Computers & Graphics 37 (2013) 41–53

Contents lists available at SciVerse ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Technical Section

Virtual reconstruction of archeological vessels using expert priors and intrinsic differential geometry information ☆

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ARTICLE INFO

Article history:
Received 18 April 2012
Received in revised form
8 November 2012
Accepted 9 November 2012
Available online 20 November 2012

Keywords:
Intrinsic geometric features
Gaussian curvature
Parabolic contours
Surface alignment
Mending
Archeological shards

ABSTRACT

This paper presents a method to assist in the tedious task of reconstructing ceramic vessels from unearthed archeological shards (fragments) using 3D computer vision-enabling technologies. The method exploits the shards surface intrinsic differential geometry information (one of many possible tools) coupled with a series of generic models to produce a virtual reconstruction and rendition of what the original vessel may have looked like. Generic models are constructed based on a host of factors including expert historical knowledge of the period, provenance of the artifact, and site location. The generic models need not to be identical to the original vessel, but they must be within a geometric transformation of it in most of its parts. The method is suited for ceramic vessels with some relief (i.e., surface with molding, carving, or stamping), as this method exploits surface intrinsic features for alignment. The alignment of the shards against the generic model uses a novel set of 3D weighted curve moments. The transformation is computed from corresponding parabolic contours on the shard and the generic model. A distance error metric is used to access the accuracy of alignment of a fragment to a given generic vessel model. The method is also extendable to surface markings. For a vessel that has no relief, color information or surface breaks can be used for the alignment. The method is tested on a subset of 3D scanned Independence National Historical Park (INDE) ceramic artifacts and the generic models created by experts. This work is part of an ongoing research activity in computational archeology that exploits many different tools and features to help in the mending process. Only the use of surface differential geometry information is reported here. This aspect is complementary to various other tools reported elsewhere by us and others, such as surface breaks, texture, color, etc.

1. Introduction

Our 3D computational archeology work is motivated by the necessity of reconstructing excavated archeological pieces prior to the discovery, preservation, and interpretation of history. The focus of the project is on ceramic and other artifacts originating from one of the best preserved and most diverse American urban colonial archeological sites ever excavated—the Mall at Independence National Historical Park (INDE) in Philadelphia, Pennsylvania. This project was deemed by INDE archeologists as having a great potential to have significant implications for archeological artifact mending, collections management, and site interpretation.

The mending of unearthed archeological ceramic shards is currently a tedious and time-consuming process. Nevertheless, it is a vital step in interpreting the archeological record and an important component in understanding and preserving cultural heritage. 3D computer vision-enabling technologies have the potential to automate at least part of the traditional reconstruction process and offer the promise of transforming the entire archeological journey from primary evidence collecting to public history interpretation.

In the data acquisition stage, several methods have been proposed for documenting or digitizing the archeological artifacts. Most of them involve 3D scanning technology. The studies in this area focus on the scanning setups in order to avoid data loss due to lighting, distance, or surface characteristics [1–3]. Sometimes objects may not be suitable for 3D scanning due to their overly large sizes. Bujakiewicz et al. [4] provide a solution based on photo-grammetric. When objects are symmetric potteries, they can be modeled in 3D using their own profile curves [5]. In some cases, not only the artifacts, but also entire 3D scenes are generated (e.g., an ancient village or buildings) [6]. There are also methods to combine 2D and 3D information of the artifacts [7]. Data acquired by 3D scanners need, in most cases, to be aligned and registered [8].

In our work, the use of cost effective and efficient computer technologies are currently tested using 18th century archeological data, specifically ceramic shards and vessels, excavated from a site in the Independence National Historical Park in Philadelphia,

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☆ This article was recommended for publication by Luis Santos.

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http://dx.doi.org/10.1016/j.cag.2012.11.001

Fig. 1. Ceramic remains and digitized model.

Pennsylvania (Fig. 1). Our work focuses on the reconstruction of archeological vessel fragments based on the 3D scan data.

When operated on a full scale, this technology will allow for more efficient laboratory work and for significant time and money savings. Computers will be able to piece back together broken fragments into meaningful vessels semi-automatically (with expert feedback). Such vessel reconstruction is a vital first step in the laboratory processing of artifacts.

