3D Shape Analysis for Archaeology

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Abstract. Archaeology is rapidly approaching an impasse in its ability to handle the overwhelming amount and complexity of the data generated by archaeological research. In this paper, we describe some results of our efforts in developing automatic shape analysis techniques for supporting several fundamental tasks in archaeology. These tasks include documentation, looking for corollaries, and restoration. We assume that the input to our algorithms is 3D scans of archaeological artifacts. Given these scans, we describe three techniques of documentation, for producing 3D visual descriptions of the scans, which are all non-photorealistic. We then proceed to explain our algorithm for partial similarity of 3D shapes, which can be used to query databases of shape, searching for corollaries. Finally, within restoration, we describe our results for digital completion of broken 3D shapes, for reconstruction of 3D shapes based on their line drawing illustrations, and for restoration of colors on 3D objects. We believe that when digital archaeological reports will spread around the globe and scanned 3D representations replace the 2D ones, our methods will not only accelerate, but also improve the results obtained by the current manual procedures.

1 Introduction

Shape analysis aims at developing efficient algorithms and technologies for "understanding" shapes. In this work we assume that a shape is a surface, represented as a "polygonal soup", which is the common representation in computer graphics in general, and the output of 3D scanners in particular.

The field of shape analysis tackles a whole spectrum of intriguing problems, including matching [1–3], segmentation [4–6], registration[7, 8], edge detection [9–11], saliency detection [12–14], completion [15–17], and more. The common denominator of all these tasks is that humans perform them easily and naturally, often by using semantics and their knowledge. When attempting to perform the tasks automatically, however, we do not assume any knowledge and therefore, the only information available to us is the geometry of the surface. Can geometry alone provide us with sufficient data to perform these tasks? For instance, when looking for similar shapes, is similarity in the eye of the beholder? Or, can similarity be defined mathematically, based solely on the geometric features of the shape?

There are numerous applications of 3D shape analysis, both within the field of computer graphics and in other domains, such as medicine, biology, architecture, and cultural heritage. This is so, because in all these fields the emerging technology of 3D scanning is gaining popularity. Once the objects are represented and visualized on the computer, the reasonable next task is to analyze them as well. In this paper we focus on cultural heritage, and in particular on archaeology.

The field of archaeology is rapidly approaching an impasse in its ability to handle the overwhelming amount and complexity of the data generated by past and on-going archaeological research. A typical excavation produces thousands of artifacts, and large stratigraphical excavations–oftentimes millions. Worldwide, current methods of recording, analysis, archiving and restoration of data can no longer cope with the higher resolution required. Moreover, in most cases, researchers cannot access all the objects themselves, as they are locked away in museums and various store-rooms.

We propose to replace some components of the tasks of the archaeologist by digital procedures. In particular, we concentrate on three tasks: documentation, looking for corollaries, and restoration. For each, we describe our efforts in automating the activity. We view this work as part of a world-wide effort to overcome the impasse created by current manual procedures [18–21].

Specifically, in Section 2 we discuss 3D visual representations, which can replace the 2D ones, currently utilized for documentation. We propose several techniques which enhance the 3D data and make it attractive for visualization. Then, in Section 3 we discuss search by partial similarity. When the digital reports contain searchable databases of shape information, the process of searching for corollaries will be reduced to querying multiple on-line databases. Finally, in Section 4, we describe our restoration results, focusing on digital completion of broken 3D shapes, on reconstruction of 3D shapes based on their line drawing illustrations, and on restoration of colors on 3D objects.

Digital archaeological reports are slowly spreading around the globe [22–26]. When scanned 3D representations replace the 2D ones, accurate, automatic methods for performing shape analysis tasks are likely to replace the labor-intensive procedures currently employed.

2 Documentation

Traditionally, artifacts are documented and published by conventionalized line drawings or 2D photographs. The line drawings are produced manually, by artists—an extremely time and money consuming procedure, prone to inaccuracies and biases. Furthermore, usually only one, and only seldom more views of the objects are illustrated in publications. The result is that not all the morphological information is recorded.

Lately, 3D scanning gets increasing popularity. Indeed, 3D images are accurate, simple, and relatively quick to generate. And, they retain all the information regarding the objects. However, they still do not convey the pertinent morphological structure in a manner that enables rapid and effortless visual recognition, which is important when objects are viewed en masse.

Non-photorealistic rendering can overcome these drawbacks [27]. This is supported by psychological scholarship that demonstrates the visual advantage of line drawings for real-time recognition, especially when texture and color are not available [28].

