ROBUST 3D RECONSTRUCTION OF ARCHAEOLOGICAL POTTERY BASED ON CONCENTRIC CIRCULAR RILLS

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ABSTRACT

In the area of archaeology surveying, documentation, classification, archivation and reconstruction of pottery, which is often found as thousands of fragments - so called sherds - at excavations is of major concern since statistics about social, cultural and technological status of a population can be made out of this information. Therefore we are developing an acquisition, classification and reconstruction system that is inspired by the archaeological methods. As a result of the manual manufacturing process, potter's wheel made archaeological objects contain concentric rills on their surface. Together with the axis of rotation, which is the cross-section of the fragment in the direction of the rotational axis of symmetry, these rills form the basis for a robust 3d reconstruction. We present a fully automated approach to pottery reconstruction based on the fragment's rills. We demonstrate the method and give results on synthetic and real data.

1. INTRODUCTION

Ceramics are one of the most widespread archaeological finds and are a short-lived material. This property helps researchers to document changes of style and ornaments. Especially ceramic vessels, where shape and decoration are exposed to constantly changing fashion, not only allow a basis for dating the archaeological strata, but also provide evidence of local production and trade relations of a community as well as the consumer behavior of the local population [OTV93].

The traditional method of documentation of fragments is a drawing of the profile line, which is an intersection of the fragment along the axis of symmetry (also called rotational axis), which can be found for fragments manufactured on rotational plates [YM97]. Finding this axis of rotation and drawing the profile line by hand requires expert knowledge and a certain amount of time. Therefore we are developing a fully automated system for acquisition and documentation of profile lines using a 3D scanner based on structured light [KS03,MSKS04]. The range- and pictorial information of a pottery fragment recorded by the 3D scanner serves as the basis for the classification and reconstruction process. The most important step is the determination of the profile of the fragment in the so-called orientation step. The term orientation describes the exact positioning of the fragment on the original vessel with the help of the axis of rotation. To automate this process, the profile has to be determined in the same way as in the manual documentation. The profile is rotated by the original axis of rotation, thus measurements like volume can be estimated.

Thus the process of documenting a fragment is improved since the important steps measuring, drawing, and describing are automated. With the help of 3-D data, the profile of the fragment is constructed. The frontal view is represented with the help of the pictorial information of the surface of the fragment and the surface model. This representation can be used for publication or for retrieval from the database, put on the Internet by other users. This will enable it to publish both the profile of the fragment and a virtual reconstruction of the whole vessel.

The paper is organized as follows: In Section 2 details on data acquisition and the rill-based orientation technique are given, Section 3 comments on the automatic profile generation are given and Section 4 shows results and finally a conclusion is given.

2. DATA PROCESSING

The acquisition method for estimating the 3D-shape of a fragment is shape from structured light [PT96], which is based on active triangulation [Besl88]. We used the Vivid 900 3D Scanner developed by MINOLTA. Optionally the object is placed on a turntable with a diameter of 40cm, whose desired position can be specified with an accuracy of 0.1°. The 3D Scanner works on the principle of laser triangulation combined with a color CCD image. It is based on a laser-stripe but a galvanometer mirror is used to scan the line over the object.

Fragments of vessels are thin objects, therefore 3d-data of the edges of fragments are not accurate and this data can not be acquired without placing and fixing the fragment manually. Ideally, the fragment is placed in the measurement area, a range image is computed, the fragment is turned and again a range image is computed. Registration is the process of aligning two or more views of an object from a scene, in our case the front- and the back-view of the fragment. To perform the registration of the two surfaces, 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. Furthermore, the distance of the inner surface to the axis of rotation is smaller than the distance of the outer surface. Finally, both surfaces should have approximately the same profile, i.e. the thickness of the fragment should be more or less constant. With respect to this property the axis of rotation is calculated using a Hough-inspired method [YM97]. 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. Due to our experiments we have seen that the method of finding the axis of rotation by the normal vectors fails for S-shaped objects. The Hough-inspired method works best for fragments of cylindrical or conical shaped vessel. So we choose a new method for estimation of the axis of rotation inspired by the manual method used by archaeologists.

