Recommendations for solution providers as well as end users (deliverable PT6)

Application to the Kantharos case study

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Context of the case study

The fragmentary Kantharos (drinking cup), which served as the theme of the case study, was unearthed at the settlement of Karabournaki (ancient Therme) in the area of Thessaloniki (Greece) and dates in the Archaic period (7th-6th c. B.C.). Although the shape of the Kantharos is widespread in ancient Greece, the specific example is unique in terms of its decoration, for not fitting sufficiently into a particular workshop so far and for its profile that does not follow the typical known examples of its time. Its fragmentary condition (although preserved in a large extent) was challenging in its completion and in particular for its lower part (base and foot). 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. Therefore its study and exhibition is of great importance for both scholars and the general public. The case study produced a 3D model via a semi-automated procedure, providing high image quality and a digital replica of the vase in real dimensions that safeguards the material characteristics of the object and enriches the archaeologist's and museologist's work. The future work that can be enabled comprises the following major issues: 1) the use of geometric features and colour information on the synthetic main body, in order to increase realism, 2) the generation of a 3D printed base where actual sherds can be placed on, 3) the creation of a multimedia application showing the phases of the Kantharos with the addition of digital storytelling and finally 4) the incorporation of the 3D model in the virtual museum of the Karabournaki excavation targeted to both scholars and the general public.

1. ***Which CH research question has to be answered / which CH application has to be realized?***

- 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?
- How would 3D model and reconstruction be used for teaching purposes in the Karabournaki university-led excavation and the excavation's Website?
- 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?
- 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?
- What drawbacks would there be regarding the 3D digitisation and reconstruction of the Kantharos (especially regarding data accuracy and image quality) and how could they be limited?

2. ***Which information related to physical / optical / geometrical structure of the object (and its surface) is relevant for the user question and why?***

- What was the initial shape of the complete Kantharos with special reference to its base and foot? Which are the data that our proposal is based on?
- What was the initial decoration (painted, plastic or other) of the complete ancient vase? Which are the data that our proposal is based on?
- Which is the original material of the vase in the 3D model and which are the reconstructed pieces? How can we distinguish original materials from digital restoration work?
- How did the handling and use of the complete vase feel like? Is there a way to observe this experience in a non-invasive way?
- What was the change of the material characteristics of the vase through time and through its location changes (created, used, buried, excavated, cleaned, rejoined, digitised, reconstructed and exhibited)?

3. ***Which data sets contain the required information or allow to derive it, and why?***

<u>Non invasive</u>

- Structure-from-Motion & Multiple View Stereovision (SFM/MVS) approach with the selection of a commercial implementation of the algorithm (AgisoftPhotoscan Professional). The method was selected due to its high level of automation in terms of data collection and 3D reconstruction. Furthermore, the feature richness of the sherds' surfaces sets them as 'method friendly'.
- For the data collection we have used 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 40.5 mm circular polarising filters. The camera sensor size was 23.5 x 15.7 mm and a 4.26 μm pixel pitch. The average ground sample distance was 36.73 μm resulting that a flat area of 1 cm in the real world was represented by 544 pixels. 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. High aperture values ensured that the front part of the vessel used from each image is in focus. Furthermore, AgisoftPhotoscan uses an energy function based method to fuse the depth maps of each images resulting that blurry areas (if any as masking is also performed on the image set) are covered by in focus areas of other viewpoints. The selected lens in combination with the manual parameters in terms of aperture, shutter speed, ISO and white balance ensured a stable data collection phase.
- For the automation of each sherd's photo shooting, 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. The EMCee protocol is supported by the control unit of the Kaidan Magellan Desktop Turntable MDT-19 and defines a set of commands related with the way the turntable rotates.
- For the accurate scaling of the 3D digital replicas, we have used the encoded photogrammetric targets offered by Photoscan. These are produced by Photoscan using a number of options related with their encoding capabilities. Large objects require more targets and hence the number of bits used in the target encoding is increased accordingly. For each shred a total of five pair targets where used. A known distance between each pair is provided by the software which actually generates them. They

were placed around each sherd during the data collection phase and distances between their centers were measured. They are placed almost equidistantly around the object. The accurate scaling is based on the known distances between the target pairs while manually measured distances between each pair centre is used as a supplementary method of scaling verification. It should be noted that the software detects targets automatically, while the real world dimensions are used within the 3D reconstruction algorithm.

