VOLUME COMPUTATION OF ARCHAEOLOGICAL VESSELS[1]

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At excavations a large number of sherds of archaeological pottery is found. Since the documentation and administration of these fragments represent a temporal and personnel effort, we construct a computer aided documentation system for archaeological fragments to form the basis for a subsequent semi-automatic classification and reconstruction. The main technical goal of this project is to perform an automated classification based on the profile section of the oriented object, which is the cross-section of the fragment in the direction of the rotational axis of symmetry. To achieve the profile, a 3d-representation of the object is necessary. The final aim is to provide a tool that helps archaeologists in their archivation process. This paper gives an overview about an automated archivation process and 3d-acquisition with respect to archaeological requirements.

Calcul de volume des vases archéologiques à partir de la forme de silhouette

Un grand nombre de fragments de la poterie archéologique est découvert lors de l'excavation. Cependant, la documentation et la gestion de ces fragments représentent un effort temporel et personnel. A ce propos, nous avons mis en œuvre un système de documentation assisté par ordinateur pour que les fragments archéologiques forment la base pour une classification et une reconstruction semi-automatique. Le principal objectif de ce projet est d'effectuer une classification automatisée, basée sur la section de profil de l'objet orienté, qui est la section transversale du fragment en direction de l'axe de rotation de la symétrie. Une représentation 3D de l'objet s'avère donc nécessaire. L'objectif final est de fournir un outil qui serve les archéologues dans leur processus d'archivation. Cet article présente une description du processus automatisé d'archivation et de l'acquisition 3D en tenant compte des conditions archéologiques.

1. INTRODUCTION

New technologies are introduced to old research areas and provide new insights for both researchers and people interested in this field. This statement can be proved especially in the field of archaeology, since there are many researchers in that area who already use new technologies and there are many people interested in the field of archaeology since so-called archaeo-parks have an increasing number of visitors [FB93, AA01].

Motivated by the requirements of the present archaeology, we are developing an automated system for archaeological classification of ceramics. Ceramics are among of the most widespread archaeological finds, having a short period of use. A large number of ceramic fragments are found at nearly every excavation and have to be photographed, measured, drawn (Figure 1) and classified.

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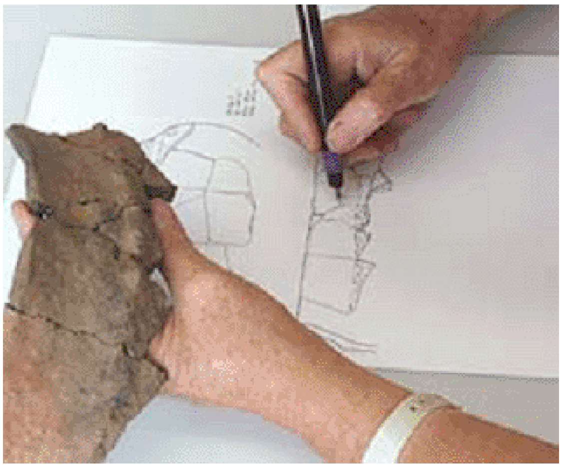


Figure 1: Manual Drawing of fragments

Because the conventional methods for documentation and classification are often unsatisfactory [OTV93], we are developing an automated archivation system [KS99] that tries to combine traditional classification methods with new techniques in order to get an objective classification scheme.

Late-roman burnished ware, which was found during the excavations from 1968 to 1977 in the legionary fortress of Carnuntum in Austria [Kan75, Kan79], was chosen as the basis for our research [Grue79, Grue86]. In addition to these sherds we enlarged our material basis with published pieces from other pannonian sites.

The purpose of classification is to get a systematic view and order on the excavation finds: treating every sherd as unique inhibits a clear view of the material (like not seeing the wood for the trees). Archaeological classification is traditionally done by typology: more or less defined forms are identified to possess certain significance and then addressed as "types". These "types" can be used as a sort of "label", which simplifies comparative the scientific field [Ric87, AA91, Sin91, Ber97, Egg01]. Furthermore, with the recognition of vessel types, patterns can be recognized. Hence, classification provides the basis for statistical analysis.

