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A novel method for estimating the complete 3D shape of pottery with axial symmetry from single potsherds based on principal component analysis

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ABSTRACT

Recording ceramic potsherds recovered during archeological excavation is an essential task for both the archeological interpretation and conservation because of the evidence they represent. However, complete vessels provide additional data such as food storage capacity, and physical dimensions that surpasses the information that can be extracted from a single potsherd. This paper proposes a novel digital approach intended to improve the archeological registration and interpretation by the complete 3D shape reconstruction of pottery with axial symmetry based on the 2D recordings of single potsherds. A 3D laser scanner and photogrammetry are used to acquire the mesh models of potsherds and complete vessels, respectively. Subsequently, 2D generator profiles are extracted from the models by calculating the contour, axis of symmetry, and diameter of the rim's potsherd. Then, a database of profile contours of complete vessels was established, classified and utilized in the reconstruction algorithm using Principal Component Analysis (PCA) in order to obtain a 3D complete representation of pottery estimated from a single potsherd. The proposed method was applied in the study of pottery developed by Pre-Hispanic civilizations on the north coast of Peru for the preparation and consumption of a maize-based alcoholic beverage. Accuracy experiments report errors of less than 6.25% for the 3D reconstruction of complete vessels from single potsherds. Nevertheless, experiments demonstrate that the use of a large enough database in the reconstruction algorithm leads to accuracy errors less than 0.66%.

1. Introduction

Pottery analysis is one of the trademarks of archeology. For most archeological research programs the analysis of pottery, one of the most ubiquitous, frequent and resistant materials, is a very important and unavoidable procedure that takes place after the collection of potsherds in the field. Ceramics provide archeologists with vital information regarding many different aspects of the human past (Orton et al., 1993). For instance, the identification, comparison, and classification of different types of ceramic forms are fundamental for the construction of ceramic typologies based upon which past cultural affiliation can be determined. The evolution of ceramic forms, and its study through seriations, can determine relationships between societies, external influences, population movements, interrelations between populations, technological spheres, availability and access to raw materials, production specialization, social distinctions, etc.

Abundant ceramic fragments are typically collected in an archeological excavation all over the world. Their relative frequency and number usually is much greater than the number of complete vessels recovered. Formally diagnostic ceramic fragments, namely, those from which the shape of the ceramic vessel can easily be determined, are the prized items in a ceramic collection. In some ideal cases, particularly when a strong typology has already been developed for the ceramic tradition, a 2D profile of the entire artifact can be extracted, usually through a manual method that includes multiple measurements and drafting, prone to human error. Herein, the profiles of fragments are manually drawn on a paper sheet by using tools such as a profile gauge and a rim chart (Orton et al., 1993). This method heavily depends on the experience and the skill acquired by the archeologist. Therefore and due to its labor intensive aspect and variability, it is expensive, time consuming, and less effective with respect to other methods

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of recording.

Assessing the form of entire ceramic pieces based on the fragment available to the archeologist, on the other hand, yields critical information in dimensions such as formal typology and variability, storage capacity (volume), physical dimensions (thickness, weight and height), amount of materials employed, labor (Orton et al., 1993). All these dimensions are particularly relevant to assess technological, social, economic and even political characteristics of ancient societies.

During the last ten years numerous attempts have been made to improve ceramic analyses conducted by archeologists, focusing on the accurate extraction of profiles from potsherds (Karasik and Smilansky, 2008; Yao and Shao, 2003; Mara and Sablatnig, 2005). In most cases laser scanners or photogrammetry have been applied. Only a few attempts have been made to develop new methodologies for reconstructing complete vessels based on potsherds. For instance, Kampel and Melero (2003) generated a reconstruction by using a prolongation of the original profile using a cubic spline that follows the shape indicated by at least 15% of the profile contour. This technique reconstructs shapes not supported by the archeological evidence, and it could produce results that do not even exist. Moreover, it requires the assistance of an expert to edit the estimation previously described which makes it highly dependent on the editor's expertize. Therefore, a computational approach able to estimate the shape of complete vessels by using a single potsherd and the knowledge of prior archeological evidence is needed.

This paper proposes a novel methodology intended to the digital reconstruction of the 3D model of a complete ceramic vessel based on the information provided by a single potsherd and a database of contours of complete pottery using statistical tools. As a study case, the proposed approach is applied to ancient Peruvian ceramic pottery locally known as *paicas* found during archeological excavations conducted at the site of San Jose de Moro in the northern Perú (see Fig. 1).

