An automated pottery archival and reconstruction system

By Martin Kampel* and Robert Sablatnig

Motivated by the current requirements of archaeologists, we are developing an automated archival system for archaeological classification and reconstruction of ceramics. Our system uses the profile of an archaeological fragment, which is the cross-section of the fragment in the direction of the rotational axis of symmetry, to classify and reconstruct it virtually. Ceramic fragments are recorded automatically by a 3D measurement system based on structured (coded) light. The input data for the estimation of the profile is a set of points produced by the acquisition system. By registering the front and the back views of the fragment the profile is computed and measurements like diameter, area percentage of the complete vessel, height and width are derived automatically. We demonstrate the method and give results on synthetic and real data. Copyright © 2003 John Wiley & Sons, Ltd.

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Introduction

New technologies are introduced to old research areas and provide new insights for both the researchers and people interested in this field. The truth of this statement can be demonstrated especially in the field of archaeology, since there are many researchers in that area who already use new technologies, and many people have become interested in the field of archaeology since so-called Archaeo-Parks became popular with visitors.1,2

Ceramics are among the most widespread archaeological finds, having a short period of use. A large number of ceramic fragments are found at nearly every excavation (Figure 1) and have to be photographed, measured, drawn and classified.

Because conventional documentation methods have been shown to be unsatisfactory,3 the interest in finding any automatic solution has increased.4 Cooper et al.5 present an approach to a largely automated estimation of polynomial models in order to assemble virtual pots from 3D measurements of their fragments. Existing techniques on the fragment reconstruction problem mainly focus on the analysis of the break curve.6 In particular, Copper et al.7 developed a method for fragment matching based on a Bayesian approach using break curves, estimated axis and profile curves. Kong and Kimia8 try to solve the jigsaw problem in two stages: first, pot sherds are joined automatically in two dimensions by using an efficient joint detection algorithm. Next, three-dimensional shape is recovered by adequate three-dimensional transformation. Leitao and Stolfi9 describe an algorithm for reassembling broken two-dimensional fragments. The procedure compares the curvature-encoded fragment outlines.

Our approach to pottery reconstruction, in contrast, concentrates on the virtual reconstruction of vessels out of one (large enough) fragment; the reassembling of broken vessels from fragments is not considered in this paper. The reconstruction can only be performed if a priori knowledge on the type and class of vessel of which the fragment is a part is provided. This fact forces us to have a profile-based classification strategy that integrates the archaeological knowledge of types and forms of vessels in a specific regional area. The classification scheme itself is provided by archaeologists and is also designed as a tool for them in order to produce correct virtual reconstructions. Mimicking the archaeological approach to pottery classification, our automated approach is based on estimation of the correct

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orientation of the fragment, which leads to the exact position of a fragment on the original vessel. In the reconstruction phase partial similarities of profiles can be detected and complete pots can be reconstructed based on the previously stored data. Figure 2 shows the automated archival process schematically, giving an overview of the intermediate steps.

The range and pictorial information of a fragment provided by the acquisition system is the basis for the further documentation and classification process. Using the data of the fragment’s inner and outer surface, the axis of rotation has to be determined for both surfaces. Once the axes are determined the profile section can be generated by registering the two surfaces on one another. Next, the longest intersection of a plane that is rotated within the rotational axis of the fragment with the surfaces of the fragment is determined. The profile section of the fragment, which is the cross-section of the fragment in the direction of the rotational axis of symmetry, is the result of the documentation step. With the help of the profile, measurements like diameter, area, percentage of complete vessel, height, width, etc. are computed automatically. Next a classification process tries to find matching profile parts of already classified vessel shapes in order to reconstruct the complete vessel shape. Note that the shape object is virtually reconstructed without putting together all fragments.

Following the manual strategy of archaeologists, the profile is first segmented automatically into its parts, the so-called primitives. Our approach is a hierarchical segmentation of the profile into rim, wall and base by segmentation rules based on expert knowledge of the archaeologists and the curvature of the profile. The segments of the curve are divided by so-called segmentation points. Our formalized approach uses mathematical curves to find the extremal and inflection points necessary to classify the original fragment. It is based on cubic B-splines.

