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Case Study Report

1. **TITLE of the case study**

Kantharos. From a buried fragment to the virtual artefact

2. **Start date:** September 2014. **Completion date:** January 2016

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4. **Author(s) name, position/status and affiliation, contact details; expertise/research interests (max. 100 words per contributor).**

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7. Type of case study: (*select from: descriptive, explanatory, exploratory*)

Exploratory

8. Up to 6 keywords:

Greek pottery, virtual reassembly, 3D approximation, visualisation, Archaeological excavation data.

9. Summary Report (max. 200 words): what has been studied, why and how; key findings.

This case study explored the contribution of 3D digitisation and reconstruction to the visualisation, the study and the dissemination of an ancient Greek vase (Kantharos) found in an excavation. The vessel is unique in its decoration and shape but common for archaeologists due to its fragmented nature and its material.

The reason for the 3D digitisation and reconstruction of the Kantharos was the need for the contribution of 3D technologies a) to the archaeological and museological study of the vase and b) to the promotion of the knowledge that the artefact can convey to the general public. The fragmented vases, although without doubt recognisable and classified by pottery experts, are not easily understood by the general public. Moreover, the Kantharos has unique features that do not allow its secure shape recognition and classification even by archaeologists.

The interdisciplinary scientific expertise and relevant publications coming from researchers of the Athena RC (both archaeologists/museologists and 3D experts) guaranteed the application of the most efficient, suitable and sustainable technologies. The findings of this case study can serve as a guide for the 3D digitisation and reconstruction of ancient fragmented pottery in general. The London Charter and the Seville principles regarding digital archaeology served as a guide during the case study and identified several issues for consideration.

10. Description of aims:

The aims of this case study comprised:

- the 3D visualisation and reconstruction of a unique ancient Greek fragmentary drinking vessel (Kantharos),
- the creation of an initial 3D model for the showcase of the Karabournaki excavation for education and presentation purposes,
- the exploration of the archaeological study potentials from the reconstructed 3D model of the vase,
- the exploration of the museological potentials from the reconstructed 3D model of the vase,
- the evaluation of the technique for the specific type of cultural heritage,
- the study of the applicability of a commercial low-cost software for Multi-Image 3D Reconstruction and
- the evaluation of the data that would be produced and of the created model for research purposes.

11. Rationale: Why was this study needed? Who is likely to benefit?

The Kantharos case study regarded the visualisation of the fragmentary drinking vessel (Kantharos) that is decorated with added snakes. The vase was handed over by the archaeologist who has unearthed it, is studying it and has worked closely with 3D experts (Seville principle 1: Interdisciplinarity).

The vessel is a piece unique in terms of decoration and shape for its time and region, while at the same time it is a typical case of a fragmentary clay vase that offers challenges in terms of its visualisation and reconstruction (Tiverios et al. 2003). Its fragmentary condition sets limitations for the study, since we cannot have a complete picture of it, and for its exhibition, since the public cannot get a full image and understand it well (Seville principle 2: Purpose).

Thus, a 3D model facilitates the vase's study, since it can be seen from every side and as close as needed, something not possible with the 2D photos (Seville principle 3: Complementarity). That way the scholars are benefited, firstly, for the study of the object itself having the 3D model available in a computer, away from the storerooms and in high quality and detail. Secondly, archaeologists have a 3D reconstruction, a possible restoration of the unique vase that helps them test their hypotheses (Seville principle 4: Authenticity and 5: Historical Rigour). The general public accesses a fragmented vase in a new and visually enhanced way that will assist it to see an intact version of the vessel and to understand it better.

Although the project regarded the visualisation of only one vase, it was a typical case, characteristic of any fragmented clay vessel, since it comprised all the principal challenges for the turning of the real Kantharos fragments to a 3D model that would present a complete vessel. Those challenges regarded: a) enough information for reconstruction, b) challenge for missing parts, especially the foot & base (we had no info for that) and the tails of the snakes that meet in the centre of each side of the body of the Kantharos. The final product (after its evaluation and tentative improvement) can serve as a guide for similar archaeological issues.

Therefore, the 3D digitised and reconstructed version of this vessel can be used as a model for other fragmentary vases that come from: a) the Karabournaki excavation, since the excavation wants to create a showcase of 3D models of vases for scholars, teaching students and dissemination through the web site (Karabournaki 2016) that is being currently redesigned (Seville principle 8: Training and Evaluation), and b) any other archaeological site or collection.

Furthermore, for the contributors from the technological field the purpose for the realisation of the project regards the evaluation of the technique for the specific type of cultural heritage, the question of the applicability of a commercial low-cost software for Multi-Image 3D Reconstruction (Shape From Motion - Dense Multi View 3D Reconstruction, Low cost and efficient 3D digitisation method), the evaluation of the data produced and of the created model for research purposes (Seville principle 6: Efficiency).

