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Short Paper

Shape analysis techniques for the Ayia Irini case study

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Abstract

The typical approach for archaeological analysis is mainly qualitative and, as such, subjective. Even when some measures are reported in the documentation of artefacts, they are often approximate or ambiguous. Conversely, the quantitative approach is based on objective metrics to produce replicable results and, coupled with digital tools, can assist the qualitative analysis in archaological research with no risk of damage.
In this paper, we present a geometric-quantitative approach for the analysis of archaeological finds and the preliminary results of an ongoing joint research project of two doctoral students within the frame of the EU GRAVITATE project.

CCS Concepts
•***Computing methodologies*** → ***Shape analysis;*** *Mesh geometry models; Shape representations;*

1. Introduction

Documentation is the process of recording information about collections; for reliability and ease of sharing, it is crucial that objects are documented consistently, using recognised standards, common record structure and homogeneous terminology. According to the UNESCO guidelines, writing a textual description of the shape and appearance of the object is highly recommended [S.08], possibly including measures. The typical approach for archaeological analysis is however mainly qualitative and, as such, object descriptions are rich but subjective and prone to ambiguities. Furthermore, even when some measures are reported, they are limited to global dimensions (e.g., height), are approximate (e.g., a curved surface measured by ruler) and are often not uniquely defined: for example, measuring the length of the arm of the statuette in Figure 3 involves choosing a distance metric (e.g., euclidean versus geodesic) and the extremal points: where exactly does the arm begin? So, measurements by different archaeologists may be quite dissimilar, the exact procedure followed very hard to specify in textual notes.

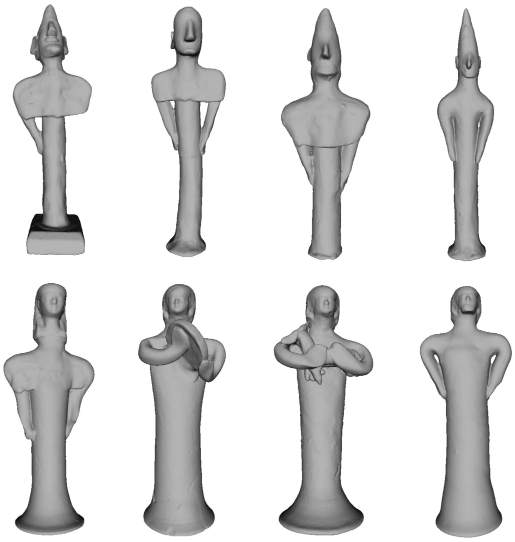

Figure 1: *A subset of the statuettes from the Ayia Irini collection*

Conversely, the quantitative approach is based on objective metrics to produce replicable results and, coupled with digital tools, can assist the qualitative one in different ways. Firstly, the use of a 3D model as a digital twin of the artefact allows pinpointing precise landmarks (measurement extrema, feature lines, areas of interest) and define them uniquely. Secondly, a variety of shape analysis tools can be applied to get quantitative descriptors directly in the digital domain, with no risk of damage for the real artefact. Finally, the study of shape descriptors allows for feature identification, automatic comparison of models (or parts of them) and classification. Indeed, archaeologists are used to classify and categorize the material remains coming from past cultures [PB10]. It is a way to understand and interpret such material. As Irving Rouse declares in his work on artifacts' classification in archaeology, 'analytic classification consists of forming successive series of classes, referring to different features of artefacts. Each class is characterized by one

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or more attributes which indicate a custom to which the artisan conformed, for example, a manufacturing technique, or a concept which he expressed in the artefacts, such as a design' [Rou60].

In this paper, we suggest digital shape analysis tools as a quantitative support for archaeological research and, in the long term, for the task of suggesting new possible classifications. We present the preliminary results of an ongoing joint doctoral research within the frame of the EU GRAVITATE project [PWM*16]. Among the case studies under investigation in project, the Ayia Irini collection of small terracotta figurines seemed appropriate to demonstrate the beneficial support of quantitative analysis to answer different archaeological research questions [Vas16] [Vas17].

