What You Give Is What You Get: Multitype Querying for Pottery

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Abstract

Precise documentation and organized storage of archaeological findings are essential for scientific research in archaeology. However, with an increasing number of findings, traditional methods cannot meet these modern requirements. Retrieval systems are to provide a variety of tools for these tasks, while being responsible for both long-term storage of findings and easy-to-use user interaction. In this paper, we discuss aspects of the retrieval of rotationally symmetric pottery. In order for that to work, specific properties have to be defined and extracted. Therefore, we will use the shape of a vessel's profile line, since most of them are solids of revolution. It turns out, that this requires the vessel to be correctly aligned to its axis of rotation. We present a new approach that exploits symmetry features of the vessel and applies an optimization method based on particle swarms. Besides an approach of automatically extracting features of the profile line, we can offer the user an interface to provide a reference model, which returns a ranked list of similar objects.

Keywords

axis of rotation, pottery, retrieval, automatic feature extraction

1. Introduction

Precise and studious documentation is an essential prerequisite for scientific research in archaeology, since it carries information about the relevant properties of ancient findings. In recent years, several projects have focussed on automating the task of documentation generation in order to keep up with processing hundreds of thousands of findings quickly.

Among these is TroveSketch, a documentation software developed at Chemnitz University of Technology in cooperation with Saxony's Archaeological Heritage, which aims at automatically investigating pottery. Here, vessels are first being captured by a 3d laser scanner. Then relevant measures are taken that are needed to produce stylized views or profile sketches.

Using a modern 3d scanner allows creating a digital copy of each finding, containing both geometric (shape) and surface (color) properties. This virtualization facilitates processing of findings independently from where the physical originals are actually being stored. However, an increasing number of digital copies ultimately brings up the question of how this data has to be stored in a way that users can access the required information capaciously and fast.

An expedient way of achieving this is creating a retrieval system, that is, a software being responsible for long term storage (archiving), meaningful categorization and practical search options. The interactive part of such a system is the user interface, offering several search masks, i.e. tools that help users to find what is on their minds as exactly as possible. Ideally, this system is available on the internet and supports cross-institute and cross-country collaboration. It must be a system covering different fields of computer science, amongst others database systems, shape matching of 3d models, text search algorithms, or automatic categorization algorithms using methods from artificial intelligence.

In the past, plenty of research concerning the retrieval of archaeological findings has been done, e.g. Rowe *et al.* (2003), and various aspects have been discussed. Therefore, our work will concentrate on two interesting facets with respect to this issue. First, we will focus on pottery that is rotationally symmetric, since it is easier to describe and analyze automatically. Second, we will use the results of this automatic analysis to offer the user the opportunity to provide a 3d reference object, for instance, as the input for a search engine, which in return delivers a list of pottery being similar to the reference.

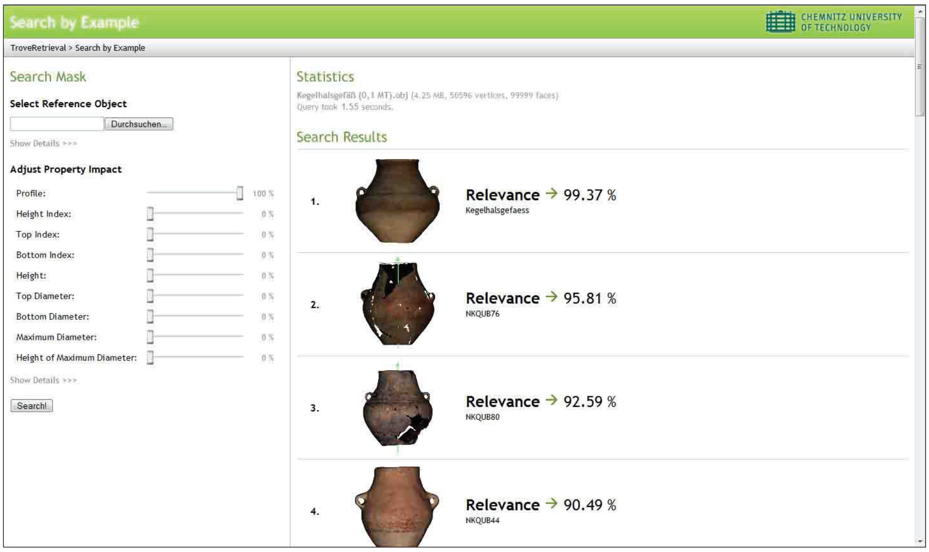

Fig. 1. Pottery search engine (screenshot).