In total, the 3D reconstructed model contributes to the better understanding and communication of the (digital) cultural heritage (Tsiafaki 2012, Tsiafaki and Michailidou 2015, Tsiafakis et al. 2004).

12. Detailed information about the cultural heritage object/site used in the study (type of object, title, subject, date, ownership, techniques/media, dimensions, description, etc) or reference to a monographic study/standard catalogue.

Object of the case study was a fragmentary Kantharos (drinking cup) unearthed during the excavations at the settlement of Karabournaki (ancient Therme) in the area of Thessaloniki (Greece) (Fig. 1) (Tiverios et al. 2003). 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. The site dates from the late Bronze Age down to the Roman times, with its peak to be in Geometric (9th-8th c. B.C.) and particular in Archaic period (7th-6th c. B.C.).

The location of the site at the edge of a promontory in the centre of the Thermaic Gulf makes it very important for trade and military reasons. Therefore, at the settlement (Fig. 2) imports from all over Aegean are unearthed. Pottery findings are the most common and they come from all the known pottery workshops of antiquity.

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

Fig. 2. The excavation of the ancient settlement at Karabournaki.

The vase (Fig. 3, Fig. 4) dates in the Archaic period (7th-6th c. B.C.) and it was found among the settlement's architectural remains (Tiverios et al., 2003). The fragmentary Kantharos is composed by a total of nine different sherds of different sizes, which were glued together by conservators, organised in two unjoined groups.

Although the shape of the Kantharos is widespread in ancient Greece (Courbin 1953, Villard 1962, Killinski 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 G 2-3 ware (Ilieva 2013). 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 piece of clay) on the upper part body of the vase. The snakes surround all the body of the vessel with their heads being inside its rim, as if they are about to drink the liquid inside the vessel. Kantharos is the vessel of the god Dionysus and a typical drinking vase for symposia (social gatherings with food and drink). This decoration points to a ritual vessel, 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). Therefore its study and exhibition is of great importance for both scholars and the general public.

Fig. 3. The fragmented Kantharos from Karabournaki

Fig. 4. The fragmented Kantharos from Karabournaki.

13. Brief description of the visual record created, incl. access information and copyright.

The 3D model created comprises the digitised sherds of the fragmentary Kantharos and the synthetic reconstructed body (Fig. 5, Fig. 5). The model is available in the “Athena” Research Centre intranet and for now is not available for the rest of the public. The "Athena" RC holds all copyright for the 3D model, which is intended to be disclosed for both researchers and simple guests in the Karabournaki excavation’s website (that is being currently redesigned, http://karabournaki.ipet.gr) after its archaeological publication.


Fig. 5 and Fig. 6. A few renderings of the 3D reconstruction's current state

14. Methodology: Step-by step description of methods and techniques (this section may need to be broken down).

14.1. Archaeological tasks

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 and Hughes 2013).

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.

The methodology undertaken during the archaeological research that preceded the 3D visualisation and reconstruction comprised the following steps:

- in hand examination of the nine fragments of the vase,
- archaeological recording of the fragments,
- 2D photographic documentation,
- complete measurements of the fragments,
- welding of the fragments where possible,
- positioning of the fragments in a circle that contributes to shape reconstruction (
- Fig. 7) and

• drawing of the preserved parts of the vase.

Fig. 7. The Kantharos’ fragments, in two unjoined groups, positioned in a circle by the archaeologists.

Moreover, the archaeologists contributed to the 3D reconstruction of the vase with:

- the provision of the basic types of kantharoi from renowned publications, like the one of M. Tiverios (1996) about ancient Greek vases (Fig. 8),
- the provision of similar vases from online repositories, like the Corpus Vasorum Antiquorum database (2016) and the Beazley Archive Pottery Database (2014) (Fig. 9),
- the provision of photographs with joined fragments, positioned in a circle in order to faithfully complete the 3D reconstruction (
- Fig. 7),
- the finding of photographs from CVA and BAPD with ancient vases showing Kantharoi being used either in symposia or rituals (Fig. 10, Fig. 10) and
- the continuous consultation to the technological team during the whole process.

