AUTOMATED INVESTIGATION OF ARCHAEOLOGICAL VESSELS

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ABSTRACT

Motivated by the requirements of the present archaeology, we are developing an automated system for archaeological classification and reconstruction of ceramics. This paper shows a method to answer archaeological questions about the manufacturing process of ancient ceramics, which is important to determine the technological advancement of ancient culture. The method is based on the estimation of the profile lines of ceramic fragments, which can also be applied to complete vessels. With the enhancements shown in this paper, archaeologists get a tool to determine ancient manufacturing techniques.

1. INTRODUCTION

Thousands of fragments of ceramics (called sherds for short) are found at archaeological excavation sites. Ceramics are among of the most widespread archaeological finds, have been used for a short period of time for classification purposes. Since the 19th century, the physical characteristics of archaeological pottery have been used to assess cultural groups, population movements, inter-regional contacts, production contexts, and technical or functional constraints (archaeometry). Because archaeometry of pottery still suffers from a lack of methodology, it is important to develop analytical classification tools of artifacts [OTV93]. Traditional archaeological classification is based on the so-called profile of the object, which is the crossection of the fragment in the direction of the rotational axis of symmetry. This two-dimensional plot holds all the information needed to perform archaeological research. The correct profile and the correct axis of rotation are thus essential to reconstruct and classify archaeological ceramics.

In this approach we use complete vessels, because sherds of excavations of living places have been dumped and reused as filling material for floors and walls. Therefore sherds virtually never reassemble a complete vessels and therefore no real ground truth is known. As archaeologists are also excavating burial places, where individual unbroken ceramics or complete sets of sherds are found, our method can be applied on, but is not limited to, individual vessels.

Conclusions about the manufacturing process can reveal important information for archaeologists, because the manufacturing technology gives information about development of an ancient culture, For example archaeologists determine between ceramics, that have been produced on slow or fast turning rotational plates. Another example would be an ongoing discussion between archaeologists about the existence of rotational plates for manufacturing ceramics in South America. The general opinion is that in this region the wheel was not invented and there fore ceramics were produced with a rotational plate (wheel) [WT02] on the other hand-side there is evidence that rotational plates were used [Car86].

As we use structured light as 3D-acquisition method, we can not make an assumption about the internal structure of a ceramic like [WT02], but we can estimate the surface with high resolution (0.1 *mm*). Therefore we can analyze the symmetry and estimate features like deviation of real surfaces with respect to a perfect symmetrical surface. Such features can help archaeologists to decide about the technological advancements of ancient cultures.

The remainder of this paper is organised as follows: Section 2 briefly describes the acquisition technique used for getting 3D surface data of the objects. The estimation of profile lines and the way how we find the proper orientation of the vessels is described in section 3. Section 4 presents experimental results and discusses them. Finally, in Section 5 we draw the conclusions and comment on future work.

2. DATA ACQUISITION

The acquisition method for estimating the 3D shape of a fragment is *Shape from structured light* (SfSL) [DT96], which is based on active triangulation [Bes88]. SfSL is a method which constructs a surface model of an object based on projecting a sequence of well defined light patterns onto the object. The patterns can be in the form of coded light stripes [KSM02] or a ray or plane of laser light [Lis99]. In the process of calibration the parameters to describe the position of the sensors in a reference co-ordinate system and the sensor characteristics of the camera are estimated [KS01]. If the geometry between the light plane and the image is known, then each 2D image point belonging to the laser line corresponds to exactly one 3D point on the surface of the object [KKS96, Shi87]. This process is also called *active triangulation* [Bes88, DT96]. The volume of the fragments to be processed ranges from $3 \times 3 \times 3 cm^3$ to $30 \times 30 \times 50 cm^3$. The *Vivid 900* 3D Scanner in our setup consists of the following devices:

- one CCD-camera with a focal length of 14mm and a resolution of 640×480 pixels, equipped with a rotary filter for color separation.
- one red laser with a wavelength of 670nm and a maximal power of 30mW. The laser is equipped with a galvanometer mirror in order to open loop control the laser beam scanning motion.

Figure 1 illustrates the acquisition setup consisting of the Vivid 900 Scanner connected to a PC and the object to be recorded. 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 colour CCD image. It is based on a laser-stripe but a galvanometer mirror is used to scan the line over the object.

