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STRUCTURE FROM MOTION SURVEY OF STATUE FOR FINITE ELEMENT MODELLING

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Abstract

Iconic sculptures are a fundamental part of the cultural heritage of a country, being also a crucial tourism pull factor for the museums housing them. However, they are frequently rather antique, damaged during the elapsed centuries and often made of fragile materials. Moreover, they can be exposed to substantial natural and anthropic hazards, such as earthquake and traffic vibrations. This is also the case of the "Sarcophagus of the Spouses" at the National Etruscan Museum of Villa Giulia in Rome, Italy, which is exposed to the vibrations generated by a surface tramway line and an underground railway line. The multidisciplinary MONALISA project will design a base isolation system starting from the finite element modelling of the statue, whose geometry is however rather complex and whose location is within a glass case. Therefore, a contactless survey procedure was necessary and a low-cost structure from motion technique delivered a geometric mesh, which was revised and simplified to be imported in a finite element code. The finite element model was then used to perform preliminary dynamic modal analyses, to be further calibrated with ambient vibration data.

Keywords: Etruscan sarcophagus; Mesh; Modal analysis; Point cloud; Real case study; Traffic.

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1 INTRODUCTION

Cultural and historical heritage of a country plays a role of paramount importance for education and developing of group identity and stimulating tourism with positive effect to economy. In recent years, cultural heritage safety and conservation are rapidly evolving thanks to the growing of advanced and non-invasive technologies and methods [1, 2, 3]. Among them, Structure from Motion (SfM) photogrammetry is a low-cost, fast, contactless, non-invasive and non-destructive technique, which has a large number of application areas (archaeology, geoscience, structural geology, etc.) including every field of cultural heritage [4]. It allows obtaining three-dimensional (3D) models of an artwork as a “point cloud” and a “polygonal mesh” starting from the acquisition of overlapping two-dimensional (2D) images of the investigated object by means of relatively cheap consumer grade digital cameras, although heavy data processing is required and use of high performance computing facilities has to be considered [5]. It also represents a high-flexible low-cost method to digitalize artworks for their fruition by virtual reality. SfM technique stems from the traditional photogrammetry [6] as a result of advances in computer vision. Unlike photogrammetry, it reconstructs the scene and automatically determines camera position and orientation by using complex algorithms, without the need of ground control points [7]. One of the main obstacle in using it is the need of heavy software and hardware resources for 2D imaging processing and data storage. By acquiring a single reference measure of the investigated object or scene, SfM photogrammetry allows obtaining scaled 3D models as point cloud and geometrical mesh with accurate metrical information in terms of geometrical shape, space position and size. Starting from the scaled models, different numerical analyses can be performed and physical replica can be obtained [8].

This methodology was tested on the “Sarcophagus of the Spouses” (Figure 1), spearpoint of the collection of the National Etruscan Museum of Villa Giulia in Rome (Italy), in the framework of the MONALISA project, funded by Lazio Regional Government and Italian Ministry of Culture.

Figure 1 “Sarcophagus of the Spouses” in its glass showcase (courtesy of the National Etruscan Museum of Villa Giulia in Rome)

The aim of this project is to develop a base isolation system for the protection of artworks from traffic and earthquake vibrations integrated with a dynamic monitoring system, based on fibre Bragg grating sensors, designed to detect the exceeding of critical amplitude and frequency vibration thresholds. Although the application of base isolation to protect buildings from earthquakes was extensively explored in the past [9], use to safeguard museum objects is less frequent [10, 11] and implementation against traffic vibrations is almost unheard of. The "Sarcophagus of the Spouses" dates back to the 6th century b.C., is made of terracotta and was digged out at the end of the 19th century in Cerveteri, Italy [12]. The Sarcophagus was selected as case study because is currently exposed to the vibrations generated by a surface tramway line and an underground railway line. The statue is a complex object with several uncertainties. Globally, it is divided into four parts: i) body-top, ii) body-base, iii) legs-top and iv) legs-base. The two tops lie on the bases along irregular contact surfaces. Each part is the result of a complex restoration process because the retrieved sarcophagus was shattered in a very large number of irregular pieces. As reported by Aureli [13] the sculpture thickness is not uniform, possibly due to the artisanal technique and the need to thicken the most stressed locations. Moreover, no data is available about the density and the Young's modulus of the material. Furthermore, during at least two restoration phases, several metal bands and struts were added to the ceramic manufact to allow the recomposing of the fragments.

The main conservation problems of this iconic statue are related to the multiple fracture lines between the recomposed fragments, the distribution of loads and the limited mechanical resistance of the terracotta. Earthquakes and traffic vibrations can cause a worsening of the general state of preservation, resulting in the reopening of existing fractures or the formation of new cracks. The development of a base isolation system for the Sarcophagus is, together with the forthcoming restoration, part of the actions aimed at its long-term protection and fruition. However, a proper design requires numerical modelling by means of finite element analyses to be applied to a geometry delivered by a SfM survey.