This paper focuses on the documentation part, in particular on the automatic orientation of fragments, followed by extraction of the profile line. Late-Roman burnished ware, which was found during the excavations from 1968 to 1977 in the legionary fortress of Carnuntum, was chosen as test data for our research.

The paper is organized as follows: in the next section we first describe the algorithm for finding the correct orientation automatically. Next the generation of the profile is shown in the third section. In the fourth section results are presented and in the final section we conclude with an outlook on future research.

**Fragment Orientation**

The acquisition method for estimating the 3D shape of a sherd is shape from structured light, which is based on active triangulation. The projector projects stripe patterns onto the surface of the objects. In order to distinguish between stripes they are binary coded. The
camera grabs grey-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.\textsuperscript{18} The image obtained is a 2D array of depth values called a range image. For on-site recording a portable 3D sensor (Eyetronic ShapeCam\textsuperscript{19}) was used.

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.\textsuperscript{20} To perform the registration of the two surfaces of one fragment, we use \textit{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. Potmann \textit{et al.}\textsuperscript{21} proposed a solution to reconstruct helical surfaces or surfaces of revolution using line geometric concepts. Their algorithm is based on the fact that the normals of the surfaces lie in linear complices. Our estimation of the axes of rotation exploits the fact that surface normals of rotational symmetric objects intersect their axis of rotation. The basis for this axis estimation consists of dense range images provided by the range sensor. If we have an object of revolution, like an archaeological vessel made on a rotation plate, we can suppose that all intersections \( n_i \) of the surface normals are positioned along the axis of symmetry \( a \).

For each point on the object the surface normal has to be computed. A planar patch of size \( s \times s \) can be fitted to the original data using the Minor Component Analysis,\textsuperscript{22} which minimizes the distance between the points of the surface and the planar patch in an iterative manner in order to compute the optimal value of the normal and discard outliers. For each point on the object, the surface normals \( n_i \) are computed using Minor Component Analysis. In order to determine the axis of rotation \( a \) all surface normals \( n_i \) are clustered in a 3D Hough space: all the points belonging to a line \( n_i \) are incremented in the accumulator. Hence the points belonging to a large number of lines (like the points along the axis) will have high counter values. All points in the accumulator with a high counter value are defined as maxima.

In the next step the line formed by the maxima has to be estimated. There are different techniques to solve this problem; in our case the PCA or principal component analysis\textsuperscript{23} is used. We have some \textit{a priori} knowledge, namely that the maxima are distributed according to a line (the axis of rotation). The PCA will determine the axis of maximal variance, which is in fact the axis of rotation. The accumulator maxima are taken as candi-

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3}
\caption{Intensity image (a) and range image (b) of a fragment with rotational axis of the front view.}
\end{figure}
have the property that all points of the rim lie in the plane perpendicular to the rotational axes) and align them vertically. Next we perform the horizontal alignment by rotating one surface relative to the other until both surfaces have a maximum number of points in a common projection normal to the fixed surface.

In the next step we have to align the surfaces of the objects to avoid intersecting surfaces. The correct match is calculated using a slightly modified ICP algorithm. The difference to the standard ICP is that we are calculating the unique transformation that minimizes the mean square distances of the correspondences between the two surfaces to a constant value instead of to zero. This distance $d_n$ is the distance of the two surfaces on a plane perpendicular to the rotational axis, where $n$ denotes the vertical position on the axis. Corresponding points of the two surfaces are estimated by computing the Euclidean distance of the candidate points on the inner surface to the normal on the rotational axis for the point on the outer surface. The point with the minimal distance is taken as corresponding point.

Next the ICP starts by iteratively minimizing the error $\delta_i$, which is the mean error of the local surface distances to $d_n$ until all $\delta_i$ are positive (i.e. surfaces do not intersect). Then all $d_n$ are updated to the mean distance of the surfaces in the direction of the rotational axis, the mean square error $\delta$ of the local surface distances are computed and the process is restarted. The algorithm ends if there are no significant improvements or the overall error increases. A detailed description of the registration algorithm can be found in reference 28.