2. Case study

The Ayia Irini collection consists of almost 2000 votive clay statues and statuettes of different size, shape and style found in a Cypriot sanctuary in the 20th century. The discovery was done by the Swedish Cyprus Expedition (SCE), led by the archaeologist Ejnar Gjerstad [GLSW35]. After the excavation, the artefacts were divided between Sweden and Cyprus and currently they are conserved in five different museums. In this study, we focus on the so called 'small human idols', mostly attributed to the Cypro-Archaic period (700-500 BC). Gjerstad's classification of the 'small human idols' was based on visual investigation of criteria such as iconography (e.g., arm position, dress, headgear), technique (handmade, wheel-made, and moulded), clay color, slip type (also in this case according to the color: e.g., light/white slip), and decoration (e.g., black and red). As Gjerstad himself admits, his first idea of classifying according to all noted typological differences (shape, technique, representation, etc.) would have created more than fifty types. For this reason, he decided to organize the material in less but bigger groups, deriving sixteen (16) groups that he named Types [GLSW35, pp. 785-786]. This classification presents ambiguities since many criteria overlap between Types. Some of these variations are explained by Gjerstad as advancement in the production technique, without taking other possibilities into consideration, such as artisans' diverging ambition and skill.

For example, various experimental studies on ceramic prove that the technique used and the manufacture level, the form and the shape of the artefact, the weight and the size, and the thickness of the material, are some important parameters that could help us to interpret the artisanal signature of a workshop, or of an individual, and his/her level of expertise [DD88, pp. 19-36] [BS09] [Bot16, pp. 32-33]. Seventy years later, another interpretation of the Ayia Irini material based on stylistic similarities suggested that stylistic features could indicate the provenance; such hypothesis brought to the creation of sub-groups pertinent to those different areas of production or imitation [Fou07, pp. 89-92, 127-132]. In both studies, even if greatly carried out and representative of interesting results, the analyses of the Ayia Irini material followed a qualitative approach.

For the study reported in this paper, one hundred and three statuettes were chosen from the different hosting institutions and digitised, both through laser scanning and photogrammetric technique, in order to produce 3D replicas to be quantitatively analysed. All sampled statuettes represent male standing figures (up to 27 cm height maximum), sometimes holding weapons, animals, or music instruments. They belong to three of the Gjerstad 'small human idols' types: Type 5, 6 and 7. The Type 5 and 6 are characterized by handmade statuettes sharing similar characteristics, which make difficult a definite attribution to a class respect to another. Moreover, some items present common characteristics that make us hypothesize the presence of production patterns that could be meaningful for the identification of workshops or even different artisans' hands. The statuettes attributed to Type 7 are made by three integrated techniques (handmade, wheel-made and moulded) and share more defined characteristics, such as the use of several moulds for the production of the heads. The traditional classification approach followed by the past studies on the Ayia Irini material and the issues identified, led to some interesting archaeological questions:

- Can quantitative analysis support the qualitative one and suggest new, objective classifications of archaeological material?
- Is the presence of fixed measurements, ratios between the parts and geometric similarities expression of a 'serial' production to be attributed to specific workshops or even artisans' hands?
- Is it possible to identify different levels of expertise according to the uniformity of the statuettes' clay width and other dimensions?
- How many moulds can be quantitatively identified in our sample? How many artefacts come from the same mould? Is it possible to identify a 'chronological sequence' through the comparison of the heads which seem to come from the same mould?

In the following, we try to identify the proper shape analysis procedures to support answering each question.

3. Research Design

We started our work by reasoning on the proper dimensions to address each archaeological question, and the suitable computational tool to measure them. As previously mentioned, the statuettes of the sample under study are diverse with respect to several factors, such as the production technique. Eith reference to Figure 1, the bodies of the statuettes are all tubular-shaped, but upper ones are produced by hand, while the remaining are wheel-made. The production technique is particularly important to identify the proper dimensions to be measured and useful to possibly detect the presence of different hands/level of expertise. For example, an experienced craftsman is able to produce by hand a more rounded and straight body respect to a novice; in the same way, operating the wheel requires good skills to achieve homogeneous thickness of the clay.

The level of expertise of the craftsman's hand could then be quantified using:

1. An estimation of the level of *roundness* of the tubular part, for hand-made statuettes;
2. A measure of how much the *thickness* of the material varies over the tubular parts of the shape (thickness' homogeneity), and
3. A *straightness* measure for the tubular part (e.g., distance from the principal axis), for wheel-made statuettes.