The traditional, manual way to determine the axis of rotation is to look orthogonal at the inner side of the fragment, where you can see rills from the manufacturing process. These rills are artifacts from tools or fingers used while giving the object its shape on the rotational plate. These rills describe concentric circles with their centers along the rotational axis. So the fragment has to be twisted and tilted until the rills are positioned horizontally. For estimation of the radii or when the rills are not clearly presented, archaeologists use circle-templates to estimate the axis of rotation given by the center of the circle-templates.

In order to improve the robustness of the approach we match segments of circles like archaeologists do with circle-templates. For a first preliminary estimation circle templates are matched orthogonal to a plane fitted into the inner part of the fragments surface. The circle template with the lowest deviation of circle centers is used to iteratively find the rotational axis described by a set of concentric circles (Figure 1).

The first step of this method is to identify the inner side of the fragment where the rills are located. For many, but not all fragments rills can be found also on the outer side. Due to the fact that the outer side can have applications like handles or decorations, we always use the inner side. As we have two surfaces (inner- and outer side) we have to find the correct 2.5D surface by measuring the curvature of both surfaces. The sign of the curvature for each vertex of the surface corresponds to a concave or convex part of the surface. To estimate the curvature we determine the geodesic neighborhood [SA01] for each vertex fitting a second degree polynomial function [VH96].

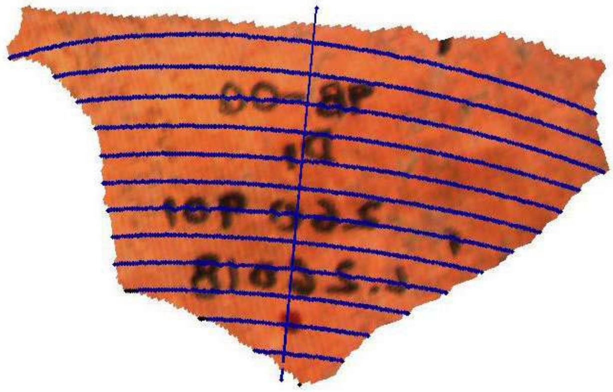

Fig. 1: Orientated fragment showing computed circular rills and axis of rotation

The 2.5D image generally contains parts of the surface of the breakage, which is not part of the inner side of the fragment. In case of bottom fragments there can even be a plane, where no concentric rills are present. Therefore we have to remove the breakage and parts of the bottom plane. This is done by segmenting the surface into parts with high, medium and low curvature and removing the parts with high and low curvature. Additionally we remove vertices along the border of the surface, because they often contain incorrect vertices introduced by the sliding intersection of the laser-beam with the surface of the fragment.

The next step is to find a preliminary estimation of the rotational axis. The algorithm is based on the manual approach, where the fragmented is tilted and rotated, so that the concentric rills can be seen as parallel lines, which are orientated horizontally. Therefore we estimate the mass point and the balancing plane of the remaining vertices of the reduced inner surface. The balancing plane is described by the two longest eigen-vectors of the mean-normalized vertices, which are estimated by using the singular value decomposition (SVD) [Strang88]. The preliminary estimation uses an iterative search for concentric circles along *n* hypothetical axes. These hypothetical axes are defined by the mass point and the longest eigen-vector which is rotated about the mass point in the balancing plane (Fig. 1).

Along the hypothetic axes we fit circles and estimate their center. In general these centers are not concentric, but when a hypothetic axis is coplanar to the rotational axis, the centers are also coplanar. For each hypothetic axis the variance of distances between the circle centers and a plane defined by the hypothetic axis is estimated. The variance can have zero, one or two global minima. In general there is one minimum. There are two minima for U-shaped fragments, where the second smallest minima describe an orthogonal rotational axis. If the fragment is part of a sphere there is no minimum, because in this case no single axis of rotation exists.