This paper is structured as follows: Section 2 handles some general aspects and previous work concerning information retrieval and, in particular, retrieval of 3d models using shape matching methods. It turns out that information to be retrieved must first be structured in order to be stored in a database, using descriptors. In section 3 we will describe what information is necessary to be stored when it comes to retrieving rotationally symmetric pottery. Section 4 discusses how to acquire this information using an automatic analysis approach, since this is essential for implementing the beforementioned search strategy. Finally, we will have a look at possible future work in section 5.

2. Fundamentals and previous work

Information Retrieval is an important task in many different parts of both the business and public sector. Usually, it is being distinguished from traditional data retrieval by defining, that it deals with a due of uncertainty. According to text-based retrieval systems, it occurs in many different ways, like how the user formulates and how the system interpretes a query. Closely related to this problem is the matter of relevancy, which in fact is quite subjective, as the users themselves have to define what is actually relevant for them.

However, when other kinds of media like pictures, music, or 3d models are to be handled, this problem seems to be even more complex. The natural setting of human associations is language, which can easily be mapped to written text, making text retrieval rather straightforward. Other kinds of media, in contrast, lack this close relation to human thinking. Consequently, different approaches of representing these objects in computers have to be found, since textual annotations are either not available or too expensive to be added manually.

With 3d models, their geometric properties can be used, which is the focus of methods in the field of shape matching. Hereby, geometric features are used to describe an object more or less abstractly, calling this a descriptor. Furthermore, some kind of similarity measure has to be defined to map two descriptor values to a real number that expresses the similarity between the described objects.

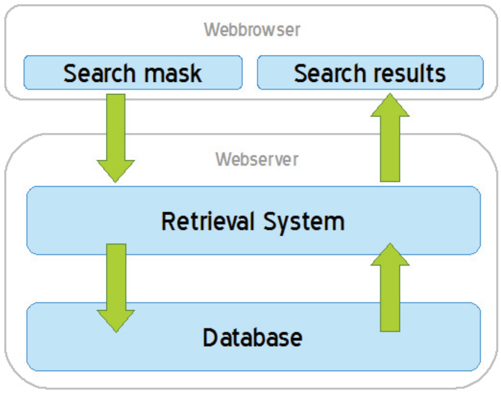

Fig. 2. The general layout of a retrieval system.

According to Hörr (2005), an ideal descriptor has several requirements to be met. First, it is expected to be selective, meaning, that the difference disclosed by comparing values must be proportional to the actual similarity of the referred objects. Second, it must be unique in a way, that each descriptor represents exactly one object, which in fact is a precondition for the previous demand. Third, it must be transformation-invariant, i.e. not depend on position, alignment, or size of an object. The latter claim can be eliminated by demanding, that the descriptor be rotation-invariant. Then, it must be robust towards noise in the object's digital representation (like triangular meshes) and the calculation of both descriptor values and similarity measures must be efficient. Finally, an ideal descriptor must clearly discriminate main parts of an objects from its smaller details.

However, meeting these requirements is difficult. Shilane *et al.* (2004) have studied 12 different shape descriptors towards their ability to classify 3d objects. None of these has proven to be universal in terms of the above stated requirements. Instead, single descriptors can be used for specific applications, e.g. to clearly discriminate man-made from natural objects. Bustos *et al.* (2005) have listed a variety of known shape descriptors, and suggested a possible taxonomy for them. A consequence of the above mentioned work is, that for each application a set of useful descriptors must be determined separately in order for that application to serve its specific purpose.

In another work, Min *et al.* (2004) have investigated different kinds of querying strategies for 3d models. According to them, an exclusive text-based search is effective, if the models are adequately annotated. However, it is clear, that even in specialized domains (like archaeological findings) this is difficult to achieve with a large number of objects. Thus, more sophisticated approaches are desirable, e.g. giving the user the opportunity to draw rough sketches of the objects s/he is looking for. Indeed, this strategy seems to be very effective, given that the user is familiar with it.