- A total of 2,851 images were used for the 3D reconstruction of nine different sherds. 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. The large number of images ensured that a single data collection phase will allow the complete reconstruction of the sherds. The availability of the sherds in our digitization premises was limited in terms of time. Each of sherds was captured by a different number of viewpoints which reflects upon its morphological complexity and size. The total number of viewpoints varies between 94 and 547 (Table 1). There were produced by providing a fixed rotation step on the turntable and a different positioning of the camera or shred based on the needs of each data collection step. The overlap between each viewpoint is ~70%.
- The average ground sample distance was 36.73μm resulting that a flat area of 1cm in the real world was represented by 544 pixels.
- 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 Ground Sampling DistanceGSD 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.

4. How have the required data been acquired and processed?

<u>Data acquisition</u>

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. 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.

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.

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 15.7 mm and a 4.26 μm pixel pitch. For the automation of each sherd's photo shooting, 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. 2, 3).The average ground sample distance was 36.73 μm 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.

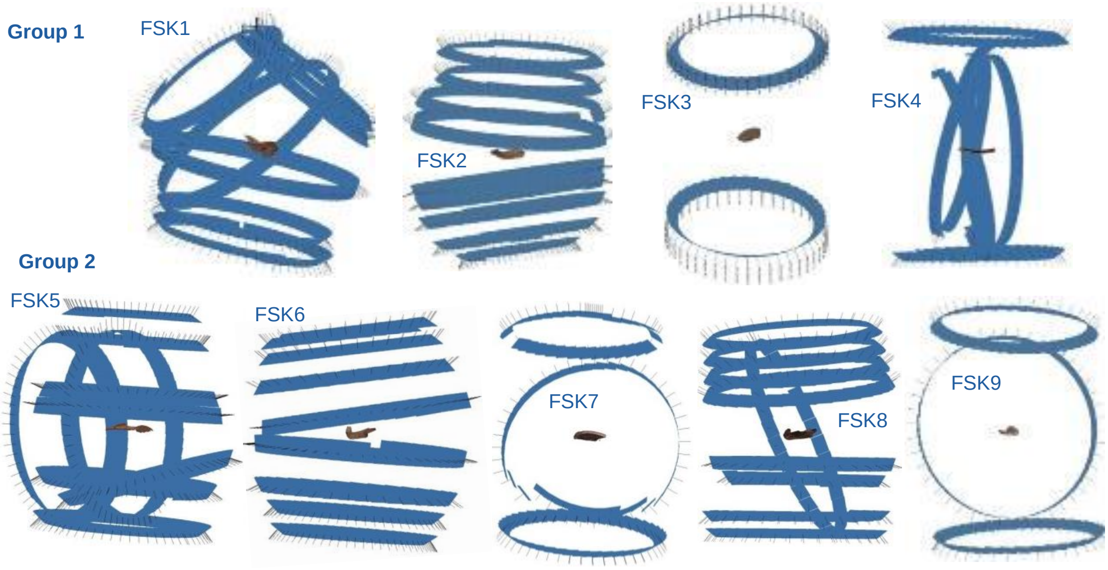

Fig.1. Image Sets Spatial Distribution of each sherd of the Kantharos (FSK)

