# 3D Reconstruction of Archaeological Pottery using Profile Primitives

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## ABSTRACT

The archivation process of ancient pottery is a very time consuming but important task for archaeologists. The basis for classification and reconstruction is the profile which is the cross section of the fragment in the direction of the rotational axis. In this work a bottom up design using a description language is the basis for the automatic classification and reconstruction. The description language holds all features of the fragment as primitives and all properties among features as relations. Classification of newly found fragments of unknown type is performed by comparing the description of the new fragment with the description of already classified fragments by computing the graph similarity. The subgraph with the highest similarity is then used to reconstruct the complete vessel out of the fragment.

## 1. INTRODUCTION

Usually a large number of fragments of archaeological pottery is found at excavation sites. These fragments are photographed, measured, drawn and catalogued. Up to now, all this has been done by hand, and means a lot of routine work for archaeologists.

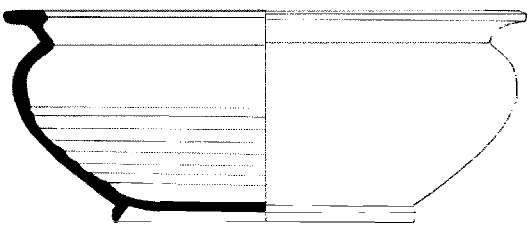


**Figure 1** Archive drawing of a bowl

Figure 1 shows a typical archive drawing which represents a bowl. To cope with the fact that this type of archivation prevents a fast comparison of different drawings in order to find two matching fragments, several attempts to automate the classification of fragments have been introduced [7,8,10]. Every fragment is archived together with a number of different attributes. Since there exists no clear standard for classification, different archaeologists use different terms and classification attributes. Common attributes for manual classification are shape, dimensions, material, period, excavation site and the like. The archive drawing is used to verify the shape parameters since different parts of the profile are segmented by horizontal lines. In Figure 1 for example the three horizontal lines on the top separate the upper edge from the body.

In order to standardize the classification which is based on the fragment's structure it can be divided into two main parts, *shape features* and *properties* which is depicted in Figure 2. The classification of shape defines the process where archaeologists distinguish between various features like the profile, the dimensions of the object like diameter and type of surface, whereas the classification of material copes with different characteristics of a fragment (so-called sherd) like the clay, color and surface properties. The profile is defined as the intersection of the fragment with the plane going through the axis of rotation of the pot to which the fragment belongs. Rotational symmetry of the original pot is assumed. The profile of the fragment is used to reconstruct the original pot from its part assemblies. It is subdivided into 3 main categories: edge, body, and base (ordered from the top of the vessel to the bottom). Each of the main categories is subdivided into subcategories. The example of the fragment structure in Figure 2 shows this subdivision of the profile exemplary. Edge and body are not subdivided for reasons of clarity on all of the examples.

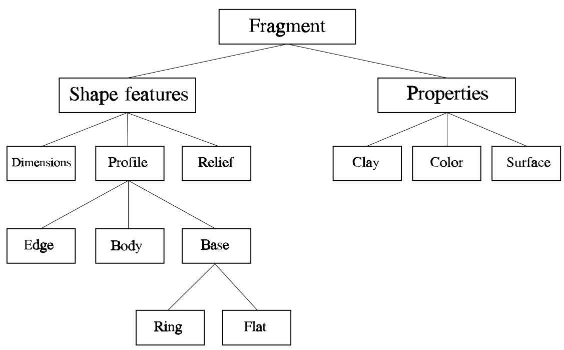
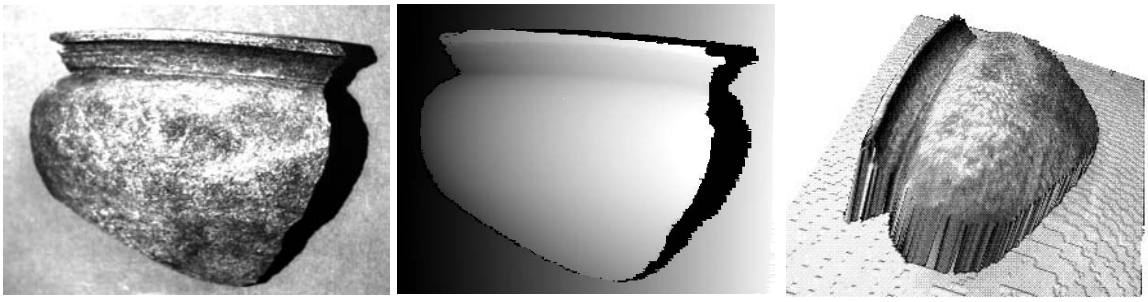