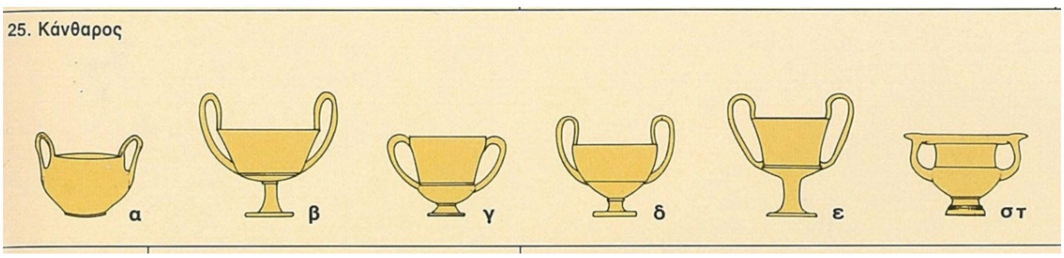

Fig. 8. The various types of ancient Greek kantharoi from the printed archaeological publication of M. Tiverios.

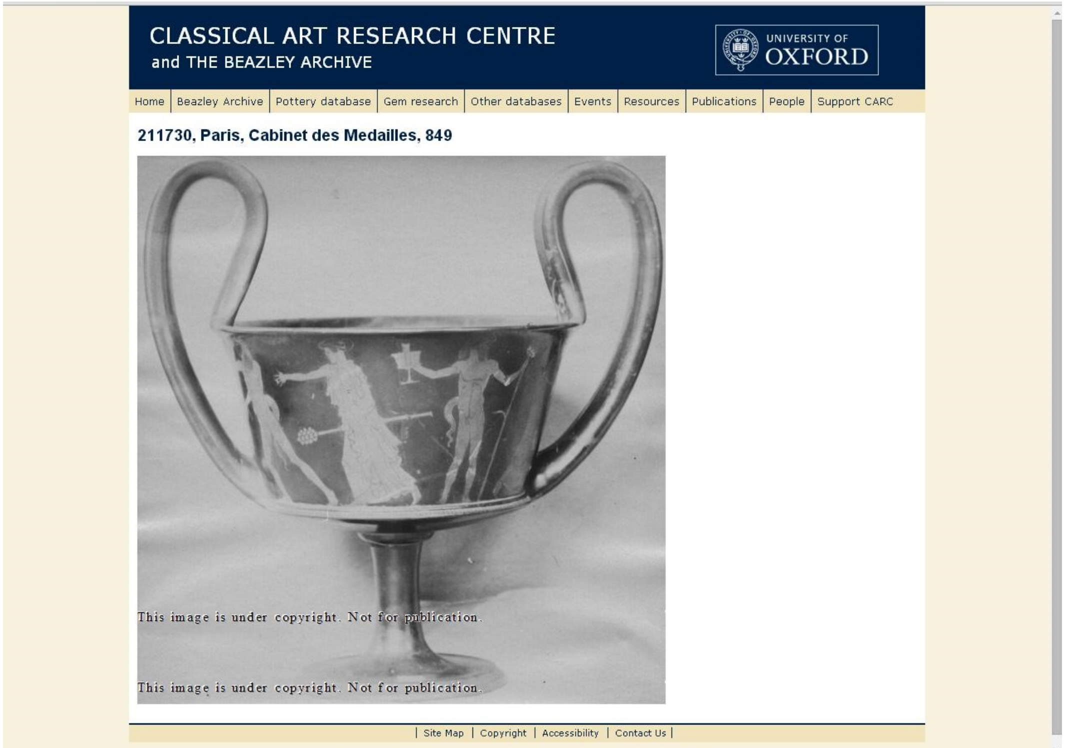

Fig. 9. An example of a Kantharos from the online Beazley Archive.


Fig. 10 and Fig. 11. Painted kantharoi in ancient Greek vases.

14.2. <u>Museological tasks</u>

From a museological point of view, a ceramic sherd is 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 and 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).

From the museological perspective our tasks comprised reviewing the major museological needs in terms of a clay vase and its 3D model. These needs relate to the following major issues: a) preservation, b) interpretation, c) presentation and d) education. Thus, a 3D model of a vase in its current fragmentary condition or reconstructed in its original form, shape and colour can be used for various purposes:

a) for comparing the 3D model with its future conservation status and noting potential gradual changes of the artefact (preservation),

b) for the study of the artefact by the researchers, using distant handling and detailed observation, measurements or comparison of the 3D model with similar vases from other i.e. online databases (interpretation),

c) for presenting the artefact in virtual exhibitions, with various topics, giving the ability to curators to experiment without having to physically move and handle artefacts and to the public to be attracted by the possibilities of modern technologies, too (presentation) and

d) for creating a virtual model of the vase that visitors and especially children can handle electronically and use it in various gaming platforms or other applications. This can be particularly useful if the vase is not in condition to be handled or presented and for people with disabilities (education).

14.3. Data collection phase

Taken under consideration the archaeological information in combination to 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 Kantharoi 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 (Seville principle 7: Scientific Transparency).

