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Constant radius geometric features segmentation in archeological pottery

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Abstract **–This paper gives a contribution to the automatic recognition of significant features of ancient ceramics, useful for the historical and/or archeological investigation. These very common type geometric features are obtained by a sweeping action that leaves negative or positive traces, characterized by a cross section with one or more constant radii. The paper proposes a novel methodology that, analyzing the principal curvatures at the points of high-density geometric models of ceramic vessels, acquired by laser scanning, identifies the nodes potentially attributable to these features of constant radius. The recognition process is not trivial since it is affected by uncertainties. To overcome the limits of a recognition based on crisp sets, the recognition rule, proposed for the feature segmentation, is implemented by a fuzzy approach. The method has been tested in the identification of embossed decorations in an ancient olla and it proves to be promising for further applications on other types of geometric features of constant radius.**

I. INTRODUCTION

Ceramic was a frequently used material for artifacts in antiquity and, for its nature of non-degradable material, is found in large quantity. Due to its brittleness, it gets frequently damaged in many fragments. Most of the archaeological work is devoted to identify these fragments, to classify and group them into sets, which pertain to the same pottery. An interest on automatic methods devoted to perform the previously mentioned activity is evidenced from the growing number of scientific papers concerning this topic. The 3D technology is the modern support to implement the methods required to pottery fragments investigation.

Generally, the methods used for analyzing archaeological pottery focus on the recognition of its axially symmetric geometry, which is a geometric property of most part of a vessel. In ancient pottery, parts, not classified in the category of axially symmetric geometry, can be frequently found. These parts can also be semantically significant and associated to recognizable geometric features. It is the case of some details, such as handles, lugs, decorations or inscriptions that can be considered useful to study and classify archaeological artifacts. In particular, some detail features result as traces left by tools, both intentionally, as for example inscriptions and decorative motifs, or unintentionally, such as working marks. In order to recognize detail features some recurrent geometric properties must be identified on the finds, by an algorithmically defined process. A geometric recurrent property is introduced in the detail features of an artifact by the action of a tool, which gives a circular (or quite circular) geometry to the cross section of the feature. These features can be part of an axially symmetric shape, as in the case of fillets or rounds, or located in a not axially symmetric part. The last case is an interesting situation since it refers to types of ceramic fragments, which are not considered by the typical automatic methods proposed in the literature to investigate ceramic finds.

In this paper, a methodology, aimed at the segmentation of some detail features of constant radius that characterize the archaeological pottery, is proposed. This methodology, analyzing the principal curvatures at the points of high-density geometric models of ceramic vessels, acquired by laser scanning, identifies the nodes potentially attributable to detail features of constant radius. The feature segmentation is based on a *recognition rule*, later described in the paper that is implemented by a *fuzzy logic*.

In the paper, an *olla*, experimentally acquired by a laser scanning, is used as case study to describe and test the methodology proposed.

II. COSTANT RADIUS DETAIL FEATURES IN ARCHEOLOGICAL POTTERY

Several detail features of constant radius may be recognized in archeological artifacts. The variety of decorative syntax that characterizes ancient pottery repertoire is wide. Therefore, it is difficult to propose a systematic coding of all known decorative motifs that characterize diverse cultures and historical periods. Some decorations are carried out by finger action, or by various tools, when the clay is fresh or on a leather state, through a sweeping action that leaves negative or positive traces on ceramic surface. In some cases, decoration consists in clay application of constant section swept geometries. These features are characterized by one or more constant radius shapes or something like them.

In what follows decorations techniques used in antiquity, where a constant radius can be recognized, are summarized:

- Negative decoration:
- Engraving, graffiti, excised decoration;
- Impression/Stamping;
- Burnishing;
- Roulette decoration.
- Positive decoration:
- Barbotine decoration
- Applied/plastic decoration
- Molded relief decoration

Negative decoration means that a decoration is done by cutting or removing clay from the artifact. This operation leaves behind marks that can be analyzed by considering them as signs arising around sweep lines. Depending on the decorative technique, the potter prints the tool in a perpendicular direction or at an angle. Traces left by the engraving may have a rounded or sloped rim. If done on clay in plastic state, the engravings are thin V-shaped sections presenting a rounded rim, a situation that allows identifying them as detail features of constant radius. If the clay, on the other hand, is dry, the groove is wider and the engraving takes on the characteristics of the graffiti or even epigraphic testimonies. The excised decoration consists, however, of removing small portions of the surface of the article with a pointed object. The result is a relief decoration and a low relief background. Depending on the nature of the tools used to realize the epigraph or the decoration pattern, also in these last examples a geometric feature with constant radius can be found.