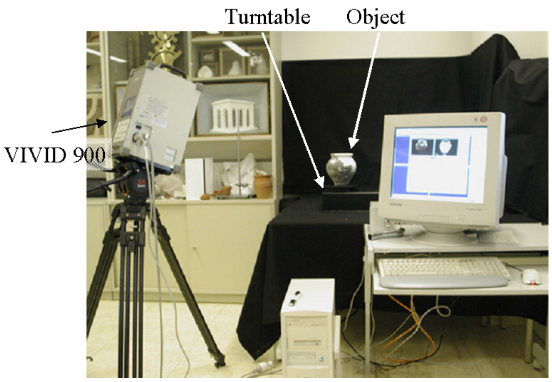


Figure 1: The Minolta VIVID 900 scanner.

Vivid 900 is a portable device, that does not require a host computer. The optional rotating table is used to index the scanned part and capture all sides in one automated process.

3. ANALYSIS REGARDING THE MANUFACTURING PROCESS

We want to present a method to answer archaeological questions about the manufacturing process of ancient ceramics, which is important to determine the technological advancement of ancient culture. The method is based on the estimation of the profile lines of sherds described in [SK02], which can also be applied to complete vessels. With the enhancements shown in this paper, archaeologists get a tool to determine ancient manufacturing techniques.

Regardless of the system used, the orientation of a sherd is the essential part of the documentation. Therefore we show how orientation is done by estimating the rotational axis.

The oldest and well approved approach for orientation is the manual method used by archaeologists for several decades. This manual approach is based on the production process of ceramics, because ceramics have been produced on rotational plates for thousands of years. Therefore ceramics have a rotational axis, which is also called axis of symmetry. This rotational axis is present for fragments of ceramics (sherds). The manual method of finding the orientation of sherds is generally applied on sherds containing a part of the rim or the bottom. As sherds are found in tens of thousands, the remaining sherds from the walls of vessels are not documented, because their manual orientation is more difficult and time consuming. Furthermore the gain of information of the sherds from the wall is minimal, because they generally contain only one or two characteristic points, which is not sufficient for classification. The manual method uses a plane with circle templates (Figure 2), which is aligned along the rim. This plane is also called orifice plane. Therefore the rotational axis is estimated orthogonal to the orifice plane and by the center of the circle templates.

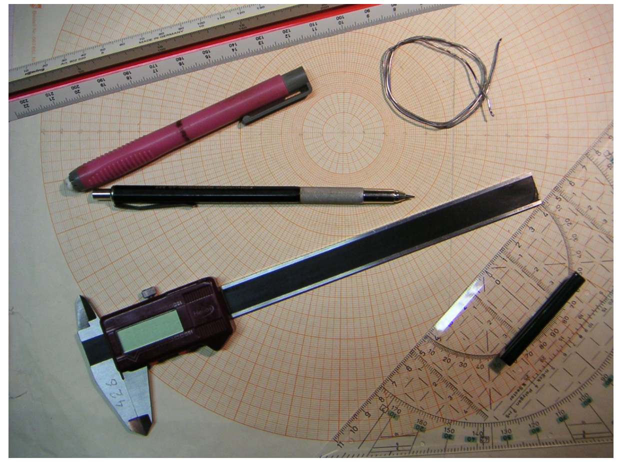


Figure 2: Tools for drawing a profile line: pens, scale paper, lead-wire, ruler and sliding calliper.

The method of using orifice-plane for orientation was first presented in [MLCT03]. For orientation, the rim has to be approximated manually by pin-pointing. Afterwards the rotational axis is estimated using the circle arc of the rim [MLCT03]. Therefore the drawbacks of this system are the required manual interaction, which requires expensive working time of experts. Furthermore sherds with a decorated or damaged rim can not be processed, because for such fragments no arc can be found for axis estimation.

Another novel method for finding the axis of rotation is the approach by Pottmann and Randrup [PR98]. This method has been designed to estimate the rotational axis for rotational and helical surface based on line geometry [PW01] using Plücker coordinates [Plü68]. It has been well tested and used for different applications [PPR99]. The drawback for this method is, that it has been designed for complete surfaces and therefore its application to sherds is not suitable [Lau01, CM02].

There exists an alternative method [CM02], which is based on the idea of tracing normal vectors towards the rotational axis. This approach is similar to previous work [Kam03], which uses a Hough-inspired method [YM97] and an accumulator space. There he normal vectors are traced through the accumulator space. For each trace the weight of the intersected voxels of the accumulator space is increased. In theory the weights of the voxels should increase towards the rotational axis, which is determined by use of the Principal Component Analysis (*PCA*) [DKK96, Jol02].

Due to our experiments on the field-trip we have noticed that the method of finding the axis of rotation by the normal vectors fails for S-shaped objects and for coarse ware. The reasons for these failures are the shape and the noise.