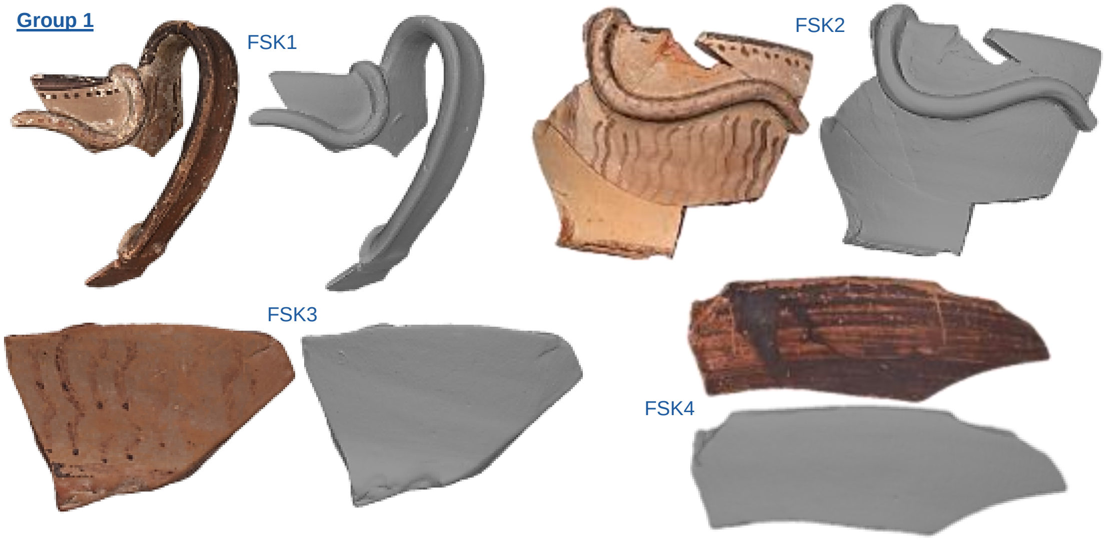

Fig. 2. Visualisation of the 3D digital replicas from the 1st group of the sherds (Vertex Paint & Smooth Normals shading)

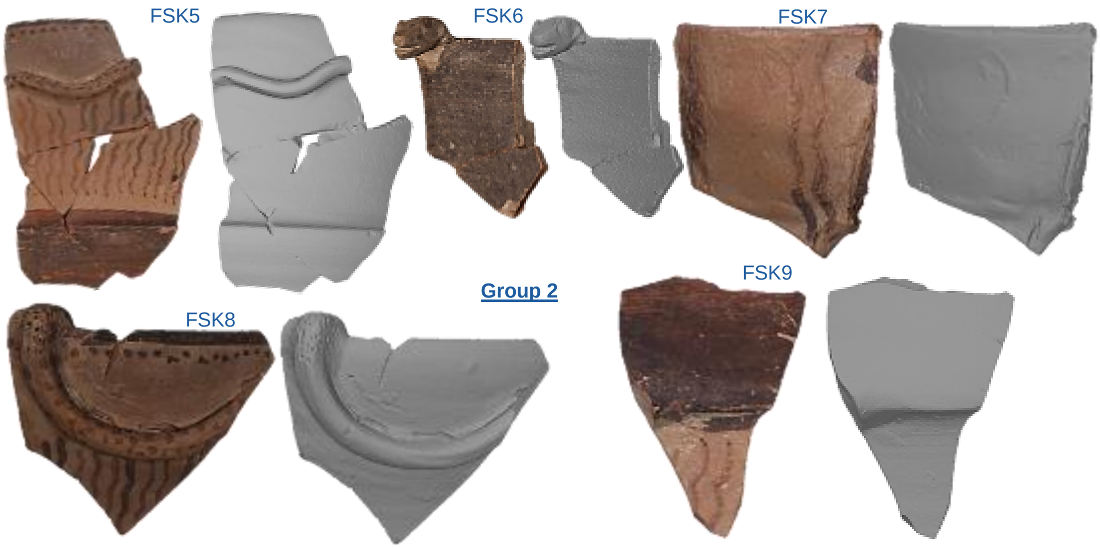

Fig. 3. Visualisation of the 3D digital replicas from the 2nd group of the sherds (Vertex Paint & Smooth Normals shading)

Table 1 presents a summary regarding the data collection phase of our case study. We can underline that the Ground Sample Distance Averaged is 36.73 μm 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. Removing the images was based on the ability to generate a complete 3D reconstruction without the use of image sets that were considered *supplementary* during the data collection phase but they were performed due to the fact that we were able to have access to the sherds once.

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.

Data processing

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. 4).

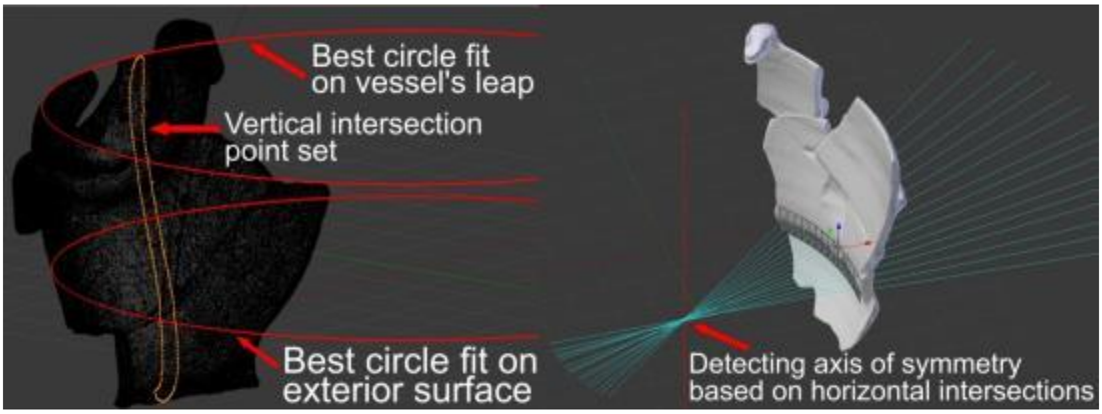

Fig. 4. Detecting the axis of symmetry.