To estimate the above dimensions, we analyse a set of slices of the shape, extracted by virtually slicing the model with parallel, horizontal planes at increasing heights. We will focus on the lower

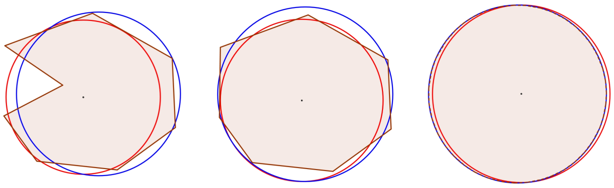

Figure 2: *Difference between fitted circle (blue one) and equivalent circle (red one) computed from the original shape (brown). As it can be seen, as the shape approaches that of a circle, the differences between fitted and equivalent one become thinner.*

part of the body, by slicing the tubular part at different predefined heights. We compute the roundness slice by slice as the average distance between the shape and its equivalent circle (circle centered on the centroid of the shape which has the same area of the slice). This can be computed even as the best-fitted circle using circular regression, however, the equivalent circle is computationally much lighter to compute and, since we are working with sufficiently round slices, it is a good approximation of the fitted one (see Figure 2).

Wheel-made statuettes present an inner cavity (due to the production technique used) which, for scanning limitations, the digital counterpart represents only partially. However, we are able to detect the cavity in the lower slices, as an inner planar hole. Therefore, thickness is computed as the average distance between the inner and outer boundary of each slice, thickness variance is then extracted over the set of slices.

Finally, straightness depends on the definition of the axis of the statuette. We could set up a linear regression system for interpolating the barycenter of the slices, but this can be too sensitive to noise (any imperfection over a slice can tilt the line). Another approach follows the extraction of the axis of rotational symmetry, but the features applied onto the tubular body (e.g., arms) affects its computation. For this reason, we focus on the tubular part, which exhibits a good symmetric structure and allows for a simple extraction of the axis (being a generalized cylinder). In particular, we opted for a vertical line passing through the barycenters' average. We compute the average distance between the principal axis and the barycenters of the slices as a measure of straightness.

Before trying to answer the second research question, we need to define exactly what are the entities that should be investigated for the presence of fixed measurements/ratios (e.g., where does the head begin?). Until now, we are planning to analyse:

1. Total size of the statuette;
2. Clay amount (volume);
3. Position and length of the arms;
4. Ratio between body parts measures.

In a first place, we considered the overall volume of the object as an indicator for both the total size and the clay amount, and we computed it as the volume of the object's OBB (Oriented Bounding Box – the smallest box containing the object). However, this estimate is too rough in practice, so we plan to switch to a volumetric representation of the object, like a tetrahedral mesh, and summing up the volume contributions of all the cells. Even if far more precise, this measure will be approximated nonetheless, due to the partial lack of the inner representation of the object.

Figure 3: *The point-wise curvature on the statuette A.I. 245, following the color bar on the right. Note how arms and head joints are highlighted by curvature.*

Concerning the arm position and length, we need to identify precisely the junction area between arms and chest, which is not trivial. It is commonly understood that the statuettes were produced in separate pieces (the body, the arms, the attributes, and the head), which where successively joined together. In many cases the junction of the arms or of the head is not clearly visible. However, sometimes a tiny relief of clay marks the joint location; we noticed that, in some statuettes, the mean curvature calculated on the mesh highlights that rim (see Figure 3).

After the identification of joints, it is possible to measure parts and look for fixed ratios among different statuettes or within the same statuette (e.g., different statuettes have arms with the same size, the head of a statuette is always 1/3 of the torso, and so forth).

The identification of the number of different moulds used and the recognition of the heads produced with each of them is a typical classification problem, and it is particularly complex when the number of classes is not known a-priori. Archaeologists refer to five moulds used for statuettes of Type 7, without however documenting which mould produced a certain head or how many heads were produced using the same mould. Comparing the shape of heads is interesting to highlight similarities among hand-made figurines as well, to reveal stylistic and provenance hints. So, we have to identify proper shape descriptors for the heads, define a similarity metric based on those descriptors and cluster the most similar statues into groups. The slicing would be most informative when performed with specific orientations and at specific positions; in particular, we identified the vertical and horizontal slice passing through the nose tip as very important. However, the contribution of all the slices provides a more robust description.

