Computer Aided Classification of Ceramics: Achievements and Problems[1)]

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Abstract:
The first aim of this project is to establish objective criteria for the definition of the form of a vessel and to create an open classification system. Secondly the main part of the classification, that is the segmentation of the profile, should be carried out on a computer aided basis.
The material basis for this exemplary attempt is provided by the late-roman burnished ware from the legionary fortress of Carnuntum. The profile sections are achieved automatically by a 3D-measurement system based on structured (coded) light and two laser-technique.
Classification and reconstruction of archaeological fragments is based on the profile, which is the cross-section of the fragment in the direction of the rotational axis of symmetry. The input data for the estimation of the profile is a set of points produced by the acquisition system. A function fitting this set should be constructed and later on processed to find the extrema and inflection points necessary to classify the original fragment. The one we propose is based on cubic B-splines.
This paper shows a method for shape classification of archaeological fragments, which is based on the profile.

1 Introduction

New technologies are introduced to old research areas and provide new insights for both the 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 [6, 31].

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.

Because the conventional methods for documentation and classification are often unsatisfactory [20], we are developing an automated archivation system [25, 11] 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 [14, 15], was chosen as the basis for our research [7, 8]. In addition to these sherds we enlarged our material

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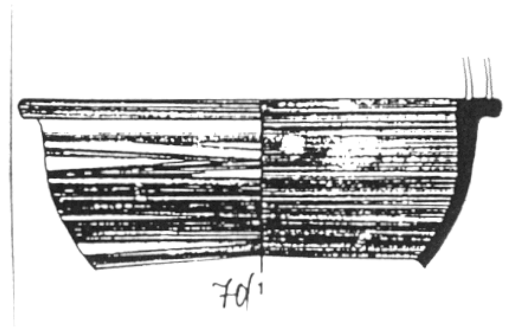

Figure 1: Drawing of a fragment of a bowl (from [16])

basis with published pieces from other pannonian sites.

Section 2 gives a short introduction into archaeological classification and explains the criteria, which were used to establish the classification system. Section 3 deals with the methods of automated data acquisition. Section 4 describes the mathematical formulation of the underlying segmentation and results of this approach are given in Section 5.

2 Archaeological Classification

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 studies and communication within the scientific field [23, 1, 28, 3, 5]. Furthermore, with the recognition of vessel types, chronological, topographical etc. 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 [13, 29, 22] - , 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 [20].

The attributes of a successful classification have been summarized by Orton and others [20, 21]:

- 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 the classification
- 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 two aspects:

- absolute measurements and ratios
- segmentation of the profile line

The first step 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. In order to make the work easier, both, x- and y-values are given as positive values. The profile line is situated in the right lower quadrant, so that not only complete vessels, but also rim fragments can be described [13].

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 [26, 1].

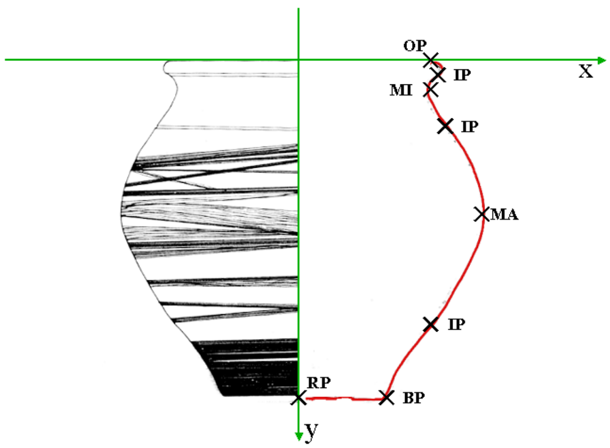

Figure 2: S-shaped vessel: profile segmentation scheme

The curve is characterized by several points, 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;

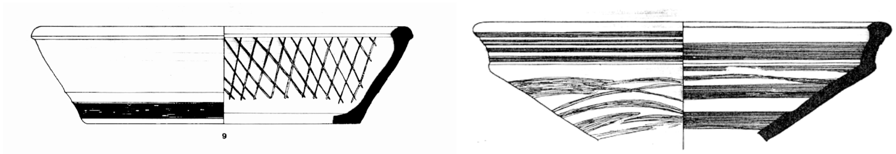

Figure 3: One piece-vessel (a) and Two-piece vessel (b)

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

- 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;
- two-piece vessels (Figure 3b): These vessels consist of two main segments: upper part and lower part;
- 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.