The impressed/stamped decoration is used to decorate clay while it is still damp with various patterns, using different instruments like individual stamps, cords or fingers. Those decorations present the necessary conditions to be examined as constant radius geometric features, considering the tools used to impress them on the pottery's surface. It is one of the oldest processes used by the potters of every civilization to decorate their works, so it is a widely diffused pattern very useful to be automatically recognized.

Burnishing is carried out before the pot is dry enough to be fired (leather-hard). It includes rubbing the surface of the pot in order to make it smooth and shiny. Large areas, such as the shoulder, can be done with a pebble or flat piece of wood, while decorative lines can be done with a blunt stick. These can be considered more as working marks, since they have a functional purpose. Therefore, it can be useful to tell apart this peculiar burnishing pattern from the signs that have a purely decorative meaning.

Roulette decoration is achieved with a small-toothed tool called roulette, which consists of a wheel turning on an axle. The patterns are produced by the continuous rolling motion of the roulette pressed into contact with a rotating vessel, leaving a continuous band of decoration in the clay. The roulette wheel impresses the clay without removing material. So, the traces left by this tool only partially adapt to the requirements required to perform a segmentation of detail features of constant radius, depending on the decoration left by the roulette instrument.

Positive decoration refers to a decoration obtained by adding clay on the surface of the artifact. This is the case, for example, of barbotine technique. Here a thicker mixture of water and clay is added by hand to the pot to create a slightly raised decoration, usually made of lines, plants and animals.

The ceramic slip would normally contrast with the rest of the vessel forming a pattern, or inscription that is slightly raised above the main surface. The geometric decorative pattern realized with this process, particularly, can be recognized as a case where the constant radius geometric features could be found.

In addition to this approach, a plastic decoration can be obtained by adding more clay on the vessel already formed, thus having a great variety of decorations, as for example bosses and ribs. The olla (jar), here used as case study, presents this positive decoration. The last technique presented here is the mold decorative technique, which uses a mold as a tool that impresses the decoration on vessel surface, thus increasing the volume of the smooth surface of the artifact.

The mold can be in different shapes and sizes, so, once again, the possibility of finding detail features of constant radius in vessels decorated with such methods depends on the geometric nature of the decoration impressed by the mold, which comes in different styles.

III. THE RECOGNITION OF DETAIL FEATURES OF COSTANT RADIUS FROM ARCHAEOLOGICAL ARTIFACTS

The detail feature of constant radius (*DFCR*) is a feature of the surface model, which develops along a line (*sweep line* of the feature) and whose transverse section, performed by a plane which is orthogonal to the *sweep line*, is circular with a radius R_i, called *characteristic radius*.

Since, in order to recognize a DFCR, the curvature radius has to be estimated, the geometric model have to be processed to locally evaluate geometric differential properties. This process is not trivial because *DRCF*s must be segmented from discrete models, such as those resulting from the 3D scanning of an archaeological artifact. The original surface is approximated by a tessellated surface composed of triangular facets that is not a differentiable surface. The *DRCF*s, too, are features of limited extension with respect to the mesh sampling, so that, the evaluation of geometrical differential properties is more difficult and affected by greater uncertainties. Furthermore, in the case of archaeological artifacts, the evaluation of differential properties is blurred by the surface irregularities: the small fluctuations of the surface curvature (due, for example, to working marks) and by the measuring noise.

Based on the previous considerations, in this paper a robust method to the automatic segmentation of *DFCR* from scanned archaeological artifacts is proposed. It consists of the following principal phases:

- Curvatures and normal estimation at all the nodes of the tessellated model;
- Identification of the values of *characteristic radius* of the *DFCR* that can be recognized in the object;
- Automatic selection of the nodes potentially attributable to *DFCR*;
- Identification and segmentation of each *DFCR*.