Our goal is therefore to combine the comprehensiveness, accuracy and efficiency of 3D scans with the eye-friendliness and the information conveyed of non-photorealistic rendering. We propose three manners to achieve that: 3D curve illustration, black & white coloring, and relief extraction. Since in all these cases, the procedures are performed in 3D, manipulation enables the archaeologist to visualize the important features, as if the artifact is held in his hand.

Curve detection: Our goal is to mathematically define a family of curves, which enhance the important features of a given 3D object. Based on this definition, an algorithm for constructing the curves on triangular meshes is designed. Since archaeological artifacts are extremely noisy, the algorithm should be robust to noise.

Given a surface, we define in [29, 30] a new class of view-independent curves, termed the *demarcating curve* , as follows. Given a surface in 3D, we can imagine it locally as a terrain with ridges and valleys [31]. Intuitively, demarcating curves run on the slopes between the ridges and the valleys. A common way to model such a slope locally, is to model it as a step edge. Ridges, valleys and demarcating curves are parallel on the step edge. The demarcating curve demarcates the concave part of the step edge from the convex part.

Formally, the demarcating curves are the loci of points for which there is a zero crossing of the curvature in the curvature gradient direction. This curvature gradient points in the direction of the fastest transition from concave to convex. Thus, $\mathbf{p}$ is a demarcating curve point if the following formula holds:

$$\kappa(\mathbf{g}_p) = {\mathbf{g}_p}^T \mathbf{II} \mathbf{g}_p = 0,$$

where $\mathbf{g}_p$, the curvature gradient, is defined as:

$$\mathbf{g}_p = \arg\max_{\mathbf{v}} \mathbf{C}_{ijk} \mathbf{v}^i \mathbf{v}^j \mathbf{v}^k, \quad \text{s.t} \quad \|\mathbf{v}\| = 1.$$

Figure 1 demonstrates that our demarcating curves effectively manage to capture 3D shape information visually. They depict the 3D texture of an object, such as the facial features and the hair.

Coloring: In order to further highlight the features, it is possible to add surface enhancement to the demarcating curves. The key idea is to color the surface according to its normal curvature in the curvature gradient direction. This coloring increases the color contrast on the feature curves, thus enhancing them. In particular, Figure 1(c) demonstrates the use of mean-curvature shading [32].

In [33] we propose another framework for enhancing artifacts. It is based on a definition of a new smooth direction field, termed the *prominent field,* defined

(a) Image (b) Demarcating curves (c) Demarcating curves & coloring

Fig. 1. A late Hellenistic lamp (150-50 BCE). The lamp is rendered with demarcating curves in (b) and with the addition of coloring in (c).

for every point on the surface. Intuitively, had the surface been an ideal step edge, this direction would be perpendicular to the ridge, valley, and relief edge. In practice, however, surfaces are not ideal step edges and thus, we need to define a direction field more carefully.

In essence, for points residing near the ridges and the valleys, the prominent direction should be equal to the first (maximum) principal direction. For points residing near the demarcating edges, the prominent direction should be equal to the relief direction. Since in practice the regions might overlap, these directions are combined as a weighted combination, where the weights are proportional to the likelihood of the point to be near a demarcating curve. Finally, to extend the definition to the whole surface, we search for the smoothest direction field that satisfies the values of the prominent field on the features.

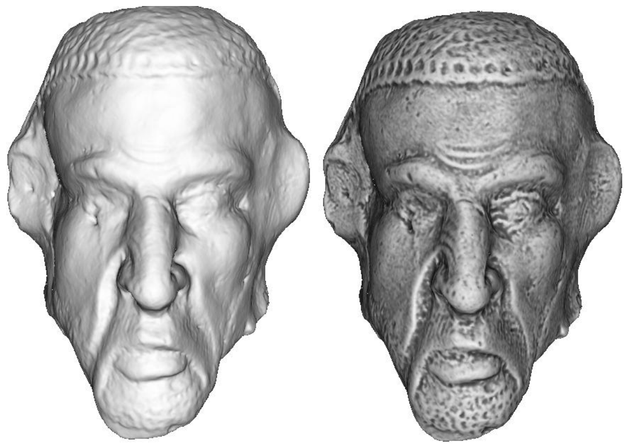
For artificial coloring, the color of a vertex is set according to its curvature in the prominent direction. The lower the curvature, the darker its color. Formally, given a vertex with prominent curvature κ_p, its color is defined as

$$color = \arctan(\lambda \kappa_p),$$

where λ is a user supplied parameter, controlling the overall image contrast.