Analysing intra-cluster differences in volume and/or shape is likely to highlight chronological sequences: in fact, we expect such differences to indicate a deterioration of the mould.

4. Preliminary results and next steps

In order to optimize the above-mentioned analyses, we need automatic ways to identify regions where specific tools apply: e.g., the tubular part of the body for measuring roundness, the head for mould identification. At a finer detail, we may also need to identify feature location (e.g., nose or ears).

We start by using the paradigm of slices to ideally segment the statuette into meaningful subparts, and use clustering to group similar slices (Figure 4). To this end, we employ a set of descriptors on slices extracted from the entire height of each statuette:

1. Elongation: $1-\frac{m}{M}$, where m and M are the minor and major axis of the MBR (Minimal Bounding Rectangle – the smallest oriented rectangle containing the shape);
2. Solidity: $\frac{A}{A_{CH}}$, where A is the area of the shape and A_{CH} is the area of its *convex hull*
3. Compactness: $\frac{4 \cdot \pi \cdot A}{P^2}$, where P is the perimeter of the shape;
4. Circular variance: error with respect to the equivalent circle;
5. Rectangular variance: error with respect to the MBR;
6. Euler number: #connected components - #holes;
7. Hole-area ratio: $\frac{A}{A_H}$, where A_H is the total area of all the holes.

Then, the clustering is obtained with a k-means approach (see Figure 4). The problem of identifying the proper number of clusters still remains.

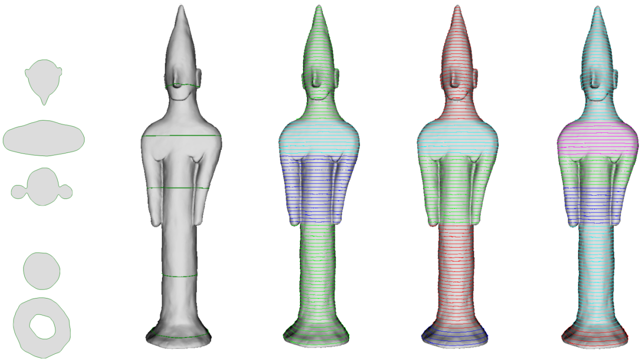

Figure 4: *Slice clustering. On the left, the A.I.130 statuette with a few slices highlighted; on the right, resulting clustering of the full set of slices into 3, 4 and 5 clusters, respectively.*

In our second experiment, we try to automatically recognize wheel-made versus hand-made statuettes (archaeologists already have this classification, but it is useful for us to automatically launch the proper descriptors depending on the case). We perform statuette clustering comparing the performance of two descriptors applied to slices:

- Eccentricity: the ratio between the axes of the MBR;
- Roundness: the average error between the shape and the circle which best fits the points of the shape.

These descriptors are properly applied to the lower body. We envisage to select slices automatically once the segmentation into meaningful parts will be satisfactorily solved. At this stage, however, we consider 100 slices from the lowest part of each statuette (about 2/5 of the statue), then we take their average and compute the variance: we expect the variance for wheel-made ones to be lower. Comparing the results with the ground-truth (archaeological classification) the classification based on eccentricity gets a F1-score of 0.6993 while roundness reaches the value of 0.8167, both with some manual tuning. These first results are very promising: in fact, the classifier based on roundness reaches a very good score; but much has still to be done.The next steps will regard the study of additional descriptors to identify new different subgroups. In the longer term, we envisage to come up with classifications either compliant with the archaeological ones, but even totally divergent.

Another interesting study we want to deepen is the arm hanging detection, starting from a check for the availability of the same curvature *pattern* and then trying to use it for the automatic extraction. Finally, we noticed that different statuettes have similar weights, so we will try to understand if there is a connection based on total amount of clay used for the construction of different statuettes. However, we need to define how to compute automatically the weight of a statuette (average density of clay times the volume?) keeping in mind the lack of inner representation issue.

Acknowledgements

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