In order to create the 3D digital replicas of the Kantharos' sherds we have used the Structure-from-Motion & Multiple View Stereovision (SFM/MVS) approach. A commercial implementation of the algorithm (AgisoftPhotoscan Professional) was selected, as it was previously mentioned, based on the results of previous published works that involved the extensive evaluation of the produced 3D data (Koutsoudis et al. 2015, Koutsoudis et al. 2013a, Koutsoudis et al. 2013b).

The data collection phase was based on the use of a computer controlled high accuracy turntable (Kaidan Magellan Desktop Turntable MDT-19) and a pair of mirrorless DSLR cameras (Samsung NX1000 – 21.6MPs) with 20-50mm lens along with 40.5mm circular polarising filters. The camera sensor size was 23.5 x 15.7mm and a 4.26μm pixel pitch. 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 have been scanned as a single sherd.

For the accurate scaling of the 3D digital replicas, we have used the encoded photogrammetric targets offered by Photoscan. They were placed around each sherd during the data collection 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 2,851 images were used for the 3D reconstruction of nine different sherds (Fig. 13, Fig. 14). The average ground sample distance was 36.73μm resulting that a flat area of 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.

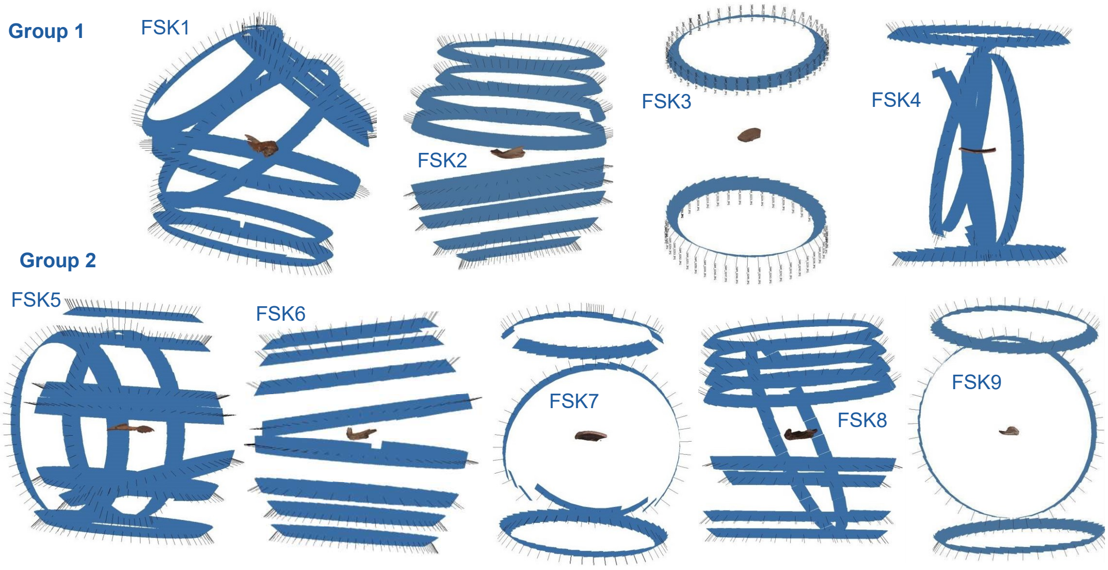

Fig. 12. Image Sets Spatial Distribution of each sherd of the Kantharos (FSK)