Once the axis of symmetry was defined, the second step was to organise the sherds into two groups and manually align them (Fig. 5, 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 sherd groups have no complementary parts and their positioning around the axis of symmetry was based only on the location of the handles.

Fig. 5.Spatial alignment of the sherds in Group 1.

Fig. 6. 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. 7). The whole alignment process was performed manually within Blender.

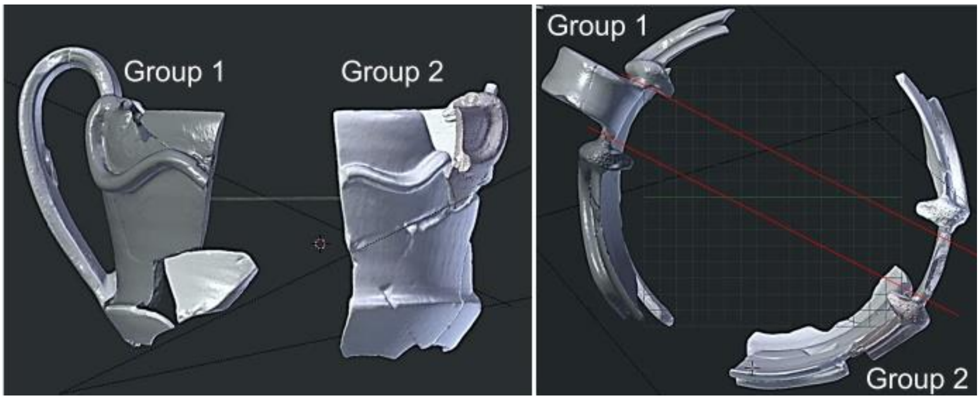

Fig. 7. Groups aligned around the axis of symmetry while using handles as a strong indicator.

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 synthetic main body) were accurately removed (Fig. 8). 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.