In the first phase of the method the normal at the vertexes are estimated by using the *medial quadric* criterion. It has been proven that this criterion is independent from the shape and the sizes of the triangles in the mesh. The principal curvatures at the nodes **p** are evaluated by approximating its neighborhood with a *5-coefficients paraboloid* [1]. The evaluation of these differential properties is fundamental since, at each node of the mesh, the *characteristic radius* is associated to the inverse of the modulus of the first principal curvature (k_1). The radius of curvature of the *sweep line* is associated to the inverse of the modulus of the second principal curvature (k_2).

In what follows, the discrete model of an ancient *olla,* acquired by a laser scanner (figure 1), is used as the case study to describe the proposed methodology and test it.

This archaeological artifact has various *embossed decorations*, mostly located on the *body* and between the *neck* and the *shoulder* of the pot. All decorations are characterized by a quite triangular cross section, whose vertices are rounded off with fillets of different radii (figure 2). So, various *DRCFs* of given radius R_i are identified and associated to each decorative prominence.

Fig. 1. The test case olla

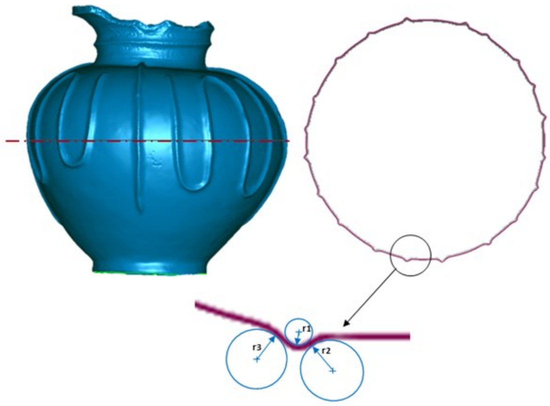


Fig. 2. A transverse section of the olla and a magnified view of the triangular-shaped cross-section of the embossed decoration

In figure 3 the color map of the radius values $R_1 = 1/|k_1|$, evaluated at the nodes of the triangulated model of the *olla,* is shown.

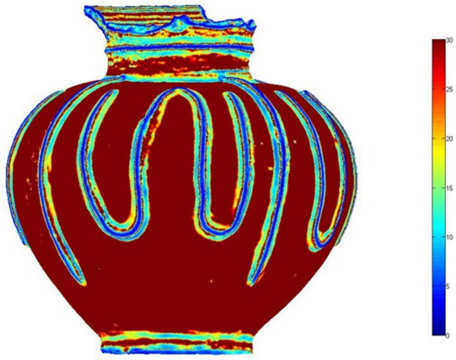


Fig. 3. The colormap of $1/|k_1|$ for the test case

A. Identification of the values of characteristic radius of the DFCR in the object

The methodology here proposed has been conceived under the hypothesis that the values of the *characteristic radii* R_i are a priori unknown and must be identified before the *DRCF*s can be recognized and segmented.

This phase of the methodology, whose flow-chart is shown in figure 4, includes an iterative procedure devoted to this purpose. It is based on the analysis of the recurrences of the R_i values estimated at the *regular* points of the model.

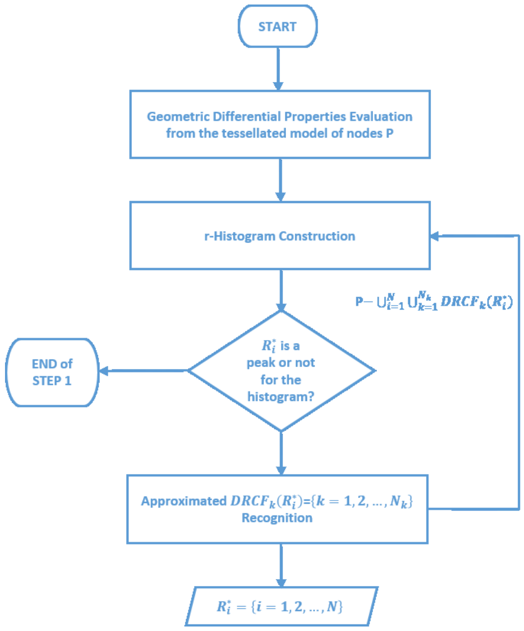


Fig. 4. The flow-chart of the method for identifying the characteristic radius values of the DFCRs.

