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Measurement of constant radius swept features in cultural heritage

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Abstract. The dimensional characterization of archaeological fragment is a very complex operation and could prove to be useful for identifying the presence of standard attributes in the ceramics found from a specific archaeological site, or for making comparisons and analysis of similarities or for studying ancient technologies used for manufacture of objects. The dimensional analysis of the fragments is now carried out manually with traditional measuring devices. Typically, the results obtained are inaccurate and non-repeatable measurements.

This paper focuses on the dimensional characterization of a specific geometric class of features: the constant radius swept features (called here CRS features). Several archaeological features, such as rims, bases, decorative motifs, processing marks and grooves are referable from a geometric point of view to the class of CRS features. These are detail features, which may be very interesting for the investigation of some aspects related to the historical-archaeological classification of the find. CRS features are often found on worn, damaged (e.g. chipped) or fragmented objects; they are frequently characterized, from a geometric point of view, by free form surfaces and by a limited cross sectional extension. In some cases, CRS features can be of axially symmetrical geometry: this occurs quite frequently in the case of archaeological pottery. For all these reasons, it is often difficult to apply traditional manual methods for the quantitative dimensional characterization of CRS features.

This paper describes an original methodology for the measurement of CRS features acquired by scanning technologies. The algorithmic implementation of this methodology, consisting of a suitable processing of the feature nodes, allows to carry out automatically the dimensional characterization of the feature.

1. Introduction

The dimensional measurement of an object, starting from the 3D point cloud acquired from its surface with a scanner, is a generally non-trivial operation. The measure requires that an ideal geometry is associated to the investigated feature. The estimation of characteristic dimensional attributes is in fact generally associated with specific shape features of the object such as, for example, the diameter of a cylinder, the distance between two parallel and opposite flat surfaces, etc. The identification of these shape features requires an adequate processing of the 3D point cloud that typically goes well beyond the direct evaluation of local dimensions, estimated as the distance between two points or as the diameter of the maximum inscribed sphere [1].

For a Cultural Heritage (CH) artefact, dimensional assessment is an even more complex operation for several reasons. Although of repeatable geometry, the archaeological object is a unique handmade piece commonly characterized by complex and non-analytical shapes. Its surface is usually rough and damaged due to environmental agents and wear, so much so that the relative geometric properties were altered and, in some cases, lost. Furthermore, the find is usually found in the form of fragments.

The evaluation of the maximum diameter or the thickness of an archaeological potsherd needs the preliminary extraction of the axially symmetric geometry, the identification of its axis of revolution and the recognition of the external wall (i.e. a shape feature). The recognition of these features can be performed manually by experts or derived from an adequate processing of 3D point clouds and surface texture data extracted from the archaeological object [2-5]. The purpose of this recognition phase is to identify portions of external surface of the find characterized by specific properties related to geometry, texture, color, pattern, decorative motifs, etc. These features often differ geometrically (for example, they can be axially symmetrical, planar or cylindrical), so it is necessary to design and implement different rules to recognize them automatically. Depending on the geometric type of the features, it is possible to determine different situation elements (axis, center etc.) and dimensional characteristics (diameter, thickness, etc.) thanks to the development of dedicated methodologies [6]. In [7], for example, a method was proposed to automatically evaluate the dimensional properties typically used by archaeologists to guide the classification of the fragment. A recent review of these methodologies can be also found in [8].

The algorithmic implementation of the aforementioned methods also allows the automation of the entire measurement process ranging from the feature recognition to the evaluation of the characteristic dimensions of the fragment, with the advantage of obtaining faster, repeatable and accurate measurements compared to those expensive performed manually by experts. In some cases, the application of these specific methodologies allows the measurement of dimensional attributes otherwise not evaluable with traditional manual methods. This is typically the case with the dimensional characterization of morphological elements not attributable to analytical surfaces (such as decorations, grooves and processing marks).

This paper concerns an approach for the dimensional characterization of a specific class of features: the Constant Radius Swept (CRS) features. Several archaeological features pertain to this class, from a geometric point of view. These features can be left by the action of fingers or tools, both intentionally, such as inscriptions, decorative motifs, pottery rims or bases, or involuntarily, such as processing signs. From a geometric point of view, CRS features derive by the sweeping action applied to a specific cross section, which generates negative or positive traces on the object surface. This cross section is composed of one or more approximately circular arcs, the radii of which remain fairly constant along the development line (or sweep curve) of the feature. Sometimes, CRS features belong to the axially symmetrical portion of the surface of the archaeological find, such as rims and grooves usually found on the archeological pottery. A fuzzy logic-based methodology was previously developed by the authors that carries out the CRS feature recognition for different object classes, such as mechanical components [9-10]. More details on the implementation of this methodology, in the specific case of archaeological finds, can be found in [11-12].