But archaeologists often leave their typologies at an "impressionistic" or indefinite level, because their main task is only to present new material. There have been many attempts to objectify and standardize shape description and classification - also in connection with systems for automated recording [Kam87, Ste89, PB97] -, but in practical archaeological research most of the consequent formal and mathematical classification schemes did not find a wider reception or application because they are often too vague, abstract, reductionistic or unpracticable [OTV93].

The attributes of a successful classification have been summarized by Orton and others [OTV93]

- objects belonging to the same type should be similar (internal cohesion)
- objects belonging to different types should be dissimilar (external isolation)
- the types should be defined with sufficient precision to allow others to duplicate
- it should be possible to decide which type a new object belongs to

In order to achieve these aims our classification scheme of the vessel form is based on

- absolute measurements and ratios
- segmentation of the profile line

The first steps are the measurements of the following parameters: rim diameter, bottom diameter, height, x- and y- values in all segmentation points. With these measurements a variety of ratios can be calculated. A special choice of these ratios is in each case characteristic for one vessel type; for example the ratio rim diameter to height or maximum diameter of the neck to maximum diameter of the belly.

The second aspect of classification is the segmentation of the vessel into its parts, the so-called primitives. The basis for this segmentation is the outer profile line that means the profile line along the outside of the vessel. The curve is described by means of a modified Cartesian system of co-ordinates. The x-axis of the system of co-ordinates lies in the orifice plane; the y-axis corresponds with the axis of rotation. The position of the curvature points is defined by means of x- and y-values. The profile line is situated in the right lower quadrant, so that not only complete vessels, but also rim fragments can be described [KAM87].

The profile of the vessel is composed of several segments, the so called primitives, for example: rim, neck, shoulder etc. If there is a corner point, that is a point, where the direction of the curve changes ``substantially", the segmentation point is obvious. If there is no corner point, the segmentation point has to be determined mathematically [She56, AA91].

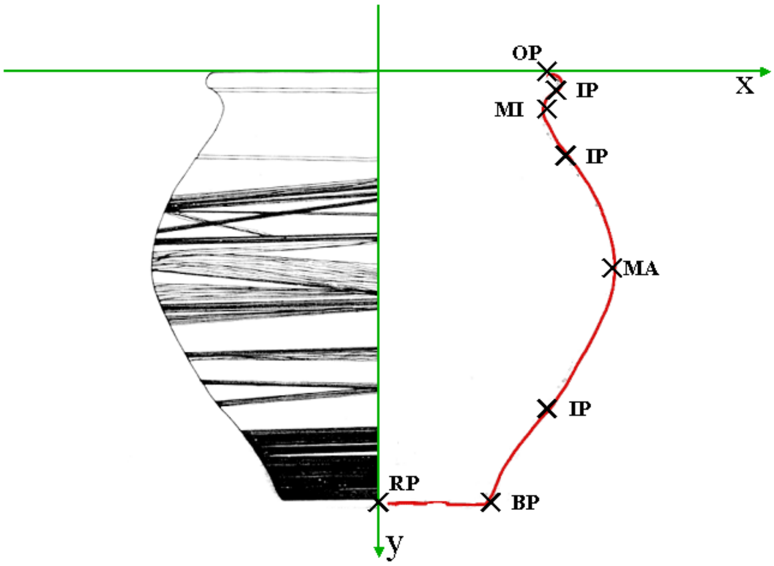


Figure 2: S-shaped vessel: profile segmentation scheme

Several points characterize the curve; Figure 2 shows the segmentation scheme of an S-shaped vessel as an example:

- **IP** *inflexion point*: point, where the curvature changes its sign, that means where the curve changes from a left turn to a right turn or vice versa;
- **MA** *local maximum*: point of vertical tangency; point, where the x-value is bigger than in the surrounding area of the curve;
- **MI** *local minimum*: point of vertical tangency; point, where the x-value is smaller than in the surrounding area of the curve;
- **OP** *orifice point*: outermost point, where the profile line touches the orifice plane;
- **CP** *corner point*: point, where the curve changes its direction substantially;
- **BP** *base point*: outermost point, where the profile line touches the base plane;
- **RP** *point of the axis of rotation*: point, where the profile line touches the axis of rotation;
- **SP** *starting point*: in case of vessels with a horizontal rim: innermost point, where the profile line touches the orifice plane;
- **EP** *end point*: in case of fragments: arbitrary point, where the profile line ends;