Computer-assisted vessel reconstructions will furthermore allow for remote research capabilities as virtually mended collection of ceramics will be studied off-site via digital proxies. Finally, the digital images created during the virtual reconstruction process will be a useful resource for virtual history presentations. Records from this research and development project will be archived as part of the INDE Archeological Records Collection.

1.1. Related work

There are a variety of existing techniques for characterizing and reconstructing fragments using computer vision technology. The techniques based on geometry can be classified into four categories, which are point-to-point, curve, surface, and shape descriptor matching. They all attempt to solve a "jigsaw puzzle" by identifying and mending 3D parts to form a single object. The unifying idea rests on finding corresponding parts and aligning all corresponding parts together.

Ucoluk and Toroslu [9] propose a 3D curve matching approach for the mending of thin-shell fragments, based on string matching of the curvature and torsion features of a discrete 3D curve. The method is said to be noise tolerant and allows for partial matching. It is designed for fragments that can be represented as closed 3D curves. The string matching algorithm is also elaborated in [10]. Another series of methods for thin-shell fragments are introduced by Cooper et al. [11–13]. These are based on the estimated symmetric axes, the profile curves, and break-curves. It is designed for axially symmetric objects. The fragments must be large enough otherwise the profile curve cannot be extracted. As long as the profile curve is obtained, an estimated model could be generated by spinning the profile curve around the symmetric axis.

For thick-shell fragments, i.e. broken pieces with large contact surfaces (fracture surfaces), Papaioannou et al. [14] present a method based on polygonal surfaces. They introduce a matching error between complementary surfaces that exploits the *z*-buffer algorithm. This method is then extended to incorporate curve matching ideas [15], similar to those in [9]. Brown et al. [16] propose another method for the matching of fresco fragments that are also thick-shell. They form a set of ribbons along the break surface and use iterative closest point (ICP) algorithm [17] to align them together. Due to the time consuming nature of ICP, they design a feature based matching algorithm [18], in which the multiple features such as color, curvature, normal, etc. are used. Similar to the jigsaw puzzles in 2D, Huang et al. [19] compute a patch based surface feature clusters for all contact surfaces and use the corresponding features to match all contact faces pairwise. Winkelbach and Wahl [20] calculate the surface normal of the points on the fracture surface and declare two points in tangential contact if their normal directions are opposite. Two fragments are mended by changing the pose and position of one fragment until maximal fracture surface (point) contact is achieved. To efficiently compute fragment matches and avoid small erosion, Brown et al. [16] regularly resampled fragment edges into a "ribbon" then the surface normal is calculated based on rearranged ribbon points.

For both thin-shell and thick-shell fragments mending, most of the matching algorithms rely on the information extracted from the fragment breaks ("jigsaw puzzle"). However, when dealing with ceramic fragments that have been in the ground for many years, sharp edges may suffer from erosion (see Fig. 2), which makes it difficult to match the boundaries or contact surfaces of associated shards. Also, a successful fragment-to-fragment matching does not guarantee that the entire 3D object can be mended correctly unless a global, multi-fragment optimization is introduced.

To avoid these difficulties, other complementary methods that rely on expert models to which fragments are aligned are sought. The matching problem in this case is a fragment-to-surface (or fragment-to-model) matching rather than a fragment-to-fragment matching. Igwe and Knopf [21] assume exact models are available for digitization or scanning before reconstruction. Using the adaptive clustering and Self-Organizing Feature Map (SOFM) technique [22], the correspondences between the fragments and the original model are established within the SOFM method. Next, transformations are estimated and used to morph all fragments back to the original model. While the use of expert models is paramount in meaningful, much easier, and tractable mending, most of the existing methods relying on exact expert models that are identical to original vessels. Such models are rarely available. This paper uses generic models based on expert priors that are *not* exact, i.e., they have built-in uncertainties. The expert generates generic models that are allowed to be morphed by a set of local affine transformations (rotation, scaling, translation, compression and shear). The generic models can be created in many ways ranging from using possible existing original design blueprint, using the archeologists' experience, or by making use of already mended vessels. As the generic model is not exact, but produced through approximations to the excavated vessels, the alignment method should allow for these model uncertainties. There are two distinct ways of solving this problem. The first is to use an iterative procedure that toggles between estimating the best local transformations and alignment through error minimization. The second is to seek robust local invariant features to these local transformations to drive the alignment. For the former approach, the ICP used