) the contribution to archaeology and museology, and 6) the communication of the vase with the general public. An open-ended question allowed them to state any other comment.

Thus, the evaluation gave very interesting ideas regarding the 3D model and its use for archaeological and museological purposes, for both researchers and the general public. All the participants highlighted the appropriateness of the methodology undertaken and the relevance to the stakeholders' needs. They considered the 3D model produced a big improvement to the traditional graphic archaeological documentation system, providing high image quality and a digital replica of the vase in real dimensions. They also noted that the model strongly contributes to the digital safeguarding of the material characteristics of the object and is especially useful in the field of visualisation through digital media.

Apart from the aforementioned remarks, the participants also underlined the need for the 3D models to become even more effective for research. They considered this specific work as a base for further research, since it is a unique type of vase, fragmentary, with specific features. For example, the collaboration with other relevant projects could try the use of automatic methods. There is without any doubt a need to avoid manual processing, as much as possible, for limiting time and costs. This automation could be applied for both the reconstruction of the vase and also for the creation of sections and other views of the vase. In general, a participant underlined the need to study the feasibility of the whole procedure, from a material and financial point of view.

Last, they all thought of the 3D model as a support for the real artefact, the authentic find that should be promoted, and for the archaeological knowledge that this find encloses. This knowledge could be communicated to the public through the addition of digital storytelling in order to achieve enhanced presentation conditions. Within this context, another 3D model with reconstruction in terms of the original colour appearance would help to create a more visually attractive object.

5. Conclusions

It is evident that the study of this unique vase is of great importance for scholars. Its fragmentary condition, though, along with its uniqueness set limitations, since archaeologists could not have a complete picture of it. Both the evaluation results and the 3D reconstructed model confirmed our initial research questions and covered our needs respectively.

From a technological point of view, the SfM/MVS 3D digitisation approach proved to be an adequate method for the generation of high quality 3D data. The semi-automated procedure allowed the generation of 3D digital replicas of the sherds without the need to apply partial scan alignment procedures that are also prone to introduce errors. The alignment of the sherds into groups was based on the vertex-based snapping tool offered by Blender. Although the result is visually adequate, the use of an algorithm that quantifies the error between the matching surfaces along with the vertex snapping tool would provide a more objective alignment of the sherds. On the other hand though and from a practical point view, such accuracy would be more important for cases where matching surfaces are not degraded to such an extent, while the available sherds represent a larger amount of the original artefact.

From an archaeological point of view, such a typical 3D model (in its fragmentary status) and at the same time unique (in its shape and decoration) vase can facilitate its study, since it can be seen from every side, whenever wanted, from everywhere and as close as needed. The archaeologists can indeed use the accurate 3D visualisation for the remote study of its shape, dimensions, decoration, etc. They can get a better sense of the vase than from the 2D photos of individual fragments; they can work with different versions of the reconstructed 3D model without disturbing the fragments themselves and choose the one that seems, by the current archaeological standards, the most correct and balanced. The potential deformation of the kantharos sherds, which was observed with the archaeological study and during the 3D reconstruction, will be significantly taken into consideration in a future scholarly publication.

Moreover, archaeologists through this 3D model can acquire a better knowledge of the shape of this unique so far vase for the ancient Greek culture. University professors can use the 3D model of the vase for a number of teaching courses related to pottery, ritual, practices, daily life, etc. In the Karabournaki excavation and its webpage (Karabournaki, 2016) a low-resolution model will be used for the site's digital collection that can serve for teaching purposes, too.

From the museological point of view, professionals can use such a high quality 3D model for comparing it with the future conservation status of the actual vase and take decisions in terms of its preservation. Moreover, they can use the model and the relative reconstruction to study the vase remotely without having to move. They can also use it in multiple ways in virtual exhibitions (i.e. when they organize the real ones) or beside the real artefact in the actual exhibition space to help the public get a full image of it and understand it better. The deployment and comparison of the rejected versions of the reconstructed vase could contribute to the understanding of the importance of typology in the study of ancient pottery and of established trends in the ancient potter's work in general.

This demonstration can be very important especially if it takes time for the real vase to be thoroughly studied and exhibited. The digital handling of the 3D model would add to this scope through interaction, while an animation with all the steps and processes in which the vase took place, from its construction to its unearthing and its 3D visualisation, would contribute to it, too. In an actual future exhibition space, the generation of a 3D-print of the model of the base where the actual sherds could be placed would allow the creation of an accurate exhibit holder.

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