The dimensional characterization of CRS features is, however, difficult to perform and subject to great uncertainties because of the relative cross-section that is usually of limited extension. Only a limited number of 3D points can be extracted during the scanning of these detail feature. These points must be approximated by an ideal geometric feature able to catch the characteristic geometric property of this class of features, that is, a circle that lies in a plane orthogonal to the sweep line of the feature. Since CRS features are potentially interesting for the investigation and the historical-archaeological classification of the find, this paper focuses on a new and original methodology for the automatic dimensional characterization of CRS features acquired by scanning technology. The methodology, with its various phases, is described in the next section.

2. Proposed Methodology

In order to describe the methodology, the tessellated model of a potsherd (Figure 1 a)) acquired by the 3D scanner FARO with a laser line probe (accuracy $2\sigma = 0.0688$ mm, sample rate $Sr = 0.25$ mm) is considered here as case study. The CRS feature, selected for the measurement, is the rim of the potsherd. For this type of feature, there are two dimensional quantities of interest for the archaeological investigation: the diameter of the rim and the radius of its local cross-section. Figure 1b) shows the CRS feature, as it was recognized by the fuzzy methodology [9-13].

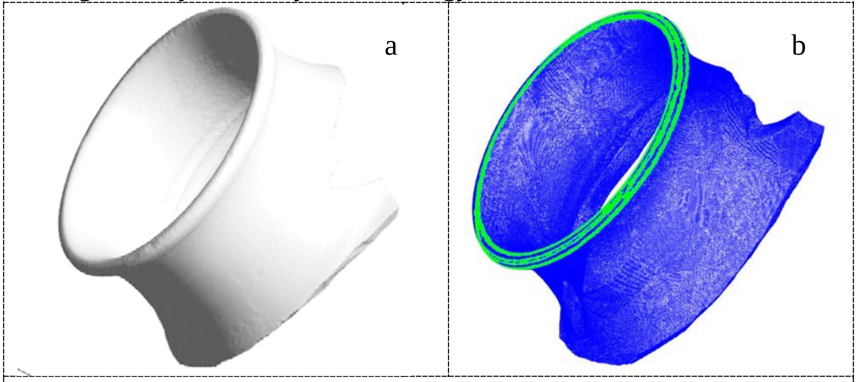

Figure 1. a) The discrete model of the potsherd used as case study here. b) The CRS feature for which the dimensional characterization is carried out.

The methodology proposed here for the automatic dimensional characterization of the rim consists of three steps.

The step 1 consists of a rough estimation of the center of curvature $\mathbf{C}^0{}_i$ associated to the principal curvature maximum in absolute value ($k^0_{1_i}$) at the points of the CRS feature (with i = 1, ..., n, where n is the number of the points recognized as belonging to the feature). The principal curvature and its center are estimated by locally approximating the surface with a 5-coeffiecients paraboloid. This estimation is affected by a very high uncertainty due to the local surface approximation with a paraboloid. The set of the centers $\mathbf{C}^0{}_i$ identifies a 3D point cloud.

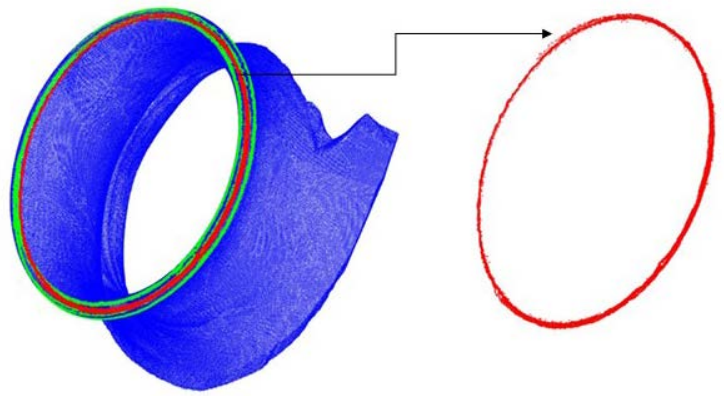

Figure 2. The CRS feature (in green) and the related point cloud composed of local centres of curvature $\mathbf{C}^0{}_i$ (in red)

In the following step, a first-attempt sweep line is estimated (it is depicted in green in figure 3). The sweep line consists of a set of n polynomial curves of 2-nd degree $\boldsymbol{\gamma}_i^0 \equiv \left(\gamma^0_{i_x}, \gamma^0_{i_y}, \gamma^0_{i_z}\right)$. Each of them locally approximates the set of centers of curvature $\mathbf{C}^0{}_i$. The curve segments $\boldsymbol{\gamma}_i^0$ are evaluated by a moving average filter that locally performs a least-squares robust regression.