3 Automated Acquisition of the Data

The profile sections are achieved automatically by a 3D-measurement system based on structured (coded) light and a two laser-technique. Figure 4 shows the inner side of a fragment on the left, its left side (broken surface) in the middle, and the profile section generated automatically on the right (Figure 1 shows the same fragment drawn by hand). The profile shown in Figure 4c was computed using a laser system and a shape from structured light technique described in [17, 12].

Figure 4: (a) Archaeological fragment - (b) -side of the fracture and - (c) computed profile section

Shape from structured light is a method which constructs a surface model of an object based on projecting a sequence of well defined light patterns onto the object. For every pattern an image of the scene is taken. This image, together with the knowledge about the pattern and its relative position to the camera are used to calculate the coordinates of points belonging to the surface of the object.

The automated 3d acquisition of the object is used for two reasons: First, there may be errors in the measuring process. Second, the drawing of the fragment should be in a consistent style, which is not possible since a drawing of an object without interpreting it is very hard to do. These are the main reasons for developing an automated 3D-object acquisition with respect to archaeological requirements.

The profiles provided by the 3D-acquisition and the archaeological classification approach have to be ”translated” into mathematical functions. In the mathematical generation of archaeological pottery profiles in 2d, the currently used approaches are based on an approximation of the reconstructed object by a piece wise linear function [9]. This method does not and cannot provide any satisfactory criteria for further classification of the archaeological objects. Motivated by the strong need for a higher precision in object reconstruction, we introduce a new method for fitting of a closed planar curve (FCPC). This method is based on the mathematical approximation constructing a cubic spline function. Cubic spline approximation is a method commonly used in many areas of approximation and provides good approximation properties: the profile reconstructed will be sufficiently smooth and at the same time will project the parts with higher curvatures (i.e. the area of the rim, where a lot of different curvature points occur). The FCPC method achieves considerable better criteria for classification of the profiles of the archaeological objects than methods using a piece wise linear function.

3.1 An Automated Segmentation

The profile determined has to be converted into a parameterized curve [27, 10] and the curvature has to be computed [2, 19]. Local changes in curvature [24] are the basis for the required rules for segmenting the profile.

This formalized approach uses mathematical curves to describe the shapes of the vessels and their parts. The profile is thus converted into one or more mathematical curves. We apply four methods for interpolation and four methods for approximation by B-splines on reconstruction of the vessel profiles (i.e. the profiles are projected into the plane). Details of the selected methods are described in [4]. B-splines were chosen for the profile representation because they can approximate the real profile within almost zero precision (they have a ’universal approximation property’)[18] and because they have a relatively simple mathematical definition.

By combining the different spline methods on subdivided intervals of the curve, the selection of the method with the best precision on a particular subdivision of the curve enables the detection of the significant ’non’-smooth parts of the curve. This (automatic) subdivision of the curve into intervals is done for two reasons. The first reason is that this division of a closed curve (i.e. not a function) is due to that any functional method can be applied. The second reason is that boundary points of these intervals are at the same time important points for an archaeological analysis done by traditional methods (we suppose that the profile is given in correct orientation).

The B-spline methods are compared from the point of view of the approximation error (least mean square of the differences of the input value and the spline value) and from the point of view of simplicity of the representation. The most appropriate method (in general, the combination of approximation and interpolation methods in single intervals), giving the smallest possible error and the simplest possible B-spline representation, is selected and the error of the whole ’reconstructed profile’ with respect to the given data is minimized. This selection together with a demonstrative creation of the curve provides the archaeologist with an as truthful as possible image of the reconstructed profile. The method was tested on profiles like shown in Figure 5.