Figure 4(e) shows the result for synthetic range data with 50 surface points for each view and a distance of 2.9 mm. The computed distance between the inner and the outer surface is 2.9 mm. The registration error is $\delta = 0.05$ mm; the mean square errors between the original and the computed axes are 0.26 mm and 0.31 mm respectively. Figure 5 shows the registration of intersecting surfaces for real data in detail: Figures 5(a) and 5(b) show intersecting surfaces due to wrong rotational axis estimation; Figure 5(c) shows the same surfaces after the ICP-based registration procedure.

The evaluation of the method (for details see reference 28) shows that the quality of the result is influenced by the number of points in the two views (resolution of the 3D scanner and the object shape for occlusions). The next parameter that influences the results is the mean curvature. Since the registration algorithm uses the axis of rotation for rough alignment, surfaces that are flat cannot be registered since rough alignment does not work. The maximum error was approximately 25%, which is acceptable in this specific application only since the main goal is to compute the profile and the outer profile is the most important attribute. However, the average error of 18% was accepted by the archaeologists since manual drawings and measurement have more errors. The rendered 3D models are also used for visualization, as can be seen in Figure 6. Figures 6(a), 6(b) and 6(c) show two more fragments as examples.
Profile Estimation

The registration of front and back view together with the axis of rotation provide the profile used to reconstruct the vessel. Figure 7 shows the 3D model of a sherd and its rotational axis rot as a vertical line along the z-axis. The black plane represents the intersecting plane $e_{\text{max}}$ at the maximum height $h_{\text{max}}$ of the sherd. The longest profile line is supposed to be the longest elongation along the surface of the sherd parallel to the rotational axis rot. The extracted profile line is shown in the $xz$-plane. Our algorithm for the estimation of the longest profile line consists of the following steps:

1. First the axis of rotation is transformed into the $z$-axis of the coordinate system in order to simplify further computation.
2. The fragment’s size is calculated by its arc length. Depending on the size we compute a number of intersecting planes $e_i$, which are used for the profile estimation. The number of planes $e_i$ depends on the length of the perimeter of the fragment. Experiments have shown that 7 to 13 profile lines return the best ratio of exactness and performance. Figure 8 shows a sample of four planes $e_i$ intersecting the 3D model and the plots of the extracted profile lines on the surface of the sherd.
3. A profile line is calculated by intersecting the 3D data of the fragment with planes $e_i$: first the distance of each vertex of the fragment to the plane $e_i$ is calculated. All vertices are sorted by their distance to the plane. Then the nearest 1% of vertices are selected as candidates for the profile. For each of those vertices, all the patches to which they belong are filtered through a search in the patch list with their index number. In Figure 9 a sherd shaded by the value of distance to the axis of rotation is shown.
(lighter values mean nearer to the intersecting plane). Every patch consists of three points that are connected through three lines. Every pair of vertices that has a point on each side 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. The result is a properly oriented profile line.

4. Next, the profile line with the longest elongation is computed: the difference between the maximum $z$-value and the minimum $z$-value of the profile line defines the height of the profile line. The remaining profile lines are used for evaluation of the estimation of the rotational axis.

Figure 10 shows two plots of diameters based on the profiles from two different fragments. The $y$-axis is the difference of the diameters to the overall mean diameter of all profiles in centimetres and the $x$-axis corresponds to the circular arc. The upper line shows the maximum diameter, the middle shows the mean diameter and the lower line shows the minimum diameter. The grey box visualizes the quality of the results by showing the overall mean diameter of all profiles versus the standard deviation. If the standard deviation exceeds a certain threshold (for example 0.5 cm) the fragment is excluded from further reconstruction.

Figure 10(a) shows a correct estimated rotational axis that results in mean diameter with a small standard deviation (smaller than 0.5 cm) along the perimeter of the sherd. Also the minimum and the maximum diameters are constant except on the left and right side, where the fracture of the fragment is located. In Figure 10(c) the mean diameter along the perimeter has a standard deviation of more than 0.5 cm (in this case 5 cm). This indicates that the estimation of the rotational axis is not accurate enough for further processing. In this case we plan to extend the algorithm for axis estimation by using additional information of the fragment, e.g. rills on the inner surface, detection of rim fragments.