Figure 2 shows the result of our coloring. It can be seen that this method increases the color contrast on the features, thus enhancing them.

Relief extraction: Often, we wish to extract the "finger-prints" of an artifact. It is possible to perform this task automatically, when it is known ahead of time that the object at hand is a relief object. These objects are composed of a basic shape or structure and added details. The problem is that the representation of



(a) Input (b) Coloring

Fig. 2. Coloring highlights the subtle features of the object.

a 3D object as a polygonal mesh, describes both the basic shape and the details with no distinction. This means that important semantic information is missing. Our goal is hence to determine the decoupling of these components, in effect segmenting the object into its base and its details.

Our key observation in [34] is that there is no need to extract the real base surface in order to estimate the details. The height function of the details contains all the needed information to separate the relief from the base. Hence, we only need a good estimation of the height and not the base surface itself. Interestingly, this turns out to be easier. We show that to measure height, we only need an estimation of the normals of the base surface, and not the surface itself. Based on the base normals, we can define relative height differences between all the points on the model. By solving a global optimization problem, we eventually reach a height definition for all the points. The reliefs are extracted by thresholding the height function.

Figure 3 illustrates challenging cases, where our algorithm manages to extract the reliefs from noisy and weathered archaeological objects. In such examples both the base and the relief are noisy and the details are lost due to aging.

3 Similarity

After finding a new artifact, the archaeologist aims at locating it in time and space. This is often done manually by leafing through thousands of pages of site reports, where photos and drawings of artifacts are found. This is a Sisyphean procedure, which is extremely time-consuming. Digitizing the findings by a high resolution scanner and creating archaeological databases, which will allow similarity to be expressed as a database query, will be a welcome alternative.

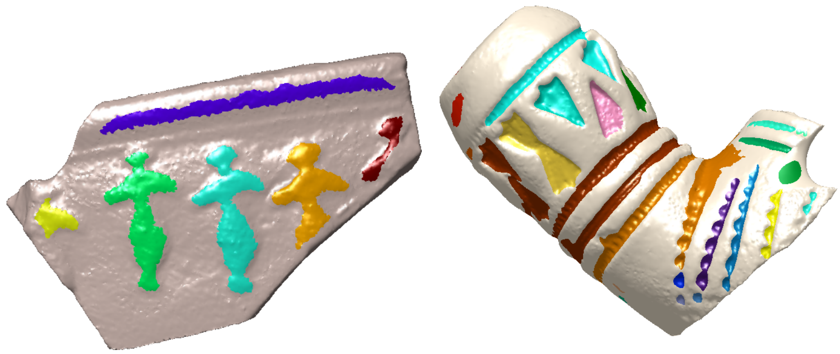


Fig. 3. Examples of relief extraction from a Hellenistic vase (left) and an Ottoman pipe (right)

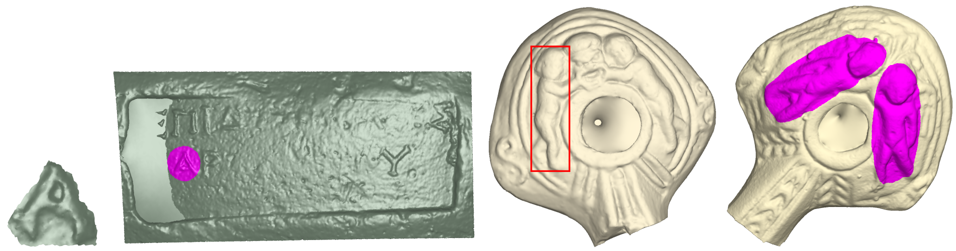
Previous work on matching mainly concentrated on determining the similarity of whole surfaces [1–3]. In the domain of archaeology, however, this does not suffice—we wish to find only similar sub-surfaces, since many artifacts are found broken. The added difficulty stems from the fact that helpful global techniques, such as scaling, alignment, or symmetry cannot be utilized.

Therefore, we wish to address *partial similarity*, where given a specific part of an unknown surface, the goal is to detect similar parts on other surfaces, regardless of the global surface this part belongs to.

We propose an algorithm that performs this task [35]. Our key observation is that though isolated feature points often do not suffice, their aggregation provides adequate information regarding similarity. We introduce a probabilistic framework in which segmentation and neighboring feature points allow us to enhance or moderate the certainty of feature similarity.