In figure 5, the histogram of the frequency of R_1 values, evaluated at the nodes of the *olla*, is reported: R_1 is the most frequent radius detected after the first iteration.

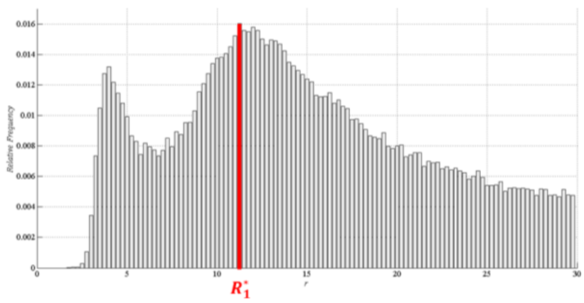


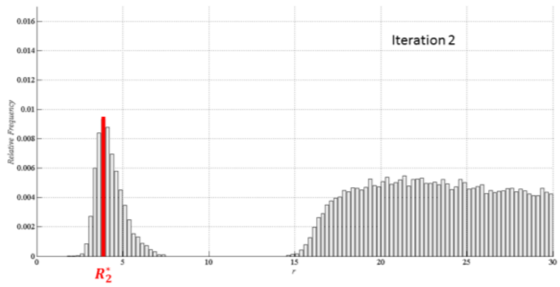
Fig. 5. The first histogram

Due to the uncertainties affecting the curvatures values, the peaks in the histogram tend to be wider and lower. Whereas in the case of high-density synthetic discrete models these peaks remain well detectable [5], this is no longer true for mesh experimentally acquired due to the measurement noise and to the surface irregularities. The blur of the peak associated to the *DRCFs* of radius R_i, is greater when the R_i value increases: the peak may expand so much to cover and cause other useful peaks to disappear. For this reason, this phase of the methodology implements an iterative procedure for going and looking for the radius values R_i. Additionally, to take into account the uncertainties affecting the value of the estimated radius $1/|k_1|$ of the surface in the node $\mathbf{p}_j$, its relative occurrence is evaluated as a fuzzy variable w_j and not as a true or false event. In this way, the frequency of occurrence of the radius gives rise to more discriminating evidences (peaks in the histogram), since the weight w_j is evaluated based on its expected uncertainty. A weight w_j=1 is assigned for an estimation of the radius that is certainly true and, on the contrary, 0 for an estimation certainly false. For intermediate conditions, the following empirical function is used:

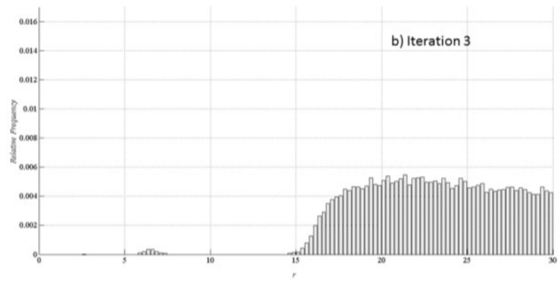
$$w_j = C_1 e^{-\gamma_j^{C_2}} \quad (5)$$

where C_1 and C_2 are empirically determined coefficients and γ_j is the maximum value of the tangent of the dihedral angle evaluated between two adjacent triangular facets belonging to the 1-neighbourhood of the node $\mathbf{p}_j$. A small value of γ_j is the evidence of a good approximation of the surface by triangles: for γ_j=0, which is the case of a very good approximation of the surface curvature, $w_j=1$. On the contrary $w_j\approx 0$ for a rough tessellation of the surface. The function w_j is evaluated for each node of the mesh. The values of R_i are evaluated as the *mode* of the histogram.

An approximate recognition of the *DRCFs* of radius R_i is performed, based on the region-growing algorithm described in subsections *B* and *C*. The aim is to detect the set of regular nodes, potentially allocable to a DRCF of radius R_i, and remove them from the histogram. In figure 5.a the histogram at the iteration 2 is shown where the new *mode* R_2 can be recognized. Figure 6.b reports the histogram at the iteration 3.



a)



b

Fig. 6.a-b. The histograms at the iterations 2 and 3 of the step 1 of the methodology

At the iteration 3 no significant peak is identified: the residual non zero relative frequencies are due to surface roughness and experimental noise.