**Results**

The resulting 3D reconstruction of fragments depends on the correct orientation of the profile section. The evaluation of the 3D representation is rather complicated since ground truth is not available due to the fact that there is no third dimension in archaelogical archive drawings and the virtually reconstructed object does not exist in reality (only its fragment). The description of shape is subject to the ideas of the archaeologists and is not standardized.

In order to demonstrate the correctness of the computed profile lines, Figure 11 shows a recorded sherd (dark object) and its computed profile section (vertical line). The computation of the virtual fragment (grey object) is based on the profile section. One can see that the recorded fragment fits into the virtual fragment, which indicates that the computation is correct. Following multiple cross-sections along the perimeter of the virtual fragment (Figure 12a) one can observe hardly any deviation from the original fragment. Some are caused by the bumpiness of the surface, because the surface is not exactly rotationally symmetric, since it is hand-made pottery.

If the orientation of the fragment is incorrect, it does not fit into the virtual object and multiple cross-sections along the perimeter of the virtual fragment show large deviations from the original object (see Figure 12b).
A computed profile and the axis of rotation are shown in Figure 13(a). It was rotated 360 degrees around the axis of rotation in order to construct the vessel in 3D. Next the resulting 3D point cloud was triangulated and the acquired texture was mapped onto the triangulated mesh. Figure 13(b) shows the reconstructed pot.

In Figure 14 the reconstruction of the virtual pot was based on an incorrectly orientated rotational axis. Since the fragment is a base fragment (fragment from the bottom of the pot), has a flat surface with hardly any curvature it, and therefore it is not possible to orientate it by the use of its axis of rotation. The image is shown to demonstrate the deviation between the cross-section of an incorrect reconstruction and the original data (Figure 12b).

Figure 15 displays a reconstructed pot (grey object) out of a rim fragment (dark object) based on the profile line (light line) and its axis of rotation (dashed line).

Experiments were performed on 40 fragments of our pottery database. The success rate for correct extraction of the profile line and consequently the correct virtual reconstruction are around 50%. This has to be seen with respect to manual archival work done by archaeologists: for coarse ware around 35% and for fine ware around 50% of the findings are used for further classification. It depends heavily on the shape of the fragment (e.g. handle, flat fragments like bottom pieces, small size). Eighteen fragments have been excluded from reconstruction due to wrong estimation of the axis of rotation.

Table 1 summarizes the results for 22 properly orientated fragments. Box and piece numbers are used for identification of the fragment. The radius $r$ is the...
estimated mean radius of the whole object. The standard deviation of the radius was estimated along the perimeter of the fragment. The thickness of the fragment is the difference between the mean radius of the inner side and the outer side. The fragment size is the percentage of the perimeter of the sherd compared to the perimeter of the whole object.

Experiments with synthetic data have shown that the correctness of the reconstruction depends on the correct estimation of the axis of rotation (see reference 28 for a detailed survey) and on the resolution of the 3D scanner used. The number of vertices of the data used ranges from 4000 to 15000, leading to a profile line with 200–300 points. The execution time using a prototype written in Matlab running on a Pentium III 1 GHz computer is less than a minute per sherd. It depends heavily on the computation of the axis of rotation (70–80% of the execution time).

Figure 14. Incorrect reconstruction of a fragment due to wrong orientation.

Figure 15. Reconstructed pot.

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Table I. Results for 22 fragments
Conclusion and Outlook

We have proposed a prototype system for the automatic archival 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 since they are better than traditional manual archaeological radius and volume estimation. The ceramic documentation and reconstruction system described is currently under development to be integrated in the virtual excavation reconstruction project 3D-MURALE. Currently we are testing our reconstruction method on a larger test set taken from our 3D-MURALE test excavation site Sagalassos and test objects with ground truth (like fragments of industrially manufactured flower pots which are perfectly symmetric) to further evaluate our method. Next we will work on the classification system based on the profile in order to classify all profiles and to find matching fragments from similar vessels and finally from singular vessels.

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References


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