To begin with our investigation in answering questions about the manufacturing process of ceramics, we choose a modern pot, which was manufactured in traditional way.

Therefore this data can be interpreted as mixture between synthetic and real data, because we used real objects, but in contrast to real archaeological fragments, we know how it was produced.

In order to find the orientation of a sherd we use a method described in [KMS05]. It is based on the identifications of circular rills on the surface of the fragments. These rills are artifacts created from tools or fingers during the manufactoring process on the rotational plate.

The first step of this method is to identify the inner side of the sherd where the rills are located. This can be done by measuring the curvature of the surface [RN97, SA83].

In the second step we find a preliminary position of the rotational axis. This algorithm is based on the manual approach, where the sherd is tilted and rotated, so that the concentric rills can be seen as parallel lines, which are orientated horizontally. Therefore we estimate the center of gravity 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) [Str88].

In a third step a line is fitted 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.

We estimate multiple profile lines, which can be overlaid by transforming them into the same coordinate system, where the *y*-axis equals the rotational axis. Therefore the distance between profile lines can be estimated. Figure 3 shows a front (a) and side-view (b) of the pot, the longest profile line (c) and multiple profile (d) lines combined with the side-view, like archaeologists show such vessels in their documentation. In case of the multiple profile lines, we have estimated, that the distance between the profile lines differs and therefore these pots and their profile lines are unique. The maximum distance between two profile lines of the first pot was 9.8 *mm* and 21.2 *mm* for the second pot.

4. EXPERIMENTS AND RESULTS

The radii (*x*-axis) between the profile lines at the same height (*y*-axis) in Figure 3d are not equal. If the profile lines were parallel, this would mean, that the pots have an elliptic (horizontal) cross-section. As it appears, the asymmetry is more complex. Therefore, we choose to analyze the pots slice-by-slice along the rotational axis supposed as orthogonal to the bottom plane.

Figure 4a shows the horizontal intersection, which we applied with a distance of 10 *mm* along the rotational axis. The distance of 10 *mm* corresponds to the manufacturing process, which has left its traces as rills as seen in Figure 3a,b. These rills are spaced 10 *mm*, which corresponds to the width of a finger or tool used to "grow" the pot along the axis of the rotational plate. The intersections at

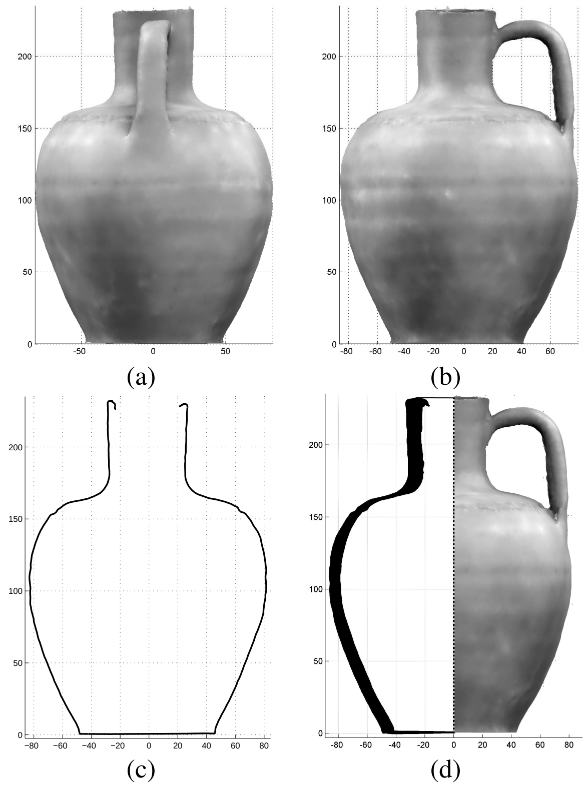


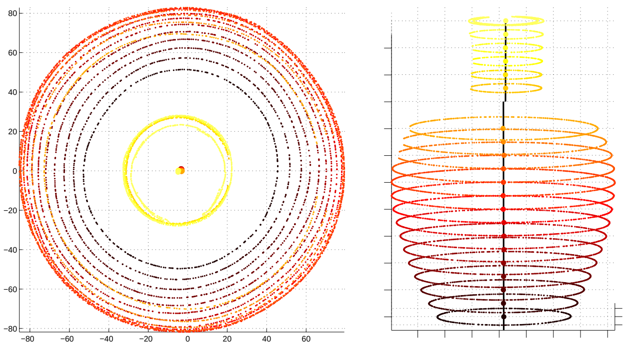
Figure 3: (a) Front-view, (b) side-view, (c) longest profile line and (d) multiple profile lines of modern ceramics, manufactured in traditional way, which are supposed to be identical.

height 160 *mm* and 170 *mm* have been discarded, because they intersect the "shoulder" of the pot with a very low angle ($<< 5°$), resulting in an intersection having a non-representative, random curvature.