**Figure 2** Fragment structure

The profile analysis has two purposes; reconstruction and retrieval of fragments of the same type. The reconstruction procedure works if the size



a) b) c)

**Figure 3** Fragment: a) intensity image, b) range image, c) object model

of the fragment covers a large part of the original pot in the vertical direction. The profile is rotated by the original rotation axis, thus measurements like volume can be estimated. However, if only small fragments (in respect to the vertical size) are available, a reconstruction out of the fragment is not possible. In this case, the fragments have to be classified correctly in order to retrieve matching fragments. A decision model is necessary to make a reconstruction out of small fragments possible.

## 2. 3D ACQUISITION

In order to reconstruct a pot out of fragments it necessary to have a 3D model of each part. This model is constructed out of the range information, which is achieved using structured light technology. Using the expert knowledge of archaeologists about the orientation of the fragment, the profile section can be determined out of the 3D model. This profile of the fragment is used for classification and is the basis for the reconstruction of pots.

The acquisition method used for estimating the 3D-shape of a fragment is called shape from structured light, which is based on active triangulation. The technique projects multiple stripes at a time onto the surface of the object. In order to distinguish between stripes they are coded either with different brightness or different colors [1]. A robust encoding method is the time-space encoding of projection directions. In this work the coded light approach is used. This method uses time space encoding of stripes by projecting a sequence of *n* stripe pattern onto the scene [6,11]. The range information is achieved by using the triangulation principle. Figure 3a shows the intensity image of a fragment which is used to illustrate the classification method. The fragment is placed within the measurement area of the acquisition device which produces the range image as the result of the active triangulation (see Figure 3b). This range image can be taken to construct an object model of the fragment, where the intensity image can be mapped onto the surface in order to produce a realistic model of the fragment (Figure 3c). The advantage of this acquisition method is that for each point on the surface of the fragment in addition to the depth information also the pictorial information is available.

## 3. RECONSTRUCTION METHOD

The 3D model of the fragment is the basis for the reconstruction method. Using this model, the profile-section of the fragment can be generated for a given direction [5]. This profile is then used for classification and reconstruction of pots. One main goal in the classification process is to find different fragments which belong to the same pot in order to reconstruct the original pot, both in electronic and "natural" ways (the parts are glued together).

Using already archived profile-sections of fragments, relations to pots can be established. In order to reconstruct complete pots, profiles with similar attributes are to be found in the archive database. Until now, archaeologists try to match a complete profile section to all existing profiles in a database using constraints like excavation layer, color, clay etc. This procedure is very time consuming and for short profiles the probability to find a match in long profiles is low. This procedure is a *top-down* strategy, since the complete profile section is used as basis for the similarity algorithm.

The second method used in this work is called *bottom-up* strategy. The profile-section is first segmented into its primitives (edge, body, ringbase, flatbase) which can be summarized into edge, body, and base. These 3 segments of the profile are stored in a so-called description of the profile. The profile is part of the fragment model which can be separated into fragment structure, description and profile: The *fragment structure* is formed by its *shape features* (or geometric features like the profile) and its *properties* (or material like clay) as shown in Figure 2. The *description* of the fragment is structured in a description language consisting of *primitives* and *relations*. Primitives are a representation of shape features, relations represent the properties. The actual profile contains *features* which are a representation of shape features. Since the description is used to perform the classification and reconstruction, features interact with the representation of the fragment structure in the description.