Figure 3: One piece-vessel (a) and Two-piece vessel (b)

On the basis of the number and characteristics of the segments three kinds of vessels can be identified:

1. One-piece vessels (Figure 3a): These vessels consist of only one main segment. Their sides extend continuously inward or outward without reaching a point of vertical tangency;
2. Two-piece vessels (Figure 3b): These vessels consist of two main segments: upper part and lower part;
3. Multi-piece vessels (Figure 2): These vessels consist of three or more main segments. A special kind of them are the so-called S-shaped vessels, which are composed of neck, shoulder and belly.

This paper is organized as follows: we started we a short introduction into archaeological classification and explained the criteria, which are used to establish a classification system. Section 2 deals with shape from silhouette for reconstruction of whole archaeological objects. In section 3 shape from structured light for the reconstruction of fragments is presented. A laser ranges sensor is described in section 4. Results are given at the end of each section. This paper gives an overview about 3D acquisition methods used for the reconstruction of archaeological finds. We conclude with a summary and an outlook on future research.

2. SHAPE FROM SILHOUETTE FOR 3D MODELING OF COMPLETE OBJECTS

Shape from Silhouette is a method of automatic construction of a 3D model of an object based on a sequence of images of the object taken from multiple views, in which the object's silhouette represents the only interesting feature of an image [Sze93, Pot87]. The object's silhouette in each input image corresponds to a conic volume in the object real-world space (see Figure 4). A 3D model of the object can be built by intersecting the conic volumes from all views.

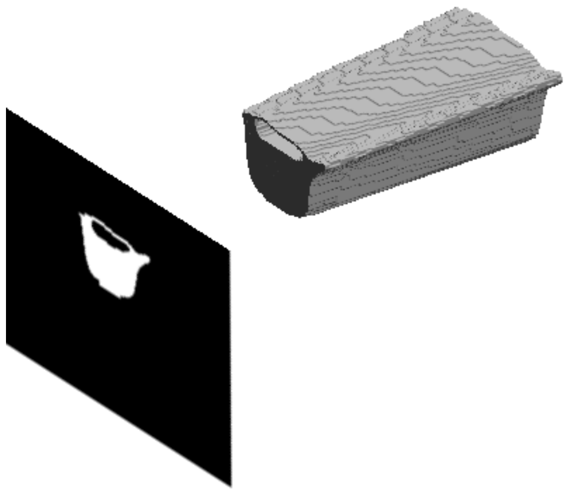


Figure 4: Image silhouette and the corresponding conic volume

Shape from Silhouette is a computationally simple algorithm --- it employs only basic matrix operations for all transformations --- and it requires only a camera as equipment, so it can be used to obtain a quick initial model of an object, which can then be refined by other methods. It can be applied on objects of arbitrary shapes, including objects with certain concavities (like a handle of a cup), as long as the concavities are visible from at least one input view. It can also be used to estimate the volume of an object. The shape from Silhouette algorithm used is described in detail in [Tos00].

The acquisition system [KT00] consists of the following devices:

- a monochrome CCD-camera with a focal length of 16 mm and a resolution of 768x576 pixels
- a turntable with a diameter of 50 cm, whose desired position can be specified with an accuracy of 0.05 degrees

An important issue is the illumination of the object observed, which should be clearly distinguishable from the background, independent from the object's shape or the type of its surface. For that reason back-lighting [HS91] is used. A large (approx. 50x40 cm) rectangular lamp is put behind the turntable (as seen from the camera). In addition, a white piece of paper, larger than the lamp, is put right in front of the lamp, in order to make the light more diffuse. The whole system is protected against the ambient light by a thick black curtain.