Dividing ceramics into segments by characteristic points (like the "shoulder") is done by archaeologists for classification. Therefore we choose to analyze the segmented object into a lower and an upper part. This means, we have two fragments, where an axis estimation can be applied, like for sherds (fragments). The estimation of the axis is shown in Figure 4b. The numeric results for the axis are, that they have a minimum distance of 4 *mm* towards each other and to the axis defined by the bottom plane. Furthermore the angles between the axes differ for 5° to 7°.

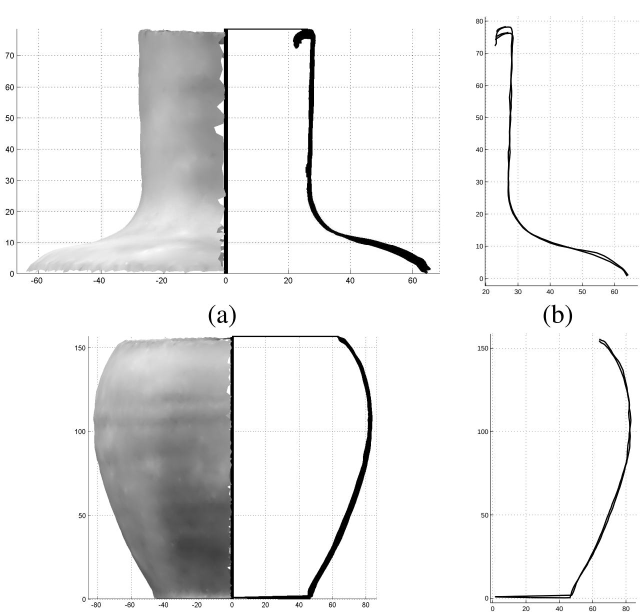
Using the rotational axis of the lower and upper fragment, we repeated the estimation of the profile lines, which are shown in Figure 5 for the upper part and lower part of the objects. The maximum distance between the profile line is 7 *mm* for the upper and 2 *mm* for the lower part. Therefore the first conclusion is, that the upper and lower part do have different axis of rotation, which means, that these parts have been produced separately and combined without the use of the rotational plate.

Based on the deviations of the profile lines shown in Figures5 d, we may say that the upper part has been made



(a) (b)

Figure 4: (a) Top-view and (b) side-view of the horizontal cross-sections - the level of gray corresponds to the height. The axis of rotation for the lower and upper part is shown as black line, defined by the centers of the concentric circles (shown as dots).



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

Figure 5: Axis of rotation and multiple profile lines of the upper part (a) and lower part (c), and (b,d) the longest profile lines of the parts of the objects.

in less quality than the lower part, which has been made by potters with different experience and/or on a slower rotational plate. Vice versa the deviation of the upper part of up to 7 *mm* compared to less than 2 *mm* of the lower part, shows that a faster turning rotational plate has been used and for the upper part more experience is required.

From the differing angle between the axis of rotation based on the bottom plane compared to the axis of rotation of the upper and lower fragment, we can conclude that either the bottom has been post-worked or the pot has been contorted before it was burned in the oven.

Even with the corrected axis for the parts of the object the horizontal intersections are not circular. The horizontal intersections are elliptic. Therefore we estimate the direction of the major and minor axis of the ellipses. And we see that the minor axis has the same direction as the orientation of the handle. This means that the symmetry of the pots was broken, when the handle was attached, while the pots were still wet. Figure 6 shows a pot, intersected by a plane, defined by the center of gravity of the pot and the direction of the major axis of the ellipses. The angle between the minor axis and the handle of the pot was 7° and 14° for the second pot.

(a)

Figure 6: Planes of symmetry of one vessel

We additionally conclude that ellipses fitted [GGS94] to the horizontal cross-sections can be used as a further feature. Therefore the distance between the foci of the ellipse is estimated. Ceramics with a distance converging towards zero (circular cross-sections) are made of higher quality.

5. SUMMARY

The proposed method regarding the analysis of the manufacturing process is part of an enhanced archaeological documentation system, which will replace the traditional documentation system of manual drawings by a fully computerized system, which can be used beyond the estimation of profile lines of sherds. This system can document sherds with increased accuracy and makes it possible to investigate other archaeological questions. Such questions concern the quality of production of ceramics, which are reflected by its symmetry or information about the manufacturing process can be revealed.

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