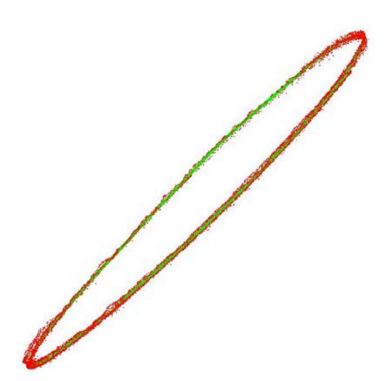

Figure 3. The sweep line (in green) estimated by a moving average filter starting from the set of centres of curvature $\mathbf{C}^0_\mathrm{i}$ (in red).

The methodology ends up with a refinement step, which serves to get the most accurate estimation of the local radius r_i, of the sweep line of the CRS feature and of its diameter. In order to estimate the radius r_i, the non-ideal feature (i.e. the region of adjacent points recognized as belonging to the CRS feature) is locally approximated by a circle λ_i lying in a plane Π_i orthogonal to the sweep line $\boldsymbol{\gamma}_i^0$ in $\mathbf{C}^0_\mathrm{i}$. In this regard, a circular least-squares fitting of the CRS points that are in the neighborhood of the plane Π_i is carried out. The local radius of the feature is the radius r_i of the circle λ_i and its center $\mathbf{C}_\mathrm{i}$ belongs to the refined version of the sweep line of the CRS feature (figure 4). The diameter of the rim is evaluated from the circular approximation of this sweep line.

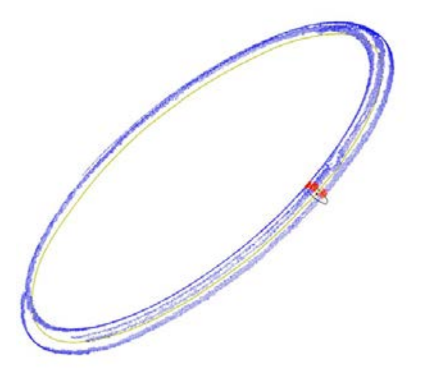

Figure 4. The refinement step, which serves to get the most accurate estimation of the local radius r_i, of the sweep line, and of the diameter of the CRS feature.

Discussion and Conclusions

The dimensional characterization of a shard is an important activity for the purposes of an historical-archaeological investigation. It is useful to identify any standard attributes in the ceramics found from a specific archaeological site, to make comparisons and analysis of similarities between finds, to study the ancient technologies used for the manufacture of the object, etc.

Dimensional analysis of fragments is carried out today manually by archaeologists. This activity starts from the manual drawing of the fragment. In the specific case of the rim of the potsherd considered here, the measurement of the diameter is traditionally carried out by using a template composed of circles with different diameters. The fragment rim is lined up with different circles until the best match is found. The results of this measurement, however, shows several problems. Firstly, what diameter of the feature did the measurement carried out traditionally quantify? Is it an external, internal or an average diameter? Furthermore, the measurement performed by the traditional methodology depends on the operator, on his/her specialization, his/her personal skills and his/her professional experience. Traditional measurements are generally not very accurate and repeatable: the same operator, in fact, can obtain significantly different measurements.

The methodology proposed here offers an alternative to the traditional dimensional characterization of the feature with the advantage of being able to be applied to different types of archaeological features (as long as they are geometrically referable to the class of CRS features), such as edges, bases, decorative motifs, machining marks and grooves. As regards the case study considered here, the methodology is able to measure, in addition to the diameter of the rim, other dimensional characteristics useful for the archaeological investigation, such as the radius of the local cross-section of the rim, allowing to extract a whole series of useful information for investigating the quality of the manufacturing technology used. The sweep line extracted from the rim, for example, is far from being perfectly circular, as is its cross-section. For this reason, the methodology proposed here implements a set of tools in order to quantify the deviations from the ideal circular references. The estimation of the deviations of archaeological features from ideal geometric properties is potentially important because it gives a measure of the ceramic processing quality due to the care of the operator in the realization of an artifact, or to the clay mixture or the firing process.

All these are new information for archaeological investigation, which become accessible thanks to the new possibilities that arise from this methodology. This large set of dimensional measurements can be stored subsequently in suitable archaeological databases. Recently, for example, an original 3D informational database has been also proposed for the automatic archiving of features coming from the semantic decomposition of archaeological pottery finds [13].

The methodology will soon be applied to dimensionally characterize different CRS features recognized by high-density 3D models of archaeological shards in order to validate it and evaluate its relative accuracy and robustness.

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