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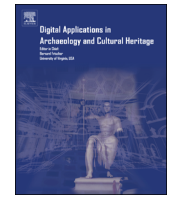

3D solid model updating of complex ancient monumental structures based on local geometrical meshes

Fernando Zvietcovich [a], Benjamin Castaneda [a,*], Renato Perucchio [b]

[a] Sección Electricidad y Electrónica, Departamento de Ingeniería, Pontificia Universidad Católica del Perú, Lima 32, Peru
[b] Department of Mechanical Engineering and Program of Archaeology, Technology, and Historical Structures, University of Rochester, Rochester, NY 14611, USA

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ABSTRACT

Finite element analysis (FEA) is used to analyze the static and dynamic structural behavior providing important information for the conservation of monuments in cultural heritage. Accurate solid models are fundamental in this type of analysis, but the structural changes introduced during the lifetime of the monument produce complex geometrical configurations that may not be generated with the desired accuracy in standard CAD solid modeling software. On the other hand, techniques such as laser scanning or photogrammetry can reproduce accurate geometrical information but only of the surface of the monument which cannot be directly applied for FEA. We introduce a novel methodology for locally updating an existing 3D solid model of a complex monumental structure with the geometric information provided by a 3D mesh extracted from the digital survey of a specific sector of the monument. The methodology starts by registering the new information from the digital survey to the existing solid model of the monument. The difference between the models is used to highlight the region of interest (ROI) to be updated. The ROI is encapsulated and transformed into a solid space where Boolean operations are used to update the original solid model. We test the procedure on Huaca de la Luna, Trujillo, Peru, one of the most important massive earthen structures of the Moche civilization. Solid models are defined in AutoCAD while 3D meshes are recorded with a Faro Focus laser scanner. The results indicate that the proposed methodology is effective at transferring complex geometrical and topological features from the mesh to the solid modeling space.

1. Introduction

The development of digital techniques for surveying historical buildings and cultural monuments has made possible the creation of accurate 3D models describing the geometry of those structures for multiple applications in heritage documentation, preservation, and archaeological interpretations (Arbace et al., 2013; Dellepiane et al., 2013; Carrozzino and Bergamasco, 2010; Rua and Alvito, 2011). Time-of-flight 3D laser scanning devices are able to record the position of millions of points describing the geometrical surface of monumental buildings (Haddad, 2011). Image-based modelling methods use 2D images measurements such as shading, texture, contours, edge gradients, etc. in order to generate a 3D model based in a mathematical model (Remondino and El-Hakim, 2006). Those methods use projective geometry under a perspective camera model. In particular, the photogrammetric method records geometrical information by applying dense stereo reconstruction algorithms on a set of unordered images describing the target object (Ahmadabadian, 2013). Computer-aided design (CAD) solid modeling has been used successfully to reconstruct the solid geometry of complex monumental structures for engineering analysis (Brune and Perucchio, 2012; Oetelaar, 2013). Although serving similar purposes, laser scanning and photogrammetry differ substantially from solid modeling CAD techniques both in their algorithmic structure and in the type of 3D reconstructions they provide. The first two are highly automatic procedures which produce a geometrical approximation to the boundary surface of the structure in the form of dense 3D point clouds and meshes. In contrast, CAD procedures are predicated on user interactive control. It consists in defining geometrically exact representation of 3D domains such as primitive geometrical entities (points, lines, surfaces, solids), positioning these into a three-dimensional space, and finally assigning controlling parameters to combine primitive entities into complex solids.

Solid models are fundamental for engineering analysis of monumental structures. Finite elements analysis (FEA), the most versatile and commonly used tool for the numerical simulation of the static and

* Corresponding author. Tel.: +51 16262000x4720.
E-mail addresses: fzvietcovich@pucp.edu.pe (F. Zvietcovich), castaneda.b@pucp.edu.pe (B. Castaneda), renato.perucchio@rochester.edu (R. Perucchio).

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dynamic response of large structures, requires 3D meshes accurately representing the outside as well as the inside geometry and topology of the domain to be analyzed. When dealing with complex configurations, FEA 3D meshes can only be constructed by operating on CAD solid models (Brune and Perucchio, 2012). Therefore, in general, 3D mesh models generated by laser scanners or photogrammetric reconstructions cannot be directly used in those applications.

Besides supporting engineering analysis, the parametric structure of CAD solid models offers additional advantages in the representation of historical buildings and monumental structures. Features in solid models are created using libraries of primitive geometrical entities, each supported by a mathematical formulation. Thus, complex 3D solid models can be edited locally without having to reconstruct the entire model, detailed architectural features can be introduced without using dense data, and accurate dimensional measurement can be easily extracted for various applications (Oetelaar, 2013). However, the creation of irregular curves and shapes in a CAD program can be exceedingly complicated or even impossible due to limitations in the mathematical formulations available in the libraries of primitives (Oetelaar, 2013). For example, structural alterations commonly found in archaeological structures, such as fractures, perforations, and breaches caused by anthropogenic and natural factors, may not be easily inserted in the CAD solid models of the monument.