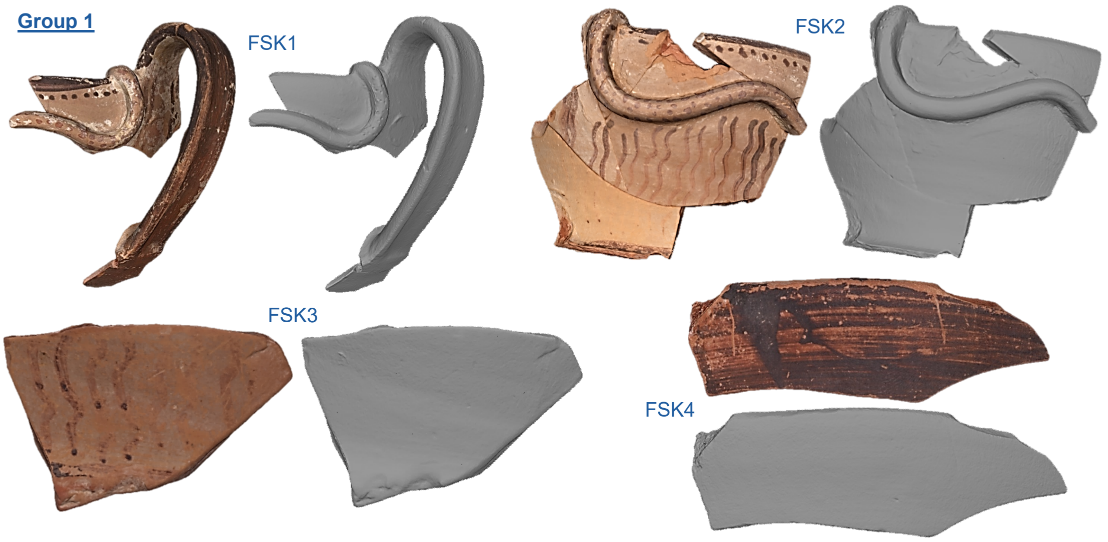

Fig. 13. Visualisation of the 3D digital replicas from the 1st group of the sherds (Vertex Paint & Smooth Normals shading)

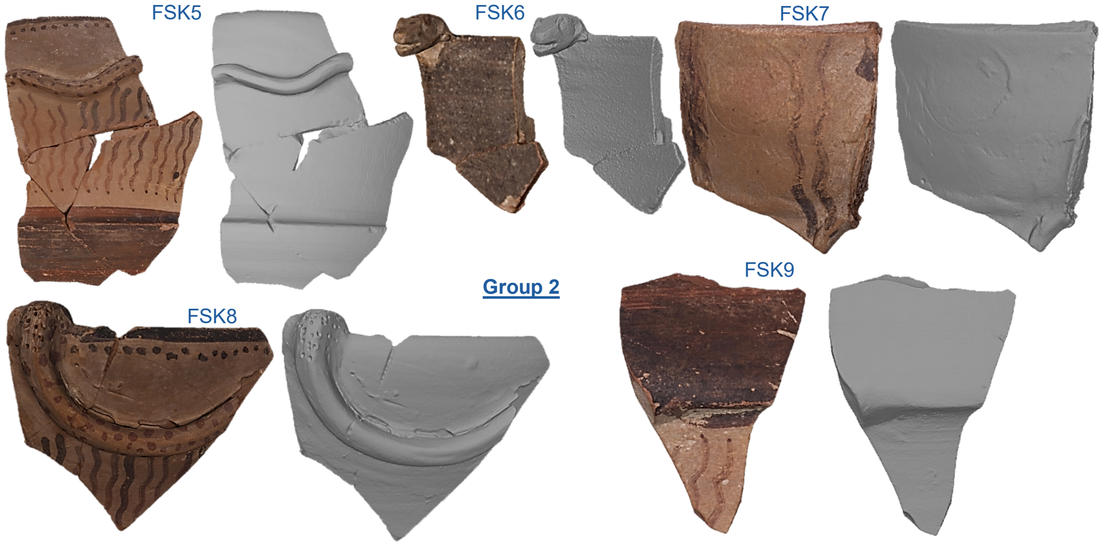

Fig. 14. Visualisation of the 3D digital replicas from the 2nd group of the sherds (Vertex Paint & Smooth Normals shading)

Table 1 presents a summary regarding the data collection phase of our case study. We can underline that the Ground Sample Distance Averaged is 36.73μm and that 1 cm of real world is presented in average by 272 pixels. Moreover, we have to state that the total number of images to ensure complete capturing of all sherds were 3,571 images, where we actually used 2,851 for the final model.

Sherd name	Number of images used for 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	~110μm
GROUP 1 - FSK 2	547	48.54	9	7,827,421	~82μm
GROUP 1 - FSK 3	94	32.84	2	1,716,631	~55μm
GROUP 1 - FSK 4	209	31.34	4	2,204,425	~50μm
GROUP 2 - FSK 5	526	39.92	9	6,908,370	~80μm
GROUP 2 - FSK 6	414	27.28	8	3,996,016	~48μm
GROUP 2 - FSK 7	150	30.38	3	3,220,855	~61μm
GROUP 2 - FSK 8	333	36.16	9	5,335,942	~70μm
GROUP 2 - FSK 9	141	37.02	3	2,401,313	~57μm
Totals/Averages	2,851 / -	- / 36.73μm	- / 6	39,566,973 / -	- / 68μm

Table 1. Performing Data collection.

14.4. Virtual reconstruction

As previously mentioned, 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. 15).