The remainder of this paper is organized as follows. In Section 2, we describe the pottery and the 3D acquisition system, involving the recording of complete pottery and ceramic potsherds of the *paicas* using a laser scanner and photogrammetric technologies. Section 3 explains the methodology and algorithms proposed for finding the orientation of a single potsherd, its diameter and 2D profile around its axis of symmetry. Section 4 explains the procedure for the creation and classification of a reference database using the profile shapes of the 35 selected *paicas*. In Section 5, we describe the reconstruction algorithm of complete pottery from single potsherds using the reference database and statistical tools. In order to assess the effectiveness of the proposed method, an accuracy test is conducted in Section 6. Finally, the conclusions of the entire work are explained in Section 7.

2. 3D acquisition system

2.1. Case study: paicas from the Moche civilization

Paicas is the local, mochica, name given to ceramic pottery containers found during archeological excavations conducted at the site of San Jose de Moro in the Jequetepeque Valley of the northern Perú (Castillo et al., 2008). Starting at least 2000 years ago, and into the present, *paicas* have been used by local population for the storage of liquids (water, unfermented and fermented beverages) and solids (corn, beans, peppers, etc.). They often have an overall oval shape and a variety of neck shapes depending on their cultural affiliation as shown in Fig. 2. The cases analyzed here predominantly correspond to paica employed for the production and storage of fermented corn by the Moche civilization(250 to

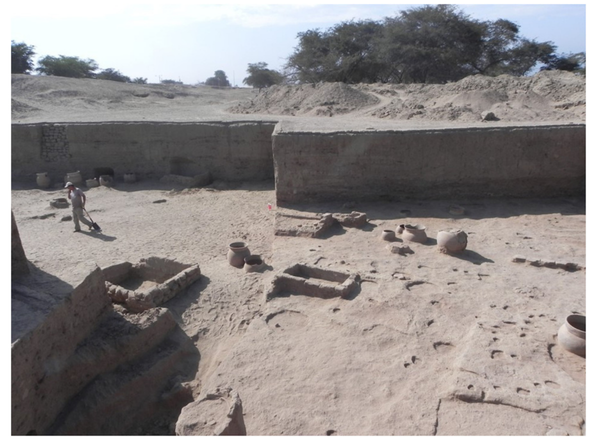

Fig. 1. San Jose de Moro Archeological Site (La Libertad, North Coast of Peru). (a) Excavation of the cemetery area.

850 A.D.). These *paicas* played an important role in ritual ceremonies, most of the time associated to the celebration of death of high status individual.

The reconstruction of these vessels is highly important, not only because it will lead to the accurate registration of how they looked but also to the better understanding of the role of these vessels within the ceremonies they were a part of. Complete and well-preserved vessels are rarely found during excavations. Most of them are already cracked and some others are much damaged when extracted from the archeological sites. However, during 25 years of continuous archeological activity, hundreds of complete vessels were rescued and the 35 best preserved are used in this research for the creation of a data-base of complete shapes.

2.2. 3D recording of complete pottery

Thirty five 3D models of *paicas* were recorded by using Agisoft PhotoScan® (Agisoft L.L.C., 2013) in a computer system equipped with a 8-core Intel i7 processor at 3.40 Ghz, 8 GB of RAM and a ADM Radeon HD 7470 with 512 MB RAM graphics card running Microsoft Windows 7 64-bit. This software utilizes dense stereo reconstruction tools to produce point clouds and meshes from a set of high overlapped images. This technique was selected due to its high versatility for taking pictures in complex scenarios in which electrical energy and computers are not available. We record an average of 52 digital images per *paica*. The shooting protocol consisted in taking pictures around the external surface of the vessel as well as the inside of it.

Fig. 2a shows the location of the photographs around a vessel estimated by Agisoft. This vessel is partially buried on the ground as illustrated in one of the photographs of the set (Fig. 2b). Subsequently, the 3D mesh model of the selected vessel is obtained through Agisoft PhotoScan® in three stages: figure alignment, geometry building, and texture building. For more information concerning the algorithms utilized in all the stages and the description of the parameters selected in Agisoft PhotoScan, we direct the reader to other works (Seitz et al., 2006; Scharstein and Szeliski, 2002). The average total time required for the software to reconstruct each vessel is 2 hours while the average resolution is 1 million points per model. A 3D mesh of the vessel is illustrated in Fig. 2c.

2.3. 3D recording of ceramic potsherds

Eleven ceramic potsherds from *paicas* were recorded with the commercial 3D laser scanner Next Engine HD (NextEngine Inc., 2012). All of those fragments are called diagnostic since they