In general, a retrieval system consists of three components, as is illustrated in *Fig. 2*. The only part visible to the user is the user interface. In case the systems is available on the internet, it is usually a set of websites providing different search masks and additional features that help the user to work with the data, e.g. allow them to download retrieved 3d models or their attached documentation. The inputs made are being sent to the second layer that contains the logic required to process queries and generate result pages to be presented to the user. The data that is being processed is stored in the third layer, which is usually a database system.

The focus of this paper is the opportunity to provide a 3d reference model as the query. By automatically analyzing this model, i.e. extracting certain descriptor values, it can be compared to the respective values of objects stored in a database to create a list of objects that are similar to the given one. As stated above, a meaningful set of descriptors has to be defined beforehand, in order for this search strategy to produce useful results.

3. Shape description

In this section, we will give a proposal of how to describe vessels in terms of specific properties in order to be able to discriminate them from each other. Therefore, we will apply to Hörr *et al.* (2008), who take advantage of the fact, that most of them are solids of revolution, eventually having attachments like feet or spouts. Nevertheless, the overall shape is usually dominated by the profile line, whose revolution around the axis of rotation forms the solid.

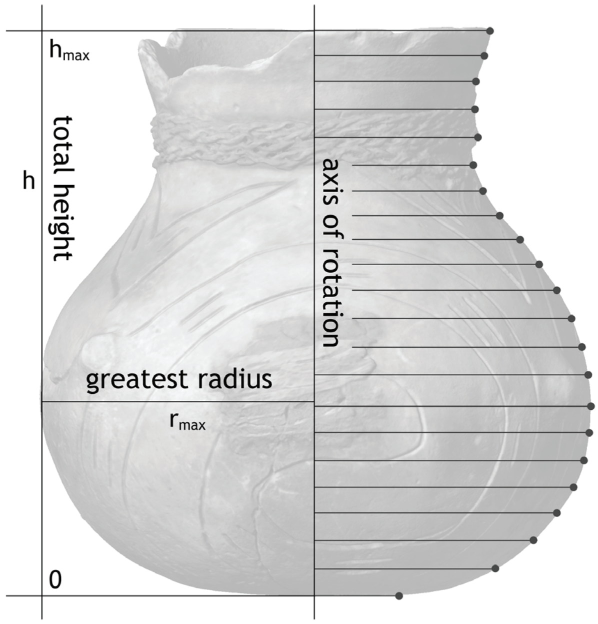

Fig. 3. Example of a profile line of a bottle.

Examining this profile line, characteristic features of the vessel can be extracted, which are either nominal or ratios. While nominal features, such as height (h_{max}), or greatest radius (r_{max}), are useful to discriminate larger from smaller objects, ratios are better in terms of distinguishing shapes. For example, consider the following simple ratio, which is called main index.

$$\text{main index} = \frac{2r_{max}}{h_{max}}. \quad (1)$$

If the main index is less than one, the vessel is rather oblong, while in the opposite case, a flat vessel has a main index of the greater than 1. In order to gain a solid abstraction of the shape of the profile line, we describe it as a function r over the interval $[0, h_{max}]$, specifying the distance to the axis of rotation for each point on the profile line.

$$r : [0, h_{max}] \rightarrow \mathbb{R}_0^+. \quad (2)$$

The beforementioned greatest radius r_{max} is one of the values of that function. By dividing each function value by r_{max}, we obtain a map, say r_{norm}, of r to the interval [0,1]. Actually, we have normalized r, saying that $||r|| = r_{max}$.

$$r_{norm} : [0, h_{max}] \to [0, 1] . \tag{3}$$

Furthermore, we can discretize the domain of r by subdividing it into, say, n disjunct parts of equal length. Then, we can describe the shape of a vessel with a series of n real numbers in [0,1], each describing the radius of the solid of revolution at a certain height. In our implementation, we have set n=50. We get our descriptor d by formalizing this to

$$d : [1, n]_{\mathbb{N}} \to [0, 1]_{\mathbb{R}} . \tag{4}$$

Using this approach, we have gained a meaningful and particularly scale-invariant descriptor of the overall shape of a vessel. Next, we have to define a similarity measure in order to be able to compare vessels to each other. For the sake of simplicity, we chose the following metric to determine the similarity of two (normalized) radius values $d_1(i)$ and $d_2(i)$ at the same height i in [1,n]:

$$sim_i(d_1, d_2) \quad = \quad \begin{cases} \frac{d_1(i)}{d_2(i)} & \text{if } d_1(i) < d_2(i) \\ \frac{d_2(i)}{d_1(i)} & \text{if } d_2(i) < d_1(i) \\ 1 & \text{else} \end{cases} . \tag{5}$$