2 STRUCTURE FROM MOTION SURVEY OF THE SARCOPHAGUS

The SfM technique was used to create a 3D model of the "Sarcophagus of the Spouses", in order to obtain data for finite element analyses and a 3D physical replica. The photogrammetric survey was carried out using a SONY ILCE 5100 digital camera supported by a tripod (objective focal length 16 mm; numerical aperture f/18; exposition time 1.6 s; sensitivity setting ISO 200; 921 600 pixels, image size about 7 MB). As the Sarcophagus is housed inside a glass showcase, the shooting session was carried out in challenging conditions because of the glass reflections of the museum hall. A set of 441 pictures were acquired, following a motion path with sequential orientation and about 60% overlapping of adjacent pictures. The images were post-processed by the photogrammetric software 3DF Zephyr [14] hosted on a node of the ENEAGRID infrastructure [15]. Following the standard procedure of the SfM technique, three sequential processing steps were performed: i) orientation of the pictures (no discarded picture); ii) sparse cloud of points production (90 600 total points); iii) dense cloud of points production (13 345 391 total points). The reliability of the dense cloud of points is confirmed by the high number of relevant points (2 646 495, about 20% of the total), which are the points identified in two or more pictures during the orientation process. With the perspective to have different data sets for both finite element analyses and 3D replication, various meshes were then produced applying a constrain on the final number of triangles: 39 995 886; 3 999 579; 200 393; 20 516; 10 542. As a final step, texturing was applied with the prospective of documenting the conservation state of the artwork (Figure 2). The mesh with 39 995 886 triangles was texturized, producing eight partially overlapping textures laying on 5 995 886 triangles each.

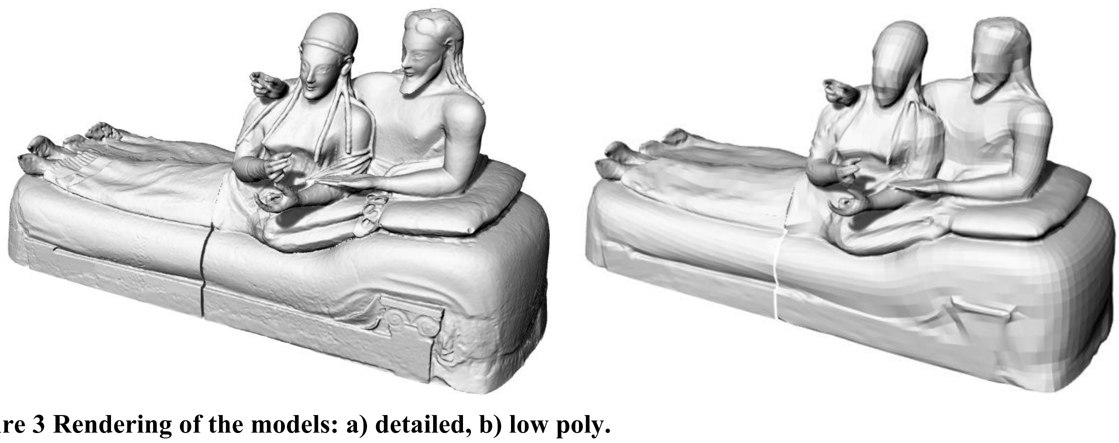
Starting from the mathematical 3D model, a replica in polystyrene of the Sarcophagus was manufactured, which will be tested on a shaking table under earthquake and traffic-induced vibrations in the absence and presence of the base isolation devices.

Figure 2 Textured mesh.

3 FINITE ELEMENT MODELLING

The use of SFM techniques is able to return sophisticated and detailed 3D mesh models. The resulting model can be extremely computationally demanding so a mesh reduction has to be applied. The original detailed mesh model was manipulated by means of Grasshopper for Rhinoceros [16]. The developed Grasshopper routine reduced the original and detailed mesh size from 1 733 261 triangular faces to 13 310 quadrangular faces, delivering a low poly model. In Figure 3 the two geometries are compared: in b) some details are lost but globally the model remains the same as in a). This manipulation allowed to import the model in the finite element software LUSAS [17].

Given that a detailed geometric model of internal space of the sarcophagus is neither available, nor possible to deliver due to conservation concerns, in the following a constant thickness homogenous model is implemented. However, the vertical transversal planar separation between body and legs is replicated in the finite element model.



a) b)

Figure 3 Rendering of the models: a) detailed, b) low poly.

As common for invaluable and unique artworks direct measurements are not possible. However, it was possible to weigh the whole case containing the sculpture and this information, coupled with dynamic identification [18], can be used in the future to estimate the thickness of the model by means of matching the results of a modal analysis. The data presented in the following is related to a 30 mm thick sculpture geometry, with a terracotta Young's modulus equal to 2 GPa [19]. As for the case, a glass Young's modulus equal to 70 GPa [20] is assumed. Additionally, a steel Young's modulus equal to 210 GPa [21] is adopted for all the beam elements.