Some attempts have been made in the context of adapting 3D solid modeling to digital heritage applications. Russo and Guidi (2011) developed a critical analysis of the importance of having a detailed 3D mesh model which describes a monument as is, and a 3D solid model of the reconstruction of non-existing parts of the same monument. Here, the creation of the solid model was done interactively in a CAD software using information from a topographic survey and historical sources. Vilbrandt et al. (2004) introduced a constructive modeling approach to generate solid models of an archaeological object based on automatically fitting a parameterized model interactively constructed to a point cloud representation of the object. Cheng (2012) proposed the use of reverse engineering software, Rapidform (INUS Technology, 2012), in order to recreate a solid model of a monument from a point cloud representation produced by a laser scanner. Boulaassal et al. (2010) developed a procedure for the creation of 3D parametric models of architectural façades from point clouds. Here, automatically extracted architectural components such as walls and openings were used for the creation of a parametric model of the façade in Maya embedded language (Autodesk, 2012a, 2012b). Finally, Guidi et al. (2014) developed a methodology in which they extract planar sections of the 3D point-based model of a monument as starting elements of its 3D polygonal reconstruction in an interactive fashion. Then, an iterative procedure refines the initial polygonal model with geometrical details from the point clouds.

The procedures described previously imply, in most of the cases, the creation of the solids and polygonal meshes manually in a CAD software. That is, they have to manually define planes, columns, lines, and primitives in order recreate the monument which is time consuming, requires a specialist in the use of a particular CAD modeler and, in some cases, it is even impossible to do for complex irregular structures. More importantly, the proposed methodologies do not address the problem of updating a portion of an existing solid model of a monument with local detailed information of its current physical state. This is of special importance when it is desired an accurate description in certain areas of the model rather than other ones.

We propose a novel methodology for locally updating an existing solid model with local mesh data utilizing computer vision algorithms. The modified solid model can be uploaded and operated upon in any standard CAD platform. In order to develop and test the methodology, we focus on the Main Platform of Huaca de la Luna, Trujillo, Perú, one of the best-preserved and most intensively studied massive earthen structures of the Moche civilization. A 3D solid model of the monument is shown in Fig. 1 and in Video S1.

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2. Case study: Huaca de la Luna (Perú)

In this section, we provide a historical and archaeological description of the monument *Huaca de la Luna*, as well as the acquisition techniques used for its 3D reconstruction.

2.1. Site description

The complex *Huaca de la Luna* is one of the best-preserved and most intensively studied massive earthen structures of the Moche civilization located in the city of Trujillo in the north coast of Perú. The monument, constructed roughly between the years 200 and 850 AD at the foot of the Cerro Blanco Mountain, is considered a political and ceremonial center of the Moche Society (Uceda and Morales, 2010).

As depicted in Fig. 2, *Huaca de la Luna* is formed by three main platforms and four plazas made of adobe bricks and mud mortar. The platform I is known as the Main Platform and is the area where the work of *Huacas del Sol y de la Luna Archaeological Project* is mostly concentrated. A particular feature of this platform is its multilayered construction method, consisting in the superposition of at least six building stages constructed one on the top of the other over approximately 500 years (Uceda and Morales, 2010). To add a new layer, the previous building was ceremonially buried by filling empty spaces with adobe blocks and constructing a new building on top of it. Openings, walls and a new façade were added, allowing the expansion of the monument in width and height. Fig. 2a shows the location of the transversal cut from north to south resulting in the planar profile section illustrated in Fig. 2b. This profile shows the known six structural layers labeled A to F, in which A constitutes the last (most recent) building, and F, the oldest known to date (Uceda and Morales, 2010).

Fig. 3a shows an idealized model of building A created using data from a standard topographic survey of the existing monument augmented by conjectural integrations. This model with those from Figs. 1 and 2 were created as part of the archaeological survey and documentation effort. It is apparent that the current structural state of the monument differs substantially from these idealized representations. Damages, often involving the destruction of sizeable portions of the structure, have been caused by catastrophic rains due to El Niño Phenomenon, earthquakes, and systematic looting. Even archaeological excavations have substantially altered the monument. Fig. 3b depicts damage in the top part of the altar produced by natural factors while Fig. 3c illustrates a mayor breach caused by looters that cuts across the upper part of the decorated façade.

2.2. Data collection: 3D acquisition

This section describes the fieldwork related to data collection and model reconstruction in the solid modeling space $\mathscr{L}$ and mesh space $\mathscr{M}$. These spaces support geometric elements called solid models and mesh models, respectively, and the operations between them. A detailed formulation of these spaces, operators, and requirements for transferring models from one space to another is described in Appendix A.

2.2.1. 3D solid modeling

The solid modeling construction was independently done by the staff of the *Huacas del Sol y de la Luna* Archaeological Project