4 Results

The complete profile is divided into intervals, so that the profile is a function for each interval. The starting point for the sub-division is defined as the left most, lower most point. The starting and ending points of each interval are based

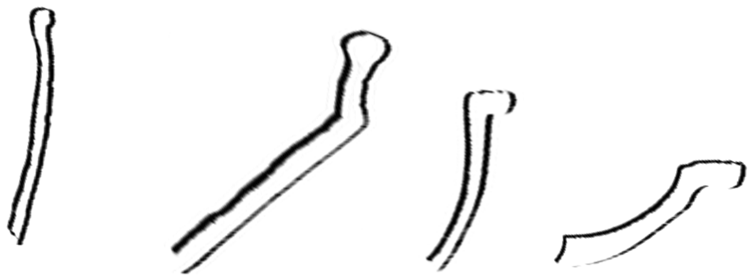

Figure 5: Computed profiles of different fragments

on the first derivatives of the profile line, detected in the profile acquired. Figure 6 shows the profile subdivided into 8 intervals.

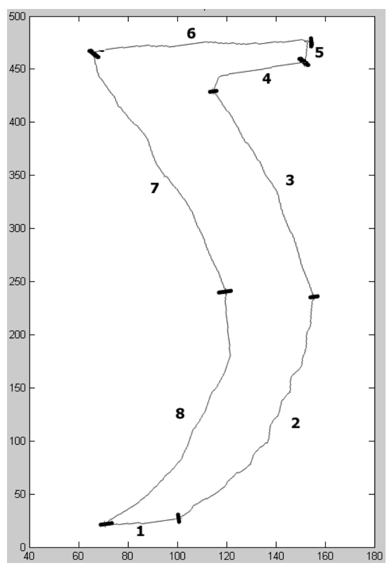

Figure 6: Computed profile subdivided into 8 intervals

When the most appropriate interpolation and approximation methods are computed and selected for each of the intervals of the curve, the method with a smaller error (in case of ambiguity, the interpolation method is preferred) is selected for the interval. The approximation error of the representation over the whole curve is computed. This representation is unique and optimal with respect to the criteria above-mentioned. An interpolation method was preferred in the intervals where a sufficient number of data with respect to the length of the interval was given. An approximation method was preferred in the intervals where there was a lack of data.

The process of applying all interpolation and approximation methods is displayed for every interval of the curve after each run of the program (see Figure 7 for the interval no. 8 of profile from Figure 6). While the curve is generated gradually for each interval of the curve, the overall approximation error is computed. The representation of the profile constructed from the methods selected is displayed (Figure 8) and compared to the data set (For practical reasons the profile is shown rotated). Table 1 displays the approximation errors for all methods in all intervals of the profile from Figure 6, including the selected interpolation and approximation methods for the corresponding interval and the overall method selected for the whole profile. The data sets contain approximately 350 data points and the length of the curve is approximately 400 points.