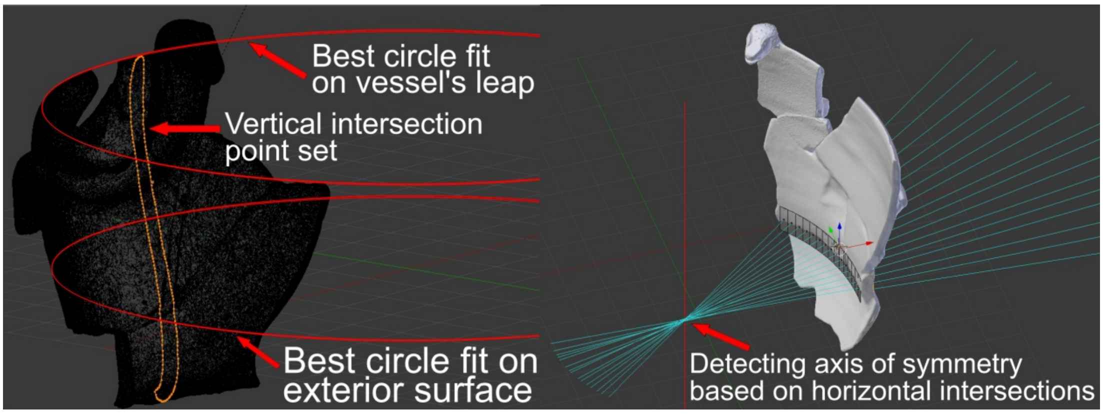

Fig. 15. Detecting the axis of symmetry.

Once the axis of symmetry was defined, the second step was to organise the sherds into two groups and manually align them (Fig. 16, Fig. 17). 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 sherd groups have no complementary parts and their positioning around the axis of symmetry was based only on the location of the handles.

Fig. 16. Spatial alignment of the sherds in Group 1.

Fig. 17. Spatial alignment of the sherds in Group 2.

In group 1 the handle is complete, while in the second ground 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. 18). The whole alignment process was performed manually within Blender.

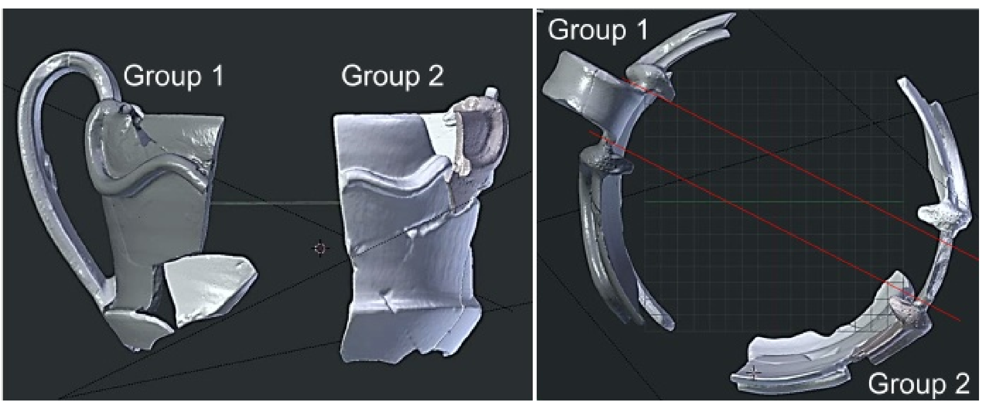

Fig. 18. Groups aligned around the axis of symmetry while using handles as a strong indicator.

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. 19). This resulted to 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. We 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.