In the case of the *olla* two values, R_1=11.4mm and R_2=3.9mm, have been identified.

B. Selection of nodes potentially attributable to DFCR

This phase of the methodology aims at recognizing the *DRCF*(R_i) for all the N radius values R_i (*i=1, 2, …N*) evaluated during the step 1.

To overcome the problem of the $1/|k_1|$ values dispersion at the nodes belonging to the same *DRCF*, it is suitable to implement a *fuzzy logic* based method. So, for each node, a *membership value* to the category of nodes, characterized by the property of having a given value of the curvature radius *r*, is automatically assigned. This value depends on specific factors characterizing the mesh node and results from a suitable set of *membership functions*. The membership functions are three and defined as follows:

– μ_e: membership of a node to the category of *non-regular* points. In archaeological sherds, these points are usually located on the fracture surfaces;
– $\mu_{r=R_i}$: membership of a node to *DRCF* having radius R_i;
– $\mu_{\neg(r=R_i)}$: membership of a node to the remaining regular surface of the vessel.

Since the generic node can belong unequivocally only to those categories, its membership functions must satisfy the *normality condition*:

$$\mu_e + \mu_{r=R_i} + \mu_{\neg(r=R_i)} = 1 \qquad (1)$$

To evaluate these functions, some suitable parameters have been identified, which influence the uncertainty associated with the evaluation of the principal curvatures at the generic node of the mesh. The dispersion of these estimates is sensitive to both the *regularity* of the surface and the *quality* of the tessellation [5].

The attribution of the *regularity* to a point **p** is performed associated at each node by the membership function μ_e, which is assumed as a linear function (Fig. 7) of the estimated value of the *sharpness indicator* *SHI*(**p**) [2].

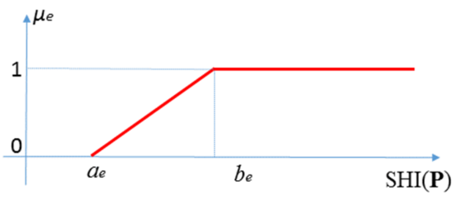


Fig. 7 The membership function μ_e

The values of a_e and b_e are determined in accordance with the results obtained in [2].

The parameter, here used, to measure the *quality* of the *tessellation* is the *factor of curvature approximation* γ [3]. This factor is defined as the maximum value of the tangent of the dihedral angle between two adjacent triangular faces belonging to the 1- ring neighborhood of the generic point **p**. Once the radius *r* is evaluated in a point **p**, the association to a *DRCF* having radius R_i is measured by a membership function $\mu_{r=R_i}$ (Fig. 8), which is trapezoidal-shaped. The membership function $\mu_{r=R_i}$ is defined by the parameters *σ* and *t*, as depicted in the Fig. 8.

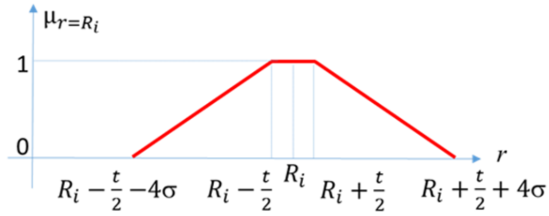


Fig. 8 The membership function $\mu_{r=R_i}$

The values *σ* and t are empirically determined by specific experiments, consisting in case studies (i.e. *DRCF* synthetically generated) designed which specific values of *γ* in the range 0.01–1.

C. Identification of the single DFCR

At the beginning of this step, the membership functions μ_e, μ_r=R_i and $\mu_{\neg r}$=R_i are simultaneously evaluated at each point of the model. In figure 9 the two maps of the membership function μ_r=R_i are shown for R_i=11.4 mm and R_i=3.9 mm.