A line is fitted then by minimizing the least-square error to the centers of the concentric circles with the minimum variance. The fitted line is used as estimated rotational axis. It is tilted orthogonal towards the balance plane to find the best line fit. After each tilt the centers of the concentric circles are estimated. For these centers a line fitting is applied. The line with the best fit is chosen as rotational axis.

3. PROFILE ESTIMATION

The processing of the profile begins with an estimation of the proper orientation of the fragment, because the calculation of several measurements (e.g. heights, diameters, etc.) depends on it. To estimate the longest profile line we use the orientated fragment. This profile is supposed to be the longest elongation along the surface of the fragment parallel to the rotational axis through two points. This profile line is located where the fragment has its maximum height. The height is defined as the orthogonal distance from a point of the fragment to the orifice plane of the object.

With the parameters of a plane that intersect the fragment where the longest profile line is located the distances between the plane and each vertex of the 3D-model are calculated. Then the nearest 1% of points are selected as candidates for the profile. For each of those vertices all the patches they belong to are filtered through a search in the patch list with their index number. In Fig. 2a fragment colored by the value of distance is shown (lighter means nearer to the intersecting plane). Every patch is a triangle, which consists of three points that are connected through three lines.

The position is calculated for all these three combinations of pairs of points of the filtered patches. The Hessian normal form is used to calculate the distances between the points and the plane. We use the sign of the distances, which corresponds to the side of the plane on which a point is located. Every pair of vertices that has both points on different sides of the plane is part of the profile line, because its connection intersects the plane. The coordinates of these pairs are rotated into the *xy*-plane and the *z*-coordinate is removed. This result is a properly oriented profile line (Fig. 2b).

4. RESULTS

We used 35 selected fragments for testing the robustness of our system. These 35 fragments were selected among the daily finds with the criteria that their size is

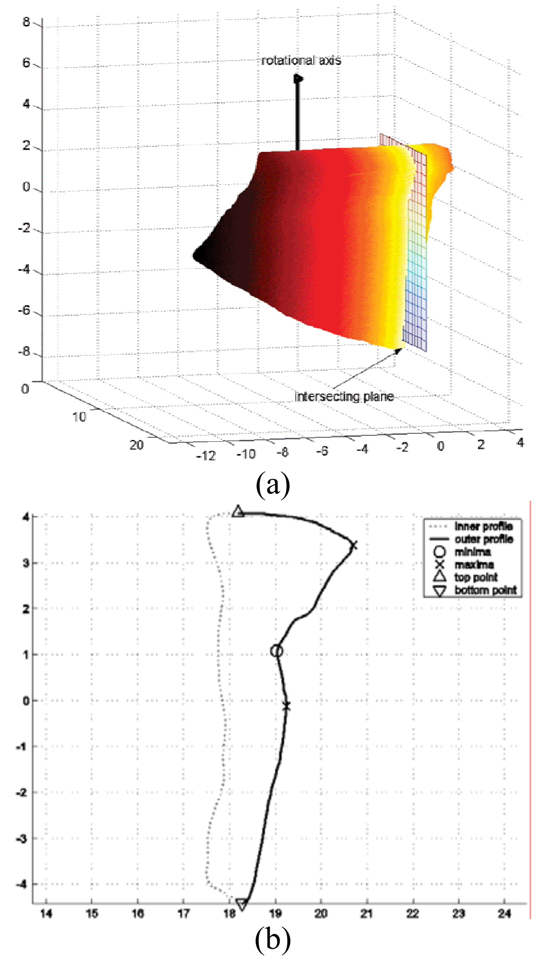

Fig. 2: Properly oriented fragment and intersecting plane for profile extraction (a) Estimated oriented profile with extremal points for classification (b)

small and their curvature is low, so that the axis of rotation is also difficult to find by manual orientation. It is important to mention that the ground truth is not present for all findings. So we can divide the results of experiments, where the three methods do not agree, into two different groups. The first group shows alternative profile lines estimated by our objective and repeatable method based on the geometry of an object, which might be camouflaged for the human eye by decorations or applications. The second group consists of fragments that have to be tagged as not processable and therefore analyzed by archaeologists to classify them not by the profile line. Instead of the profile line, properties like material or context to other finds can help to classify a fragment, when no profile line can be found.