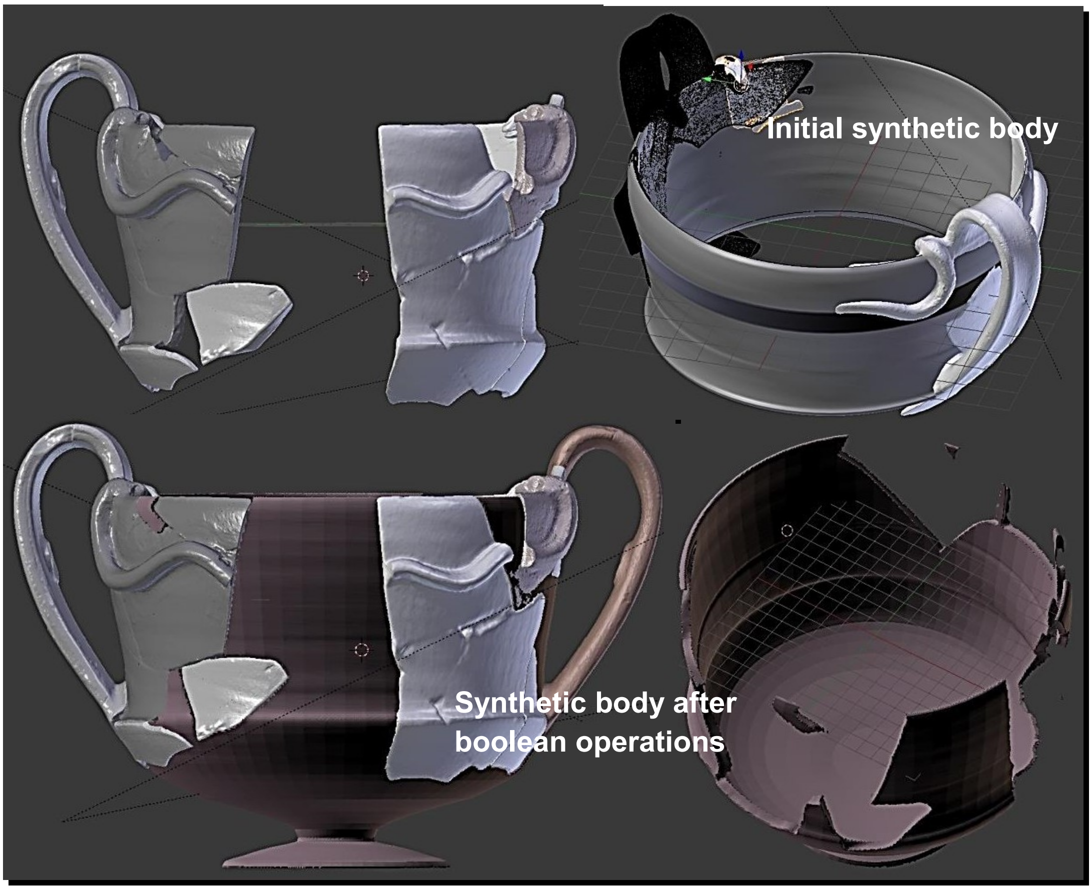

Fig. 19. Create Missing Parts.

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. Fig. 20Fig. 1 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.

Fig. 20. Different viewpoint renderings of the virtually reconstructed Kantharos.

15. Technologies, tools, software/hardware used:

The technologies, tools, software/hardware used comprise the following:

- application of the Structure-from-Motion & Multiple View Stereovision algorithms,
- use of Agisoft PhotoScan Professional version as a trusted software,
- use of a computer controlled high accuracy turntable (Kaidan Magellan Desktop Turntable MDT-19),
- use of a pair of Samsung NX1000 - 21.6Megapixels, 20-50mm lens with 40.5mm circular polarising filter (Sensor size: 23.5 x 15.7 mm - Pixel pitch, which is a measure of the distance between pixels, is 4.26 μm - Manual lens calibration at various (probable for usage) focal lengths using Agisoft Lens has been done in the past),
- use of photogrammetric targets for 3D data scaling and white balancing palette,
- use of 3D modelling functionalities – Lathe to generate a synthetic main body and
- performance of boolean operations (difference) between sherds and synthetic main body to produce a synthetic main body where all sherds would be fitted.

16. Analysis:

Taken into account the way that archaeology and museology work with pottery, we wanted to see 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 restrictions of traditional pottery studies (need for physical handling, numerous sherds, remote location etc.). 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, a better 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 et al. 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.

17. Standards employed; data formats and protocols:

For the 3D digitisation the Structure-from-Motion and Multiple View Stereovision algorithms were applied, whereas Agisoft PhotoScan, the Professional version, was used as a trusted software implementation. The selection of software was based on previous published works on produced data evaluation (Koutsoudis et al. 2015, a; Koutsoudis et al. 2015, b; Koutsoudis et al. 2014; Koutsoudis et al. 2013).

The "Athena" RC has an ISO 9001:2015 certificate for its services on 3D digitisation of cultural heritage. The raw 3D data (point clouds) were stored in the XYZRGB file format while the processing has been performed on triangulated mesh data types stored in the Wavefront .OBJ file format. The STL file format will be used in case we consider performing 3D printing on the synthetic data produced during the reassembly of the vessel.

18. Description of outcomes and issues:

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 known for introducing 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 3D model of a typical (in its fragmented 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 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 the future scholarly publication.

Archaeologists through the 3D model of the Kantharos that was created 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 currently redesigned webpage (Karabournaki 2016) a low-resolution model will be used for the site's digital collection that can serve for teaching purposes, too.

Museum professionals, too, 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 an 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 electronic 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-printed base where the actual sherds could be placed would allow the creation of an accurate exhibit holder.

19. Evaluation:

Following the completion of the 3D digitisation and reconstruction an evaluation took place, in order to examine our approach and its results (Seville principle 8: Training and Evaluation). 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) closed 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 (Appendix A). An open-ended question gave them the space 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 indeed the 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 thing, 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 better 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.