Since having n such values to be compared, we simply add these and divide the result by n. This results in a normalized similarity measure for two profile lines, say d_1 and d_2, lying in [0,1].

$$Sim(d_1, d_2) = \frac{1}{n} \sum_{i=1}^{n} sim_i(d_1, d_2). \tag{6}$$

In addition to this profile line descriptor, the user can choose other geometric properties[1] to be regarded in the retrieval process, by simply adjusting the strength of their impact on the calculation of the similarity value, as is shown in *Fig. 1*.

4. Automatic analysis

In this section, we describe the process of automatically analyzing a reference model, that has been supplied by the user. First, the vessel has to be aligned to its axis of rotation, since we cannot anticipate, that it has already been aligned. Knowing the axis of rotation is a fundamental prerequisite for any feature extraction on solids of revolution. Therefore, we introduce a new method that determines the axis both robustly and fast. Afterwards, we use a cylindrical voxel grid to efficiently calculate the values of our descriptor and other features that depend on the profile line. We have tested our implementation on an ordinary computer and found, that an average request takes about 1 to 2 seconds to deliver a ranked list of similar vessels.

4.1. Axis of rotation

Calculating the axis of rotation of an object with both position and alignment being unknown is not straightforward. The standard methods, which have been introduced by Halir (1999), Kampel (2003), and Cao and Mumford (2002), respectively, use the fact, that normals on the surface of an ideal solid of revolution point to its axis. However, since calculating the normals for large polygonal meshes is time consuming, these methods are not applicable for a server application that is expected to deliver a search result quickly. Furthermore, they are not robust enough when processing vessels with large handles or rich garnishments on the surface, since these features add a lot of noise to the set of surface normal vectors.

Instead, we have developed a new approach, which explores the strengths of symmetries within an object. Since most real-world objects have imperfect symmetries, Zabrodsky *et al.* (1995) have suggested to handle symmetry as a continuous feature rather than saying, that an object is or is not symmetric. On the basis of this, Kazhdan and Podolak *et al.* (2004; 2006) have developed several shape descriptors for both reflective and rotational symmetries. According to their work, the strength of these symmetries can easily be calculated for random planes or lines, respectively.

So, in order to find the axis of rotation, we have to find the line that yields a maximum of rotational symmetry with respect to the given object. Since there is an infinite number of possible lines, we have to apply an optimization approach, which examines

[1] Which are described in Hörr *et al.* (2008) as well.

Fig. 4. Examples of vessels aligned to their respective axis of rotation.

different lines in an iterative way and thus maximizes the strength of rotational symmetry.

Therefore, we have chosen Particle Swarm Optimization (PSO), which has been developed by Eberhart and Kennedy (1995). It has been inspired by the behaviour of fish schools or bird flockings. The algorithm starts with a set of usually few hundred particles living in an n-dimensional problem space. With each iteration step, the particles record their current fitness value as well as the position of their best fitness value reached so far (which is called local best). In addition, the algorithm remembers the optimal position reached by any of the particles at any time (global best). Then, a velocity vector is calculated for each particle, which is composed by the current velocity, as well as the directions to the local best and global best positions. We refer to the referenced literature for a detailed description.

In our application, the fitness value is the strength of rotational symmetry. Since we can uniquely describe a line in three-dimensional space with two vectors (position and direction), our problem space has 6 dimensions. However, we have discovered, that this is still too expensive. Therefore, we break down the task in the following way. We exploit the fact, that a solid of revolution has an infinite number of reflection planes that intersect each other in the axis of rotation, which hence is contained in each of the planes. So, we first use the PSO approach to find a plane of maximum reflective symmetry, and then search for a line within this plane yielding a maximum of rotational symmetry. We can describe a plane in three-dimensional space using spherical coordinates, and a line in two-dimensional space using polar coordinates. Thus, we gain two optimization runs in a three- and two-dimensional problem space, respectively.