As shown by the figure, the membership functions $\mu_{r=R_i}$ show a certain variability, which is the measure of the uncertainty in the *DRCF* recognition. This uncertainty will be resolved during the next *region growing phase* when neighboring nodes, if recognized *similar* to the growing region F_j of radius R_i, are aggregated to it. This is performed by an algorithm based on the *fuzzy* concept of *dissimilarity* between the analyzed point (**P**$_k$) and the growing region F_j [4] in terms of μ_e, μ_r=R_i and $\mu_{\neg r}$=R_i.

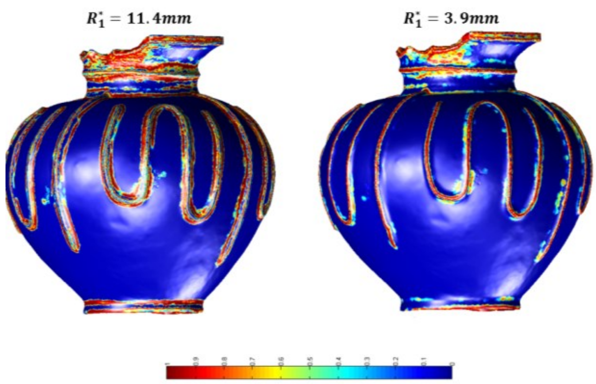


Fig. 9 The color map of the membership function $\mu_{r=Ri}$ for R_i=11.4mm and R_i=3.9mm

The region-growing algorithm starts at the *seed node* $\mathbf{P}_s$ where the maximum of the membership function

$\mu_{r=R_i}$ is reached. A comparison between the node $\mathbf{P}_k$ on the boundary of the growing region F_j and every node belonging to its 1-ring neighborhood is carried out using the *dissimilarity function* D. When D not going over a given threshold value, a new node is added to the region F_j. Once all the nodes in the 1-ring neighborhood of $\mathbf{P}_k$ have been examined, the procedure continues considering the 1-ring neighborhood of all the other boundary nodes for the growing region. The growing algorithm stops when dissimilar nodes are met or all the nodes are analyzed. The threshold coefficient for the *dissimilarity function* is a parameter of the method that requires being empirically set.

Figure 10 shows the results of the recognition of the constant radius features in an ancient olla.

IV. CONCLUSIONS

With this work, a contribution to the automatic identification of significant features of artistic ceramics, useful for the historical and/or archeological investigation, is provided. A new type of geometric feature is identified and a method for its automatic recognition is proposed. These are very common type geometric features that are obtained by a sweeping action that leaves negative or positive traces, characterized by a cross section with one or more constant radii, on ceramic surfaces.

The recognition process is not trivial since it is affected by uncertainties. In particular, the ceramics investigated are ancient finds. So, for the aims of the work, a non-conventional logic is used to overcome the limits of the classification based on crisp sets.

The method has been tested in the identification of *embossed decorations* in an ancient olla and it proves to be promising for further applications on other types of constant radius geometric features.

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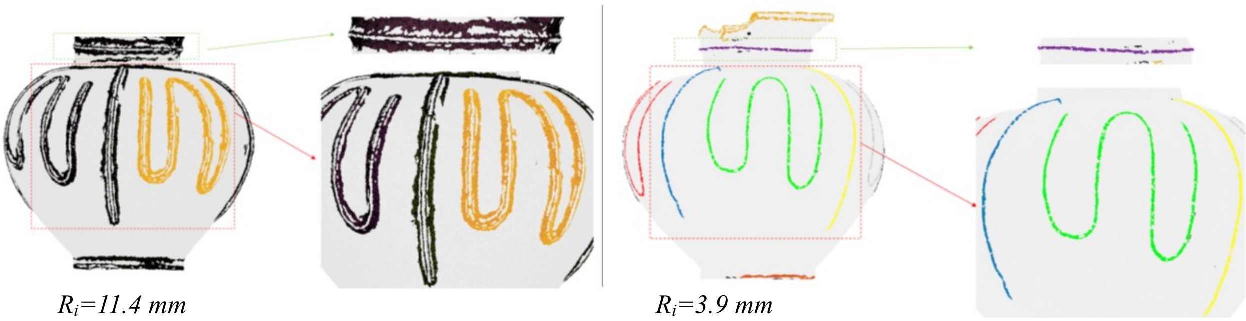

Fig. 10. The results of the recognition of the constant radius features in an ancient olla