20. Significance to COSCH and future work enabled:

The Kantharos case study dealt with a different material and category of cultural heritage assets that other case studies included in COSCH. Pottery is one of the most widespread and popular categories of cultural heritage, and the case study has given a common use case scenario for the COSCH KR.

Thus, this case study has contributed to the global knowledge of the use and application of 3D in a major field of archaeology, the pottery studies and in particular the fragmented objects, which are the rule for archaeological finds, while intact objects are the exception. It has significantly contributed to the visualisation of pottery and its diffusion, by creating a reconstruction of a very fragmented vase, a real case scenario for all archaeological excavations. The methodology undertaken can serve as a model and guide for other similar projects, especially those dealing with pottery.

Nevertheless, the case study has contributed to the WG5 of COSCH by testing the related concepts, applying relevant methods and processes, and dealing with issues in historical visualisation of Cultural Heritage within scholarly applications. It has also contributed to the WG2 in terms of the techniques used for the 3D reconstruction.

Moreover, the case study has contributed to the reinforcement of the collaboration between COSCH members for evaluation purposes. The remarks and suggestions of various COSCH members from different disciplines have given us valuable insights to our case study, in terms of its implementation, the archaeological and museological questions asked, the promotion of the final model to both researchers and the general public etc. The case study and its evaluation comments can contribute to the needed evaluation and the guidelines that will be set at the end of the COSCH project.

The future work that can be enabled after this case study comprises the following issues:

- The continuation of the archaeological study of the vessel with the new elements derived from the 3D visualisation and reconstruction,
- The publication of the vessel based on and using the 3D visualisation and reconstruction, too,
- The creation of variations based on other Kantharos shape prototypes,
- The use of geometric features and colour information from sherds to simulate surface properties and create texture maps on the synthetic main body, in order to Increase realism,
- The use of 3D puzzle solving algorithm created within the PRESIOUS project to achieve better sherds alignment (not sure though if any better results can be achieved as sherds' edges contain extensive damage),
- The generation of a 3D printed base where actual sherds can be placed on,
- The creation of a multimedia application showing the history and various phases of the Kantharos (discovery, use, destruction, burial, excavation, conservation, 3D digitisation and reconstruction) and finally
- The creation of a virtual museum in the Karabournaki excavation and the incorporation of the Kantharos 3D model as well as information about the digitisation and reconstruction case study targeted to both scholars and the general public.

21. Conclusions:

Based on the scopes of COSCH and having in mind the London Charter (Denard 2009) and the Seville Principles (López-Menchero Bendicho 2013) we went on to carry out this case study. In order for the 3D visualisation and reconstruction of the fragmented Kantharos to achieve a high level of intellectual integrity, these scopes and principles served as important guides throughout the whole procedure.

The choices made, during the 3D visualisation and reconstruction, were kept close to the initial aims of the case study and the desired outputs. The 3D technology was used in order to add to a pure archaeological pottery study and contribute specific potentials to it. The limited time and budget available for the completion of the case study determined the technique and methodology used, along with our previous related published work with the latter. The choices made achieved our principal aims, which were, firstly, to assist the archaeological work regarding the study of the vessel, as well as, secondly, to provide a means for the communication of a very fragmented vase to the general public.

Most importantly, the leading role that both a) the excavator of the vase (a pottery expert) and b) the technology expert (with big experience in 3D modelling of cultural heritage) played in the 3D digitisation and reconstruction team ensured that all the available research sources (regarding, on the one hand, pottery and archaeological data and, on the other hand, the latest advances in 3D technologies and techniques) were taken into consideration during the work carried out.

The documentation of the case study from its initial stages to its completion was thorough enough to make clear to all potential users the relevant aims, methodology and output. Reports, presentations, team meetings and scientific publications all documented the process and the knowledge there. Moreover, our commitment to use the work done in the currently redesigned excavation website will vastly contribute to the sustainable dissemination of all the parameters of the 3D digitisation and reconstruction of the Kantharos to various groups of public (researchers, professors, students, general public etc.).

The digital preservation of the computer-based visualisation data is secured through rigorous digital archiving, while a 3D printed model of the reconstructed vase is going to be made, in order to have a real three-dimensional record of the work done. This will immensely help the archaeological work, too, since the fragments could be put on top of the suggested reconstruction.

Apart from the relevant scientific publications, all the work done during the 3D digitisation and reconstruction of the Kantharos will be made available in the new Karabournaki excavation website. This will serve as an example of the contribution of the new technologies to the archaeological study and to its dissemination to the public. Moreover, the excavators, working in academic and research institutions, will disseminate the work and the relevant outputs in presentations and educational sessions (lectures for students, educational programs for schools etc.).

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23. List of Appendices:

A. Answers from the evaluation questionnaire in charts