Prior to any acquisition, the system is calibrated in order to determine the inner and outer orientation of the camera and the rotational axis of the turntable. The calibration method used was exclusively developed for the Shape from Silhouette algorithm used and it is described in detail in [Tos99] and [KT00].

Figure 5 shows the reconstructed 3D models of the two pots from three sides. For these models octree of resolution of 256^3 voxels was built, based on input images from 36 views.

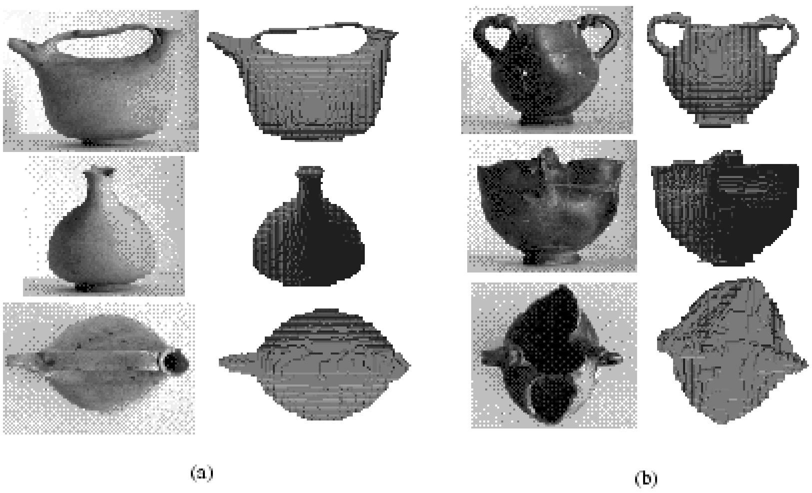


Figure 5: Constructed models of real objects in different voxel resolution

The results with both synthetic and real input data show that there is a certain minimal octree resolution required to obtain an accurate model of an object, especially for highly detailed objects, like the two pots used for tests with real images. Concerning the number of input views used for obtaining a model of an object, it turned out that beginning from 12 views, the constructed model does not change significantly. In our tests the octrees built from 12 views were almost the same as the ones built from 36 views, except that they took much less time to construct.

The results with synthetic data, where we had a perfect transformation matrix, showed that the error in the dimensions of the model lies within or is slightly higher than the error introduced through the minimal voxel size. The error with real data depends additionally on the accuracy of the calibration algorithm. The results also showed that the algorithm works much better with oval objects, i.e., with objects that do not have completely flat surfaces or sharp edges.

3. CODED LIGHT FOR 3D RECONSTRUCTION OF FRAGMENTS

Our documentation system for archaeological fragments is based on the profile, which is the cross-section of the fragment in the direction of the rotational axis of symmetry. Hence the position of a fragment (orientation) on a vessel is important. To achieve the profile, a 3d-representation of the object is necessary.

Archaeological pottery is assumed to be rotationally symmetric since it was made on a rotation plate. With respect to this property the axis of rotation is calculated using a Hough inspired method [YM97]. To perform the registration of the two surfaces of one fragment, we use a-priori information about fragments belonging to a complete vessel: both surfaces have the same axis of rotation since they belong to the same object.