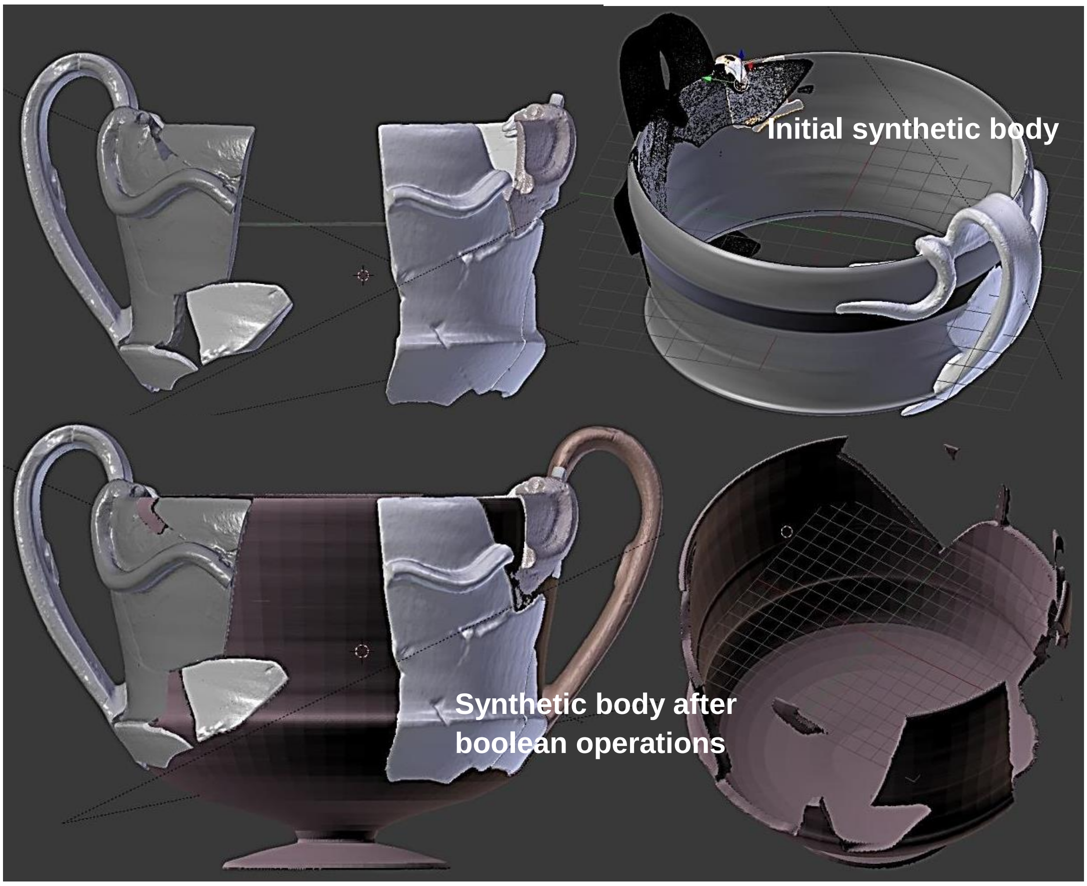

Fig. 8. Create Missing Parts.

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. 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.

Fig. 9. Different viewpoint renderings of the virtually reconstructed Kantharos.

5. ***What was the result of the documentation process?***

- Provision of the basic types of Kantharoi from renowned publications, like the one of M. Tiverios about ancient Greek vases.
- Provision of similar vases from online repositories, like the Corpus Vasorum Antiquorum database and the Beazley Archive Pottery Database.
- Provision of photographs from Corpus Vasorum Antiquorum and Beazley Archive Pottery Database with ancient vases showing Kantharoi being used either in symposia or rituals.
- Provision of photographs with joined Kantharos fragments, positioned in a circle in order to faithfully complete the 3D reconstruction.
- Digital visualisation of original fragments of Kantharos with the Structure-from-Motion & Multiple View Stereovision (SFM/MVS) approach.
- Virtual reassembly of the fragments of the vase and missing parts completion of the Kantharos through a manually implemented pipeline using Blender and Matlab.
- Visualisation of original fragments versus synthetic main body.
- Selection between several versions of the model, mainly according to various Kantharoi's bases, of the best fitting one to the potential initial state of the vase.
- Understanding of the potential original shape of the Kantharos and consideration of the sherds degradation and/or deformation on the matching surfaces.

- Creation of a model for its comparison with the future conservation status of the actual vase.
- Creation of a video with the procedure of the 3D digitization and reconstruction.

6. What was very particular and might (largely) change in similar cases?

The specific vase is unique in terms of its decoration, for not fitting sufficiently into a particular workshop so far and for its profile that does not follow the typical known examples of its time.

7. Which practical / conceptual / object related aspects need to be highlighted?

- The vase digitised, though unique for its decoration, is extremely common in archaeology in terms of its fragmented nature and the complete lack of information regarding its base and foot.
- The 3D model produced is a big improvement to the traditional graphic archaeological documentation system, providing high image quality and a digital replica of the vase in real dimensions.
- Need for the 3D models to become even more effective for research. This specific work can serve 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 the need to avoid manual processing, as much as possible, for limiting time and costs, in terms of the feasibility of the whole procedure, from a material and financial point of view. This automation could be applied for both the reconstruction of the vase and for the creation of sections and other views of the vase.
- The 3D model is 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.
- The case study was conducted by both a) the excavator of the vase (a pottery expert) and b) the technology expert (with big experience in 3D modeling of cultural heritage). This is an important element when an end-user is thinking about digitisation and reconstruction techniques.

8. What are the limitations and sources of error?

Data acquisition: 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.

Data processing: 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.

9. ***What are the benefits of the recording technique(s)/method(s)/data in comparison to traditional methods?***

- Ability to semi-automatically perform a data collection phase while ensuring the quality of the resolution and accuracy by using the specific software solution (AgisoftPhotoscan).
- The ability to extract better, in terms of resolution, 3D data reconstructions in the near future due to the continuous increase of GPU processing power and available RAM. Given the fact that 20MPs images were captured during the data collection phase, the software can provide one more 3D reconstruction resolution step (defined as ultra high) which has not been used due to the current limitations of hardware.
- Creation of several versions of the reconstructed model through a semi-automated procedure and selection of the best fitted one,
- Creation of a digital replica of the vase in real dimensions and in high quality that the archaeologists can easily handle, manipulate and study,
- Creation of a detailed model for its comparison with the future conservation status of the actual vase,
- Use of the digital model in various digital platforms, such as the excavation Website and the excavation virtual museum, and as digital material for university lectures.