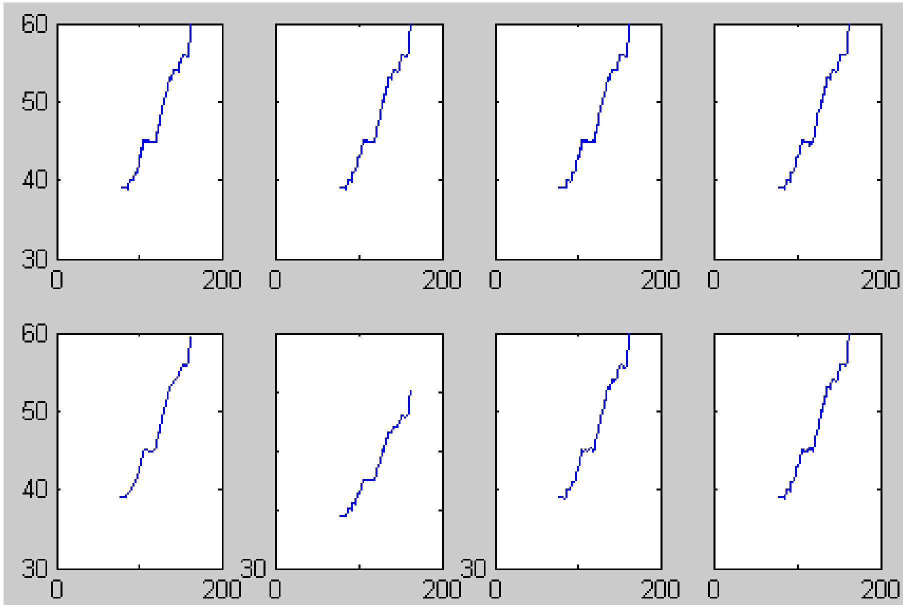

Figure 7: Interval nr. 8 computed with 8 different methods

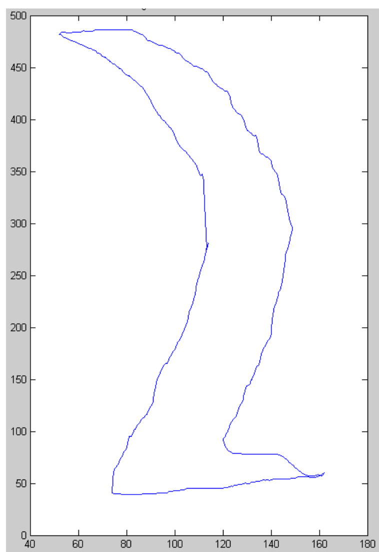

Figure 8: Glued intervals

5 Conclusion and Outlook

The method presented for selection of an 'optimal' representation (optimal with respect to the considered methods and selection criteria) of a (2-dim) profile of an archaeological fragment computes and displays a unique solution. The representations achieved, the first part of an automated system for classification of archaeological fragments, are the input for the second part of the system, the classification. The profile parts, (the so-called primitives), and their absolute measurements and ratios, are used to perform the classification. The segmentation (division) into primitives depends on the orientation of the fragment. In order to achieve a unique representation, it is important to set a unique orientation for all fragments.

The classification will be solved in the high dimensional real space, thus the uniqueness and the high precision of the

method/interval	1	2	3	4	5	6	7	8
cs1	0.2163	0	0.6047	0.0781	1.1685	2.2497	1.1424	0.0884
cs2	0.2163	0	0.5994	0.0782	1.1686	2.2514	0.1433	0.0884
cs3	0.2163	0	0.5994	0.0782	1.1686	2.2514	0.1430	0.0883
cs4	0.2163	0.6169	2.1080	0.0877	1.4510	2.3485	0.1615	0.0991
cs5 $(tol = 5)$	0.2163	2.3114	0.5994	1.1816	2.9430	2.2514	2.2073	0.0884
cs6 $(p = 1)$	0.1350	0	0.6229	0.07812	1.1687	2.2496	0.1646	0.0884
cs7	0.2163	5.9470	5.5298	0.5015	6.9127	6.2323	0.8617	1.0675
cs8	0.2163	0.0032	0.6014	0.1308	1.1850	3.8347	0.1430	0.2551
select. intp.	1	1	2	1	1	1	1	1
select. appr.	6	6	5	6	6	6	8	6
overall select.	6	1	2	1	1	6	1	6

Table 1: Approximation errors for all methods in all intervals

profile representation are very important. The method has been tested on synthetic and real data with good results. The current work focuses on finding a unique orientation of profiles and on the final identification of vessels.

This work is also closely related to the recently granted EU project 3D MURALE which stands for 3D Measurement & Virtual Reconstruction of Ancient Lost Worlds of Europe. This project aims to virtually reconstruct a complete archaeological site including landscape, buildings, and artifacts in 4 dimensions, where the 4th dimension stands for the time component. It should be possible to see also the history of the site from its beginnings to its destruction in order to understand the historic significance of the site. Finally this technique should be applicable to any archaeological site serving three purposes: for visitors at the site to see how the remains could have looked like in reality, for virtual tourists to see what can be seen on spot, and for archaeologists to ease their work in respect to reconstruction and classification of artifacts and buildings. A consortium was founded to virtually reconstruct a site in Turkey called Sagalassos [30]. The MURALE consortium consists of 2 industrial and 5 academic partners, from 4 different European countries (Austria, Belgium, Switzerland, and the UK). MURALE is intended to add an additional technological layer to an extensive, ongoing excavation project.

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