We already proposed a rate of successfully processed fragments for daily findings in general (KS03]. With our new approach, we could increase this ratio for fragments that could not be processed based on the Hough-inspired method. The ratio for our 35 fragments is approx. 50% of the fragments have the same result for all three methods. For 30% of these fragments the radii varies less than 20mm and the orientation differ for a maximum of 20°. The remaining 20% were not properly processable.

Sherd Locus No. from Area D2	Δr (mm) min/max	$\Delta\alpha$ min/max	min Correlation	max Correlation
19732-305940-6	10/20	5°/15°	Man.-*Prof.*	*Prof.-3DS.*
19742-305996-2	10/15	15°/45°	Man.-*Prof.*	Man.-*3DS.*
19743-306028-4	5	20°	*Prof.*n.a.	
19743-306051-2	0/15	5°/15°	*Prof.-3DS.*	Man.-…
19732-305940-1	25	5°	Man.n.a.	
19732-305940-1	5	10°	Man.n.a.	
19742-305996-4	60	5°	Man.n.a.	
19742-305996-1	15/15	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
19743-306028-6	10/10	5°/5°	Man.-*3DS.*	*Prof.-3DS.*
19743-306028-4	10/40	10°/30°	Man.-*3DS.*	Man.-*Prof.*
19742-305996-3	20	5°	*Prof.*n.a.	
19743-306028-2	20/50	5°/50°	Man.-*Prof.*	Man.-*3DS.*
19732-305940-7	5/50	10°/80°	n.a.	all
19732-305940-11	15	20°	*Prof.*n.a.	
19739-306012-5	5/10	5°/5°	*Prof.-3DS.*	Man.-*3DS.*
19732-305940-5	5/15	10°/10°	Man.-*3DS.*	Man.-*Prof.*
19743-306028-3	5/10	5°/5°	Man.-*Prof.*	*Prof.-3DS.*
19739-305994-2	20/25	5°/15°	Man.-*Prof.*	*Prof.-3DS.*

Tab 1: Comparison of Profile-Lines.

Tab 1 shows the numerical result of the comparison. The first column is the unique *id* of the fragment describing the area, locus number and a serial number. The second column shows the maximum and the minimum difference Δ r between the radii at the top-point of the rim. The third column shows the angle between the rim-part of the different profile lines reduced to uniform height of 20mm. The last column shows the pairs, with minimum and maximum correlation of the three profile lines. The results for the radii Δ r have been grouped into 5mm steps, so for example a value of 10 means that Δ r is between 5mm and 10mm. A similar grouping has been applied to Δ α, which is grouped by steps of 5°.

5. CONCLUSION

In this paper a new technique for orientation of fragments based on the rills on the inner side of the fragment was presented. This method is similar to the traditional manual way of estimating the axis of rotation and therefore these two methods were directly compared. The differences between the computerized profile lines and the hand drawings are significant. The radii at the top and bottom point differed only by 0.1mm, but for radii measured along the profile line the maximum difference was ±0.2mm including even a change of the sign of the curvature, which can have an influence on further processing such as classification. So all results showed, that the computerized profile is more accurate than the manual profile.

Since there are still some fragments that cannot be processed using our two methods, we will investigate further improvements based on [PW01] for estimating the axis of rotation, because most of the surfaces contain noise in form of surface roughness and geometrical distortions, which are rather unique compared to industrial applications or experiments with synthetically generated objects.

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