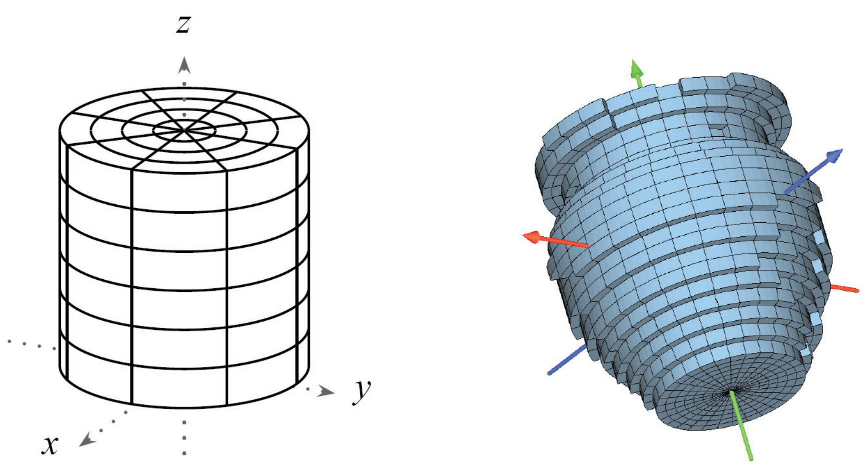

Fig. 5. Scheme of a cylindrical voxel grid (a) and example of such a rasterization (b).

We have discovered, that each optimization run takes an average of about 50 iteration steps until it breaks. The axis of rotation is correctly determined in practically every case in less than a second, even with pots having large handles. Even very flat or ballshaped objects are aligned, as is shown in *Fig. 4*.

4.2. Profile line

Now that the vessel has been aligned to its axis of rotation, we have to extract the properties listed in section 3, by calculating the profile line. For this purpose, we rasterize the vessel into a cylindrical voxel grid along the axis of rotation. Hereby, the Euclidean space is subdivided into disjunct cells, each discriminated by indices for height, shell, and segment (*Fig. 5*).

When extracting the profile line from this representation, two important things have to be taken into account. First, vessels can have handles or feet, which have to be removed before. Therefore, we propose a very simple approach. We count the number of black voxels (i.e. surface voxels) for each circle described by both shell and height index, and delete those, if their number is less than 80 percent of the number of segments. Second, vessels are not perfectly symmetric with respect to the axis of rotation. Thus, for each height, we have to make a

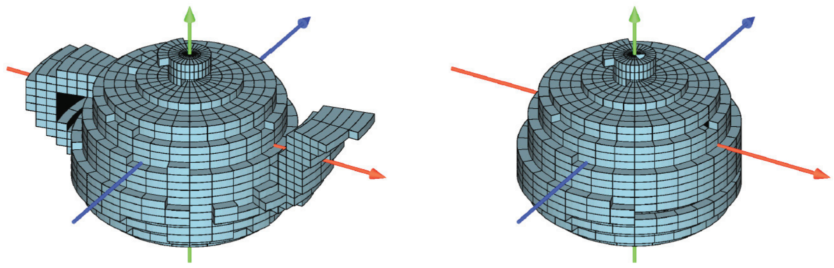

Fig. 6. Example of attachment removal for a teapot.

proper estimation of the distance of the point on the profile line. We do this by simply collecting the shell indices of each black voxel for a certain height in a list, which is then being sorted. The median of these indices then represents the voxel that contains the profile point.

We found, that both approaches yield a robust representation of the profile line of a vessel. Hereby, the most computionally expensive part is the rasterization, which finally depends on the number of triangles of the supplied mesh.

5. Outlook

In this paper, we have presented a proposal for a retrieval system, that allows the user to supply a reference model of pottery as a query in order to retrieve similar objects. Since these are rotationally symmetric, we can define and automatically extract characteristic features derived from the shape of a vessel's profile line. This requires the vessel to be properly aligned to its axis of rotation, for which we presented a new, fast approach based on particle swarm optimization.

However, the overall goal is creating a retrieval system that covers several parts of scientific work in archaeology. Hereby, automatic classification is of great interest. First experiences have shown, that classifying pottery based on many simple features can yield useful results (see Hörr *et al.* 2008). It is our attempt, to integrate and use the results of automatic classification approaches in order to improve the retrieval of pottery.

Furthermore, as we have shown, that exploiting symmetries for finding the core feature of a vessel's shape, i.e. its axis of rotation, we will examine whether symmetries or partial symmetries are useful to describe pottery in a way that makes them distinguishable.

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