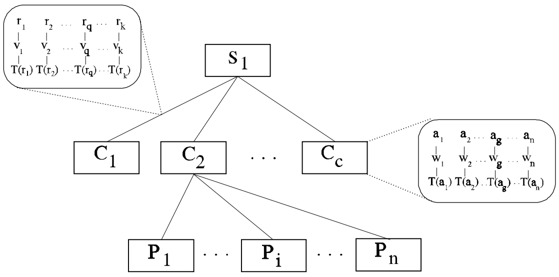



**Figure 4** Description language graph

From the description language point of view, the modeling can be interpreted as a syntactic pattern recognition approach in which the primitives are transformed into the vocabulary and the relations are transformed into a grammar [4]. This approach makes use of the idea of shape decomposition, it divides complex shapes into simple elementary units, i.e. primitives. This can be seen as an application of semantic networks [2], since semantic networks are labeled, directed graphs where nodes represent objects, sub-objects, or shape primitives and arcs represent relations between them. A set of attributes that describe different features is attached to each node; a set of attributes that describe different properties is attached to each arc. Once the fragment is transformed to this representation all operations for classification and reconstruction can be executed on this graph structure. The advantage of a description language lies in the uniqueness of representation, different fragments result in different descriptions, similar fragments result in similar descriptions [9].

Formally, the description language is a graph $G=<\boldsymbol{O},\boldsymbol{R}>$, where $\boldsymbol{O}=\{\ m\ |\ 1\leq m\leq n\ \}$ denotes the set of nodes and $\boldsymbol{R}=\{<c,d>|c,d\in \boldsymbol{O}\}$ the set of arcs. A node $\boldsymbol{O}$ consists of different sub-objects or primitives. Each node has different attributes *a*, with weights *w*, and tolerance *T(a)*. Two nodes are in relation according to $\boldsymbol{R}$. Each relation $<c,d>$ is decomposed into *k* subrelations between the same nodes, each with a weight *v* and a tolerance *T(r)*. Figure 4 shows the graph and the inner structure of nodes and arcs. The shape primitive $S_1$ is subdivided into *c* different shape primitives (such as profile, diameter and the like). For each of these shape primitives *n* different sub-primitives (such as edge, body and the like) are defined. Since the manual segmentation of the profile varies tolerances and weights are included in the description. Note that all attributes and relations contain numerical values.

The weights *w* and *v* are necessary for classification. Each property has a certain weight in order to verify the corresponding description to a given fragment. The verification of fragment to description consists of verifying whether the number and type of features and primitives are the same. Next, attributes and relations are checked whether they match within given tolerances. The verification process is carried out by comparing all attributes of a node and its successors with the model. The confidence for a node can be computed based on the result of the comparison:

$$conf(p) = \sum_{g=1}^{n} w_g \cdot T(a_g) + \sum_{<p,q> \in R}^{m} v_{<p,q>} \cdot conf(q),$$

where $w_g$ are the weights of the attributes of the nodes and $v_{<p,q>}$ the weights of the sub-relations of the arcs. Observe that *n*, the number of attribute values, and *m*, the number of arcs, depend on the node *p*. Moreover, for leaves we have:

$$conf(p) = \sum_{g=1}^{n} w_g \cdot T(a_g).$$

This enables us to compute the confidence of a node by summing up the weighted tolerances of each attribute of the node and the overall confidence of the subgraph connected to this node. By computing the consistency for different descriptions the one with the highest confidence value can be chosen if the confidence is above a certain threshold.

For a given profile all primitives are represented in the description of the given profile. Therefore the profile has to be segmented into the individual primitives. Since this segmentation is based on the expert knowledge, this procedure is carried out by archaeologists manually. This segmentation is carried out for all profiles to be classified.