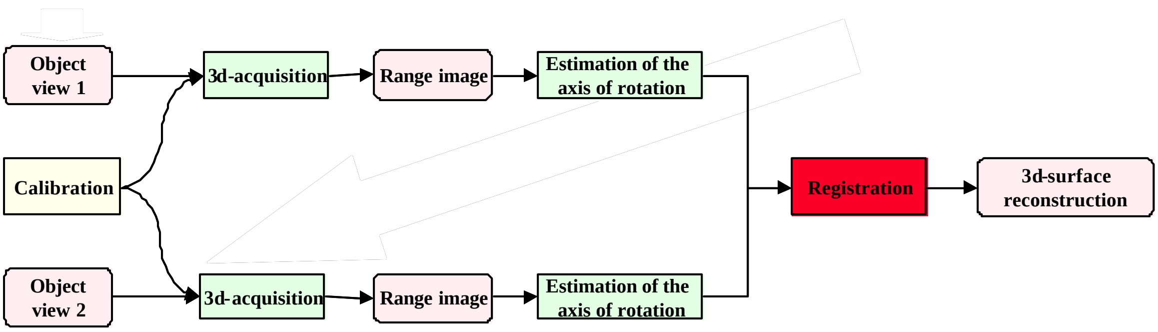
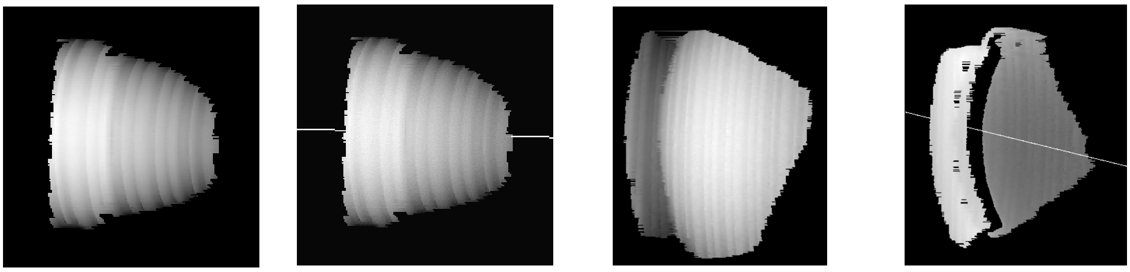


Figure 6: 3d surface reconstruction overview

Figure 6 gives an overview of a 3d-surface reconstruction from two object views. The first step consists of sensing the front- and backside of the object (in our case a rotationally symmetric fragment) using a calibrated 3d-acquisition system. We register the resulting range images by calculating the axis of rotation of each view and bringing the estimated axes into alignment. The method is described in detail in [Kam99].

In our acquisition system the stripe patterns are generated by a computer controlled transparent Liquid Crystal Display (LCD 640) projector. The light patterns allow the distinction of 2^n projection directions. Each direction can be described uniquely by a n-bit code. A CCD-camera is used for acquiring the images.

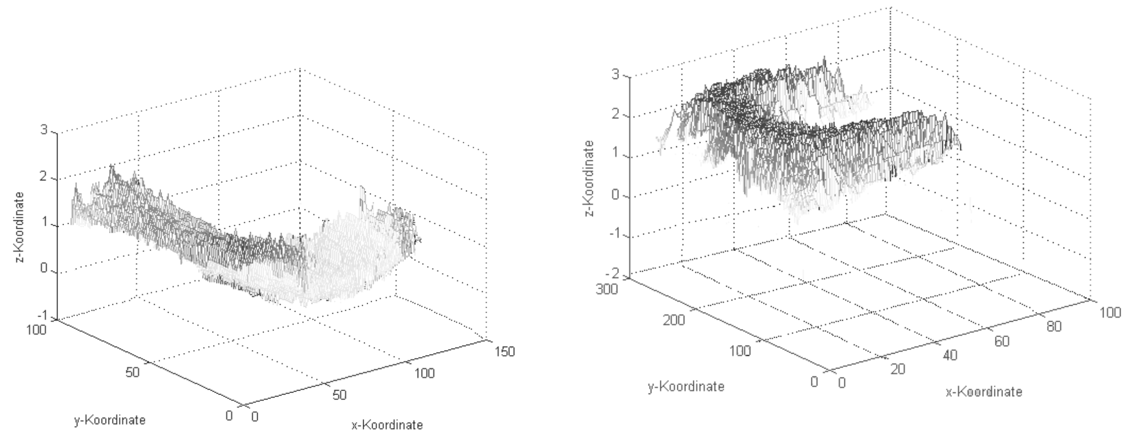
The projector projects stripe patterns onto the surface of the objects. In order to distinguish between stripes they are binary encoded. The camera grabs gray level images of the distorted light patterns at different times. With the help of the code and the known orientation parameters of the acquisition system, the 3d-information of the observed scene point can be computed. This is done by using the triangulation principle. The image obtained is a 2D array of depth values and is called a range image (Figure 7).