Specifically, at first, the salient points are detected and their similarity is computed. Considering only a subset of the vertices, rather than the whole set of vertices of the mesh, not only improves the performance, but also enhances the results, since non-distinctive vertices are ignored. Then, the surfaces are segmented into meaningful components and their segments are matched. Next, given the above similarity measures, they are integrated. The goal is to compute consistent correspondences between the salient vertices. Finally, the similar region(s) in one surface is determined according to the correspondence established in the previous stage.

Figure 4 demonstrates the usefulness of our algorithm for the domain of archaeology, in which the data is very noisy, and hence challenging. In particular, in Figure 4(a) the input query is a Greek letter (A) extracted from Hellenistic stamps. Our algorithm manages to detect the letter, even though the letters may differ in shape and the scale ratio is unknown. In Figure 4(b) a cupid from a Hellenistic oil lamp is the query. Our algorithm matches this query to the cupids on a different oil lamp. The poses, as well as the shapes of the matched



(a) query result (b) query result

Fig. 4. Partial similarity results on non-identical inputs. (a) Detecting a letter extracted from a different stamp. (b) Detecting cupids on Hellenistic oil lamps.

cupids differ, i.e., the query cupid has hair while the matched cupids do not, the matched cupids have wings while the query does not, etc.

4 Restoration

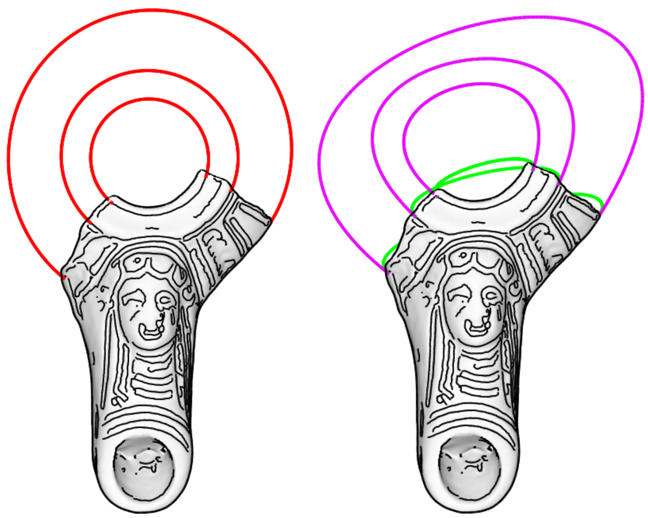
Restoration refers to bringing back an object to a former condition. In this section we use the term restoration quite liberally, under the goal of conveying some sense of how the artifacts looked like before they were damaged. We focus on three tasks: completion of broken objects in a manner similar to that performed in drawings, reconstruction of a 3D object from its 2D line drawing, and colorization. Other types of restoration, such as pattern restoration, reconstruction of an object from its pieces etc. are left for future work.

Shape completion: Traditionally, archaeological artifacts are drawn by hand and the artist "completes" the missing data by sketching the major missing feature curves. Our goal is to "complete" the artifacts similarly, albeit in three dimensions. We therefore wish to mathematically define 3D curves, which satisfy several properties, considered to be aesthetic. Furthermore, we devise an algorithm for constructing these curves.

We are inspired by the 2D Euler spirals, which have a long and interesting history. In 1694 Bernoulli wrote the equations for the Euler spirals for the first time. In 1744 Euler rediscovered the curves' equations and described their properties. The curves were rediscovered in 1890 for the third time by Talbot, who used them to design railway tracks. Kimia et al. [36] showed how these spirals can be utilized for 2D curve completion. The characterizing property of these 2D curves is that their curvature evolves linearly along the curve.

In [37] we define the 3D Euler spiral as a curve for which both the curvature and the torsion change linearly with arclength. This property is acknowledged to characterize eye-pleasing curves [38].