Figure 5 describes an example for the retrieval. Each fragment has a unique number when archived. Together with all attributes the fragment is stored in the description. The left side of Figure 5 shows a profile which was classified as and separated into edge (E048), border (B012), and ringbase (R145). These primitives are the basis for the classification and reconstruction process. On the right hand side of Figure 5 a fragment which is not yet classified is depicted, thus the type of the pot is not yet known. The profile is manually segmented into its primitives by an archaeologist and the according attributes like color, surface, and dimensions are determined. In order to classify the fragment (find the pot in the database that matches the fragment) the generated description is compared with already existing descriptions. If the profile primitives of the fragment can be found in the description and other attributes are matching within a given tolerance the type of the fragment can be classified as bowl. Furthermore missing parts of the fragment (like the base in this case) can be reconstructed based on the already stored information.

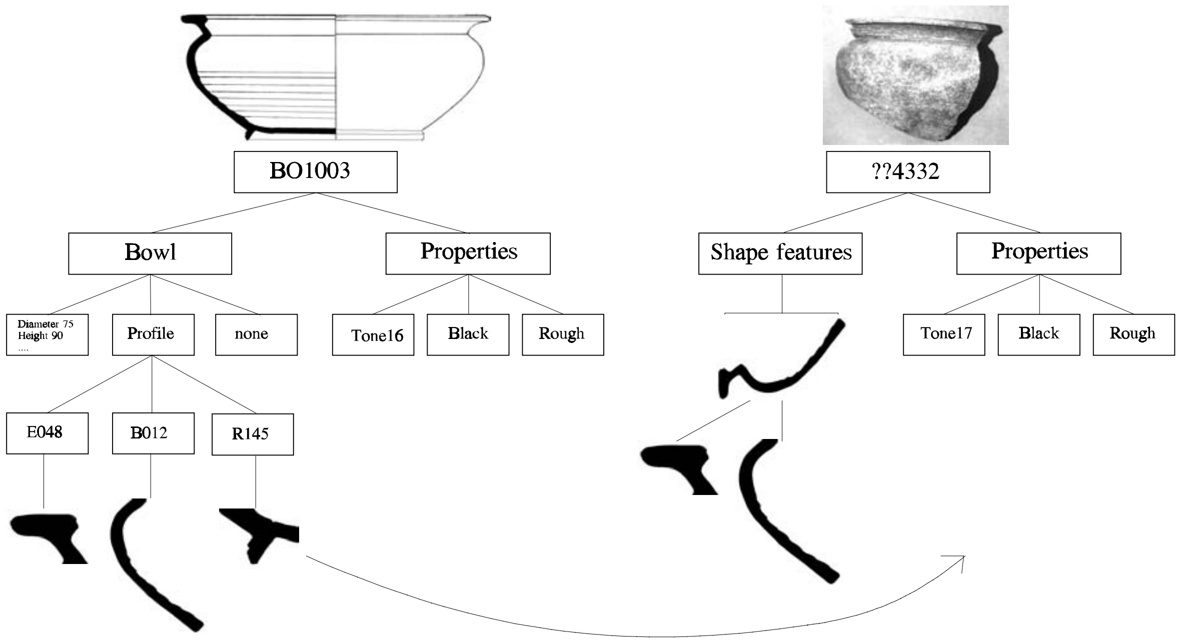



**Figure 5** Retrieval of similar fragments: a) description of known bowl, b) description of unknown fragment

## 4. CONCLUSION AND OUTLOOK

The advantage of this method is that part similarities of profiles can be detected and complete pots can be reconstructed based on the already stored data in the archive. The bottom-up design using a description language for the reconstruction process makes a detection of similar fragments in the database possible, because the matching process starts with the comparison of the entire primitives with already existing relations. Future work will be guided towards automated segmentation of the entire profile using mathematical models.

## 5. REFERENCES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