(a) (b) (c) (d)

Figure 7: Front- and back-view (range images) and their axis of rotation of a flowerpot (a, b) and an archaeological fragment (c, d).

To find out if the method is working on real data we used a totally symmetric small flowerpot with known dimensions and took a fragment which covered approximately 25% of the original surface. The range images of the front- and back-view consisted of approximately 10.000 surface points each (Figure 7a, b). The mean distance d between the surfaces is 5.64mm and the registration error δ=1.42mm. The distribution of the registration error delta for the flowerpot is shown in Figure 8a. The registration error increases towards the top of the pot, because of the irregularity of the distance between the surfaces at that region since the flowerpot has an edge (upper border) where inner and outer surface are not parallel.



(a) (b)

Figure 8: Distribution of d **for registered flowerpot (a) and archaeological fragment (b)**

Figure 7c and d show the front-view, back-view and the axis of rotation of a real archaeological fragment. Registration tests with this fragment resulted in registration errors of approximately δ=1.7mm and a mean distance of d=5.8mm.

Figure 8b shows the distribution of δ of a registered archaeological fragment. Marginal peaks are caused by shadow regions of the back-view (see Figure 7d) at the border of the fragment, where either no range data is processed or the range information is unreliable. The increase of the registration error δ reflects the uneven surface of the fragment.

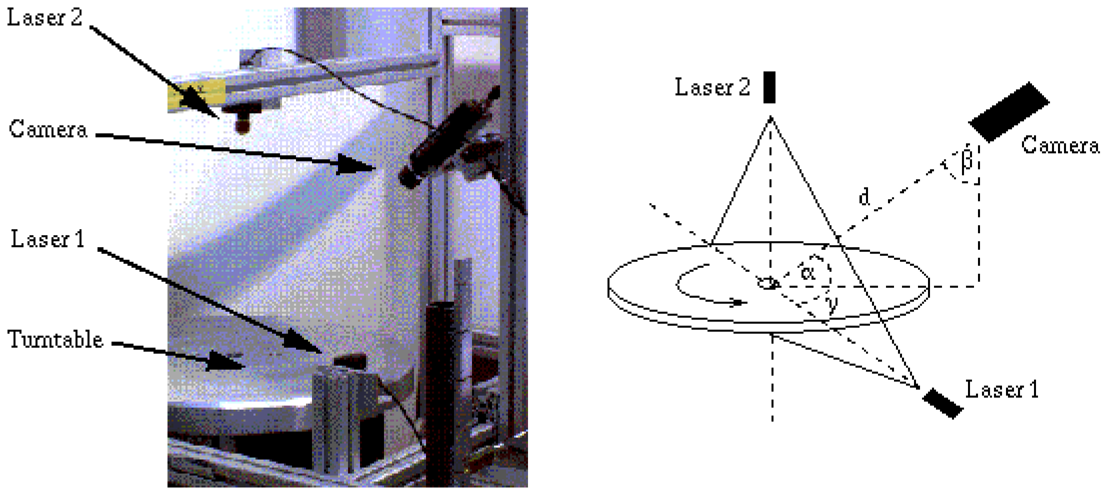
Further problems that arise with real data are symmetry constraints, i.e. if the surface of the fragment is too flat or too small; the computation of the rotational axis is ambiguous (worst case: sphere) which results in sparse clusters in the Hough-space, which indicate that the rotational axis is not determinable.

4. LASER RANGE SENSOR

The acquisition method used for estimating the 3d-shape of objects is shape from structured light, based on active triangulation [PT96]. The camera is positioned between the two lasers facing the measurement area. The complete system consists of

- 1 turntable with a diameter of 50 cm, which can be rotated about the z-axis, used to move the object of interest through the acquisition area.
- 2 red lasers to illuminate the scene, one mounted on the top (distance to rotation plane is 45 cm), one beside the turntable (distance to the rotation center is 48 cm). Both lasers are extended with cylindrical lenses to spread the laser beam into one illuminating plane. The laser light plane intersects with the object surface, forming one laser stripe.
- 1 CCD-camera (b/w) with a 16 mm focal length, a resolution of 768x572 pixels, and a distance of 40 cm to the rotation center. The angle between the camera normal vector and the rotation plane is approx. 45 degrees. A frame grabber card is used to connect the camera to a PC.
- 1 Intel Pentium PC under Linux operating system.