We proved that our 3D Euler curves hold the following properties, found to characterize aesthetic curves [39, 40]. They are invariant to similarity transfor-



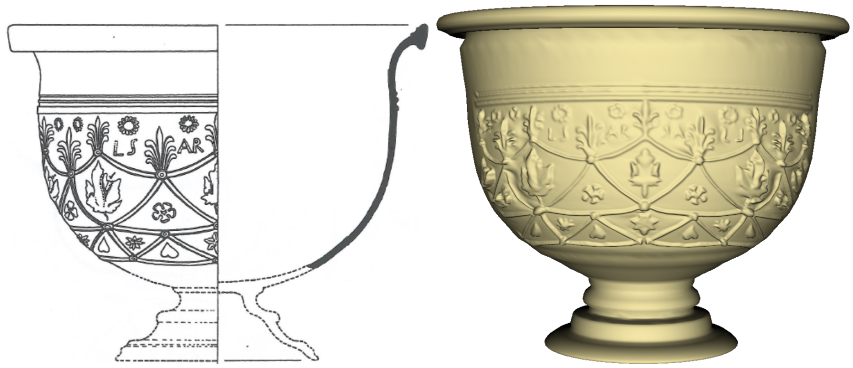
(a) Our completion (b) Hermite completion

Fig. 5. 3D Euler spirals (red) complete the curves on a broken Hellenistic oil lamp – curves that would most likely be drawn if the model were complete. They are compared to completion by Hermite-splines. The scale of the Hermite splines is determined manually (magenta), since the automatically-scaled splines (green) are inferior due to the large ratio between the length of the curve and the size of the model. Note the perfect circular arcs of our curves.

mations; they are symmetric, i.e., the curve leaving the point x_0 with tangent T_0 and reaching the point x_f with tangent T_f coincides with the curve leaving the point x_f with tangent T_f and reaching the point x_0 with tangent T_0; they are extensible; they are smooth; and they are round, i.e., if the curve interpolates two point-tangent pairs lying on a circle, then it is a circle.

Figure 5 demonstrates the use of our spirals for completion in shape illustration. It shows a broken Hellenistic oil lamp, along with curves that would most likely be drawn if the model were complete. These curves are three dimensional and are used jointly with our demarcating curves, described in Section 2.

Reconstruction from line drawing: In some cases, a line drawing of an artifact, as documented in the site report, is the only available source of information. Our goal is to reconstruct a surface, given a line drawing of a relief object. Automatic reconstruction from a line drawing is a challenging task due to several reasons. First, the lines are usually sparse and thus, the object is not fully constrained by the input. Second, the lines are often ambiguous, since they may have different geometric meanings—they can indicate 3D discontinuities, surface creases, or 3D step edges. Third, the input may consist of a large number of strokes that need to be handled by the algorithm efficiently. Fourth, these strokes are inter-related. For instance, the decorations may be either pro-



(a) the original drawing (b) our 3D reconstruction

Fig. 6. Reconstruction of a Roman vase from a manual drawing consisting of 571 curves.

truded or indented as a whole, and a solution in which some of the lines indicate protrusions and others indentations is less likely.

In [41] we propose a solution to the problem. We divide this problem into two sub-problems: reconstruction of the base and reconstruction of the details (i.e. the relief) on top of the base. We address each of them separately, as follows.

For the base, since the drawing in under-constrained, we pursue a data-driven approach, which is able to reconstruct highly complex bases. As available databases are not guaranteed to contain a model that accurately fits the line drawings' outline, the retrieved base has to be modified. Hence, our algorithm consists of two stages. First, given the drawings, it finds the most similar model in the database. Then, the model is deformed, so as to obtain a base whose orthographic projections are very close to the drawings, while preserving the shape of the matched model.

For the second sub-problem, reconstruction of the details, we introduce an algorithm for generating the relief on a given base. We assume that the details can be described as a height function defined on the base and that the lines of drawings of relief objects indicate changes of the height function. Therefore, we want to compute the relief object, such that near the curves the shape of the cross section matches the shape of a 3D step edge, whereas elsewhere its shape is smooth and similar to the base. Specifically, we need to compute the height for the step edge of every curve in a consistent manner. The key idea of our method is to reduce the problem of restoring the height of every step edge to the problem of constrained topological ordering of a graph. Once the relief is defined locally, in the curves' neighborhood, we need to reconstruct the rest of the mesh. We do it globally, by defining the relief as the smoothest function that coincides with the relief obtained locally for every curve.

Figure 6 shows the reconstruction of an intricate relief of a vase. Though the drawing consists of 571 tightly interconnected lines, the reconstruction achieves visually-pleasing results.

Colorization: Colorization traditionally refers to the computer-assisted process for adding color to black-and-white images and movies. For 3D models, colorization has hardly been explored. Instead, models are usually textured by images. There are, however, applications that do not need rich textures, but rather require colorization by just a handful of colors. For such applications, texture mapping is not only an overkill, but it might also produce incorrect output. More importantly, it requires an image that is similar to the model and contains the right texture—an image that does not necessarily exist. Archaeology is such an application.