In Figure 4 the finite element model of both case and sculpture is presented. Both the sculpture parts, the glass panes and the stone plate at the bottom of the exhibition case are modelled by means of three or four nodes shell elements. Beam elements are used for the small frames supporting the sarcophagus, as well as for the foots and joists at the base of the case. The model presents 15 027 nodes, 58 beam elements, 150 four nodes shell elements, 28 994 three nodes shell elements for a total of 90 162 degrees of freedom.

The modal analysis delivered the first three modes shown in Figure 5. Mode 1 presents a deformation mainly oriented along the longitudinal, *x*, direction. On the contrary, mode 2 features a torsional response mainly. Finally, mode 3 displays a vertical response of the horizontal beams of the frame supporting the sarcophagus, made possible by the discontinuity between the parts of the sculpture. It is worth noting that these three modes depend mainly on the stiffness of the steel frame base under the sculpture, which makes the role of the terracotta and glass elastic moduli less crucial.

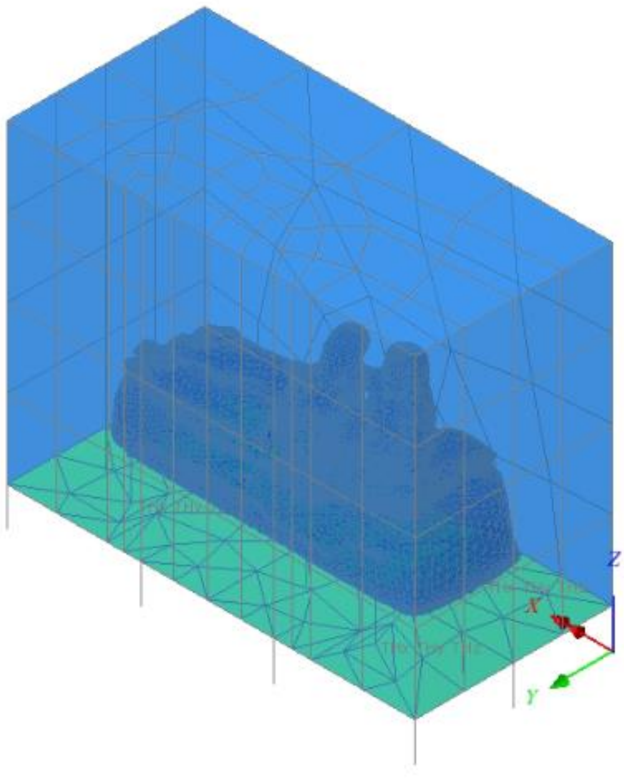


Figure 4 Finite element model and reference axes.

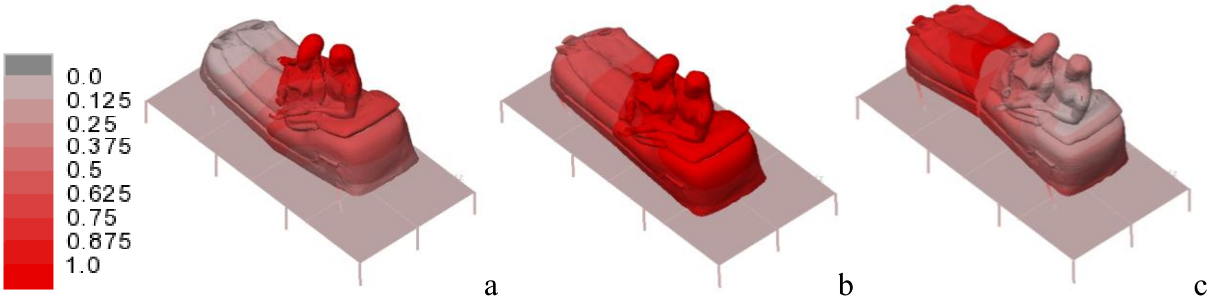


Figure 5 Total modal displacements of the a) first (6.4 Hz), b) second (8.0 Hz) and c) third (9.4 Hz) modes. (Glass panes hidden for presentation purposes)

4 CONCLUSIONS

Iconic sculptures are a crucial pull factor for museum visitors, as well as fundamental evidence of historical and cultural achievements. However, they are frequently fragile due to used material and previous damage, while being set in city locations exposed to traffic vibrations. These conditions are also those of the "Sarcophagus of the Spouses", part of the collection of the National Etruscan Museum of Villa Giulia in Rome (Italy). In order to reduce the intensity of vibrations, both due to traffic and earthquakes, the MONALISA research project aims at designing a base isolation intervention. Numerical simulations of this retrofit solution are necessary to validate the design and they will be carried out resorting to a finite element model. However, the geometry of the sarcophagus is very complex, requiring a detailed survey. Conservation concerns involved the use of a contactless technique, while budget limitation suggested low-cost solution. Therefore, a structure from motion survey was carried out, delivering several polygonal meshes depending on the needed detail level. The mesh imported in the finite element code was further simplified, to reduce computational effort and improve the numerical solution. Then the model was used to perform modal analysis, whose results will be used in the future to update the model to match the dynamic identification carried out with motion magnification.

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