Figure 9 depicts the complete hardware setup (a) and its geometric arrangement (b).



(a) (b)

Figure 9: Acquisition system

An iterative process for 3d surface reconstruction in static environments is defined by the following steps, which depicts this process

- Image acquisition: The scene is captured by the CCD-camera. The result is a greyscale- image, which shows the intersection between the laser plane and the object that is a line.
- Feature extraction: The line shown in the camera image is extracted. The result is a set of 2d points.
- Registration: The set of 2d points extracted in the previous step is transformed from the world coordinate system in its object coordinates.
- Integration: Each registered point is integrated into the existing model computed and integrated at the previous iterations of the acquisition process.
- Next View Planning: The next viewing angle is computed based on the algorithm shown in the previous section and the turntable moves to the calculated absolute angle. The process repeats until the turntable revolves one complete rotation.

▪ 3d-model visualization of the reconstructed surface.

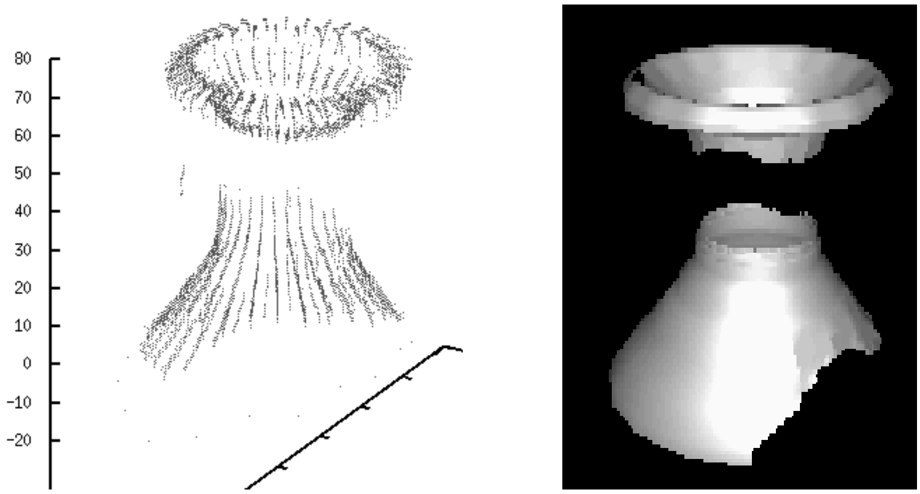


Figure 10: Reconstruction of pottery

Figure 10 shows the reconstruction of the head of an amphora after the acquisition process. The choosen angles are between 4 and 12 degrees. The analysis of the reconstruction data shows that the axis of symmetry is switched from the center of rotation by 1.8mm in x-direction and 2.1mm in y-direction. In order to scan the whole image 36 steps were necessary. Figure 2b shows the rendered object after the surface reconstruction process. The visualization results from a modified z-buffer-algorithm.

5. CONCLUSION AND OUTLOOK

We have proposed a prototype system for 3d acquisition of archaeological fragments. The work was performed in the framework of the documentation of ceramic fragments. The methods proposed have been tested on synthetic and real data with reasonably good results. It is part of continuing research to improve the results from multiple, various objects since the technique has some drawbacks. The first one refers more to the calibration algorithm, which makes many simplifying assumptions about the acquisition system.

The achieved fragment representations, the first part of an automated system for classification of archaeological fragments, are the input of the second part of the system, classification. The classification will be solved in the high dimensional real space and therefore the uniqueness and the high precision of the profile representation are very important. The current work focuses on finding a unique orientation of profiles and on the final identification of vessels.

For archaeological applications, the object surface has to be smoothed in order to be applicable to texture mapping and therefore ceramic documentation, for classification, however, the accuracy of the method presented is sufficient since the projection of the decoration can be calculated and the volume estimation is much more precise than the estimated volume performed by archaeologists.

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