Specifically, the common perception of the great statues and buildings of ancient Greece and Rome is that they were all pure unpainted stone or green tarnished bronze. However, lately researchers have been arguing that these statues were quite alive, vibrant, and full of color [42]. Unfortunately, after centuries of deterioration any trace of pigment leftover when discovered, would have been taken off during the cleaning processes done before being put on display. Researchers argue that the number of colors and hues used by the artists was limited. In addition, chemical analysis can often estimate the original color. In this case, colorization algorithms will be able to restore the look of the scanned statues.

We propose a novel mesh colorization algorithm [43], which can restore the look of such scanned statues. It does not require mesh segmentation, which often fails to correctly identify complex region boundaries. Our algorithm is inspired by the image colorization algorithm of [44]. There, the user can scribble some desired colors in the interiors of various regions of the image. Colorization is then formulated as a constrained quadratic optimization problem, where the basic assumption is that adjacent pixels having similar intensities should have similar colors

The extension to meshes is not straightforward, due to two issues. First, a fundamental assumption in images is that the work is performed in the YUV color space, and that the intensity Y is given. To determine whether two neighboring pixels should be colorized using the same color, their intensities are compared. In the case of meshes, the intensity channel does not exist. Therefore, a different technique is needed for determining whether neighboring points should be colorized similarly. Second, a limitation of [44] is that colors may bleed into each other. This is fixed in subsequent papers, by applying edge detection that bounds the regions [45]. On meshes, however, existing edge detection algorithms often generate broken curves, through which colors can bleed.

Our algorithm handles these challenges [43]. The key idea is that nearby vertices with similar geometry should get the same color. We thus present a vertex similarity measure that can be used to determine whether two vertices should get the same color. Based on this similarity, we formulate an optimization problem that can be solved efficiently. Moreover, we introduce a new direction field on meshes. We show how the optimization problem can be modified using our direction field, so as to prevent bleeding despite the fact that surface edges are broken.

(a) color scribbles colorization (b) color scribbles colorization

Fig. 7. Only a few scribbles are needed to colorize the cloth, despite its folded structure. Note how the fingers are separated from the folded cloth or the hand-held objects.

To colorize a model, the user scribbles the desired colors on the mesh. For each face the scribble passes through, the closest vertex is colorized with the color of the scribble. These colored vertices are considered the user defined constraints. The algorithm then automatically propagates the colors to the remaining vertices of the mesh in two steps. First, a similarity measure between neighboring vertices is computed and assigned to the corresponding edges. This similarity is based on our variation of spin images [46]. Then, given the scribbles and the above similarities, the colors are propagated to the whole mesh. The optimization attempts to minimize the difference between the color at a vertex and the weighted average of the colors at neighboring vertices, where the weight is large when the descriptors are similar. The output is a mesh in which every vertex has a designated color.

Figure 7 shows a couple of examples where convincing results are generated by our algorithm, given a small number of color scribbles. Note how our algorithm manages to distinguish between the individual fingers and the cloth or the other hand-held objects. Moreover, despite the multiple folds of the cloth, it is easily colored using only a few scribbles that cross it.

5 Summary

A lot of progress has been recently made in shape analysis in computer graphics. However, little of this progress has had a profound influence on archaeology. In this paper we describe our work, performed in the last several years, whose goal is expose the progress in shape analysis to the domain of archaeology. We believe that the mutual interaction of these areas has to potential to impact both fields. In computer graphics, algorithms for solving fundamental problems, such as completion, reconstruction, and matching, which manage to handle the complex archaeological data, will expose the limits of the current techniques. Hence, new algorithms developed for this domain are likely to advance the state-of-the-art. In archaeology, automation may transform the way archaeologists work. Computerized techniques and tools will enable the archaeologist to process the findings immediately and automatically. It is required that the artifacts are scanned by a 3D scanner and represented as polygonal meshes—no metadata or semantics are being used.

We view our work as part of a world-wide effort to overcome the difficulties and enable fast, accurate, and user-friendly analysis of archaeological artifact. In this paper we present several works. In particular, in the section on documentation we describe 3D display by feature curves, by black & white coloring, and by relief extraction. In the section on similarity, we introduce an algorithm for detecting partial matches. In the section on restoration, we discuss shape completion, reconstruction of an object from its line drawing, and virtual colorization. Our data is available for academic research purposes.

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