Precise 3D Recording for Finite Element Analysis

The Case of a Greek Statue from the Archeological Site of Delos

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***Abstract* — Lately, 3D laser scanning and Photogrammetry are becoming a standard in Cultural Heritage recording. In this contribution, a combination of both methods is presented for the precise 3D geometric documentation of a plaster copy of a Greek statue from the archeological site of Delos. The 3D model was generated for the structural assessment of the original statue and its supporting mechanism via finite element analysis (FEA).**

***Index Terms* — 3D laser scanning, image-based modeling, structural assessment, finite element analysis, digital heritage.**

I. INTRODUCTION

During the last decade, 3D surface models have become essential products in CH conservation and restoration projects. Latest theoretical advances in Photogrammetry and Computer Vision, as well as the technology outbreak in computational capabilities have made image-based 3D documentation a conclusive reality in the field of cultural heritage (CH) [1]. In addition, the improvement of contemporary terrestrial laser scanners (TLS) and their wide commercialization have turned them into a valuable tool for 3D documentation.

The combination of TLS point clouds and image data can be significantly effective in the recording of objects with complex morphology and precise photo-texturing of 3D surface models ([2], [3], [4], [5]). Although, TLS allows the fast generation of accurate 3D representations of objects geometry, it cannot fully replace image-based 3D modeling, e.g. when detailed texture mapping is required, when the access to the monument is restricted or when large and complex archaeological sites need to be reconstructed [6]. On the other hand, image-based modelling can be insufficient in certain cases, such as the 3D reconstruction of texture-less objects. Hence, data fusion between active and passive methods, i.e. laser or structured light scanning and photogrammetric processing, is an important research topic in the context of Cultural Heritage (CH) [5], [7]. Moreover, surface reconstruction from point clouds of complex objects is a demanding task [8].

In the present paper, a plaster copy of Gaios Offelios Feros statue (the original statue is on display at the Archaeological Museum of Delos) has been reconstructed in 3D through a fusion of laser scanning and image-based modelling techniques. The final surface model was further optimized and converted into a 3D Solid Finite Element Model with the use of the FE Code Abaqus.

This work was performed in the framework of a research project funded by the French School of Athens[1].

II. DATA COLLECTION

The main scope of the work presented herein is the study of various methods of support of the original statue via Finite Element Analysis, in order to determine the most appropriate one, from the structural and the aesthetical point of view, to be applied for its exhibition at the Archeological Museum of Delos. For this, an accurate and complete 3D model of the statue is required. Due to the scaffolds that currently support the original statue, its position that didn't facilitate neither the placement of the laser scanner at adequate positions nor a detailed capture of image data, and in order to avoid any risk for damaging it, an exact copy of the statue has been chosen for scanning instead of the original. This copy was constructed using a plaster cast of the statue and its base and is currently located in the French School at Athens.

During data acquisition procedure, the following tasks were performed:

- 3D scanning of the statue in two different placements (Fig. 1a)
- 3D scanning of the statue's base
- Acquisition of highly overlapping images of the statue and its base

[1]http://www.efa.gr

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Fig. 1. Data collection

The two objects were scanned with an accuracy and density of 2mm. The statue was placed in two different positions facing upwards and then downwards to completely capture its surface. In order to achieve minimum occlusions and sufficient overlapping for the individual scans, a careful positioning of the laser scanner was applied. This resulted in 37 individual scans (Fig. 2) of ~2mm resolution (TABLE I). Five additional scans were obtained for the detailed modelling of the base of the statue.

TABLE I. SENSOR SPECIFICATIONS

	Laser Scanner Specifications
Error	2mm at 50m
Noise	0.3 mm at 10m distance, regarding objects of 90% reflectance (noise compression mode)
Beam diameter	3mm at exit
Scan density	2mm
	RGB Camera Specifications
Resolution	18MP (5184 x 3456 pixel)
Pixel size	4.3μm
Focal length	17 mm

Fig. 2. Individual point cloud with RGB texture from one scan station.

The statue was also densely photographed using a DSLR camera with a fixed interior orientation (TABLE I), in a configuration that would allow a full 3D reconstruction. The images were taken in four parallel strips at different heights for each positioning of the statue. A custom made telescopic pole has been employed for the image acquisition (Fig. 1b). This step is essential for completing the laser scanning model in order to avoid possible surface occlusions created by the object's complexity.

III. 3D RECONSTRUCTION FRAMEWORK

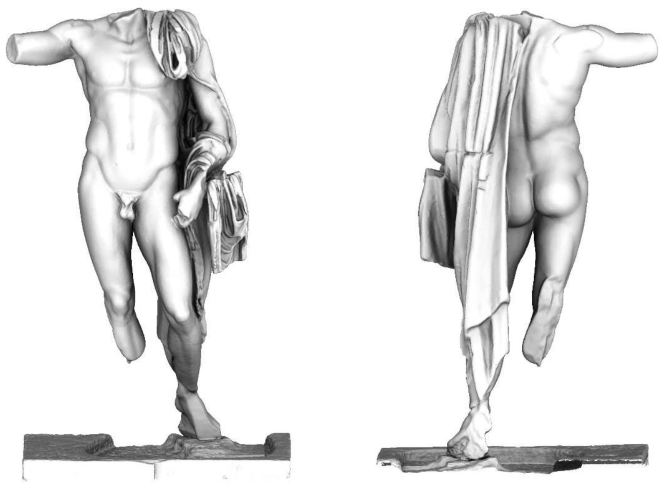
The individual point clouds from each scanning position were aligned into a uniform model by a surface matching approach on their wide overlapping areas. A global registration of all scans was performed through the ICP algorithm (reference). The standard deviation of this step was 1.5mm with an average distance between neighboring points of 0.75mm. The resulted point cloud comprised of 13.5 million points and described sufficiently most statue details.

However, there were specific parts of the statue that could not be scanned adequately due to their complexity, e.g. inside the deep and narrow fabric folds or the statue's left hand area. It was practically impossible to place the scanner above the statue or fix the statue in a more suitable position.

To handle these difficulties, the occluded regions of the 3D model had to be completed with point clouds obtained via image-based reconstruction techniques. At first, suitable overlapping images were selected from the captured image set. These images were relatively oriented through a hierarchical Structure from Motion scheme [9], [10], [11], implemented by our team. Image pairs were firstly identified among images and sparse matching was then performed employing state-of-the-art features with their descriptors (SIFT [12], SURF [13]) at multiple image scales. By means of closed-form algorithms, image orientations were initialized and finally exterior and interior orientation parameters were refined through a typical self-calibrating bundle adjustment solution. In a consequent step, dense stereo matching algorithms [14] were applied to selected image pairs, and results were combined into a unified 3D point cloud.

The fusion of the two acquired point clouds (photogrammetric and laser scanning) was performed in two steps. First, control points were extracted from the laser scanner data to fix the arbitrary scale of the photogrammetric surfaces. Then, a registration of the two datasets was performed through ICP with a standard deviation of 2mm.

The fused point cloud was then triangulated in 3D, in order to create the surface mesh model (3D TIN), which is needed for the structural assessment. Fig. 3 shows a shaded representation based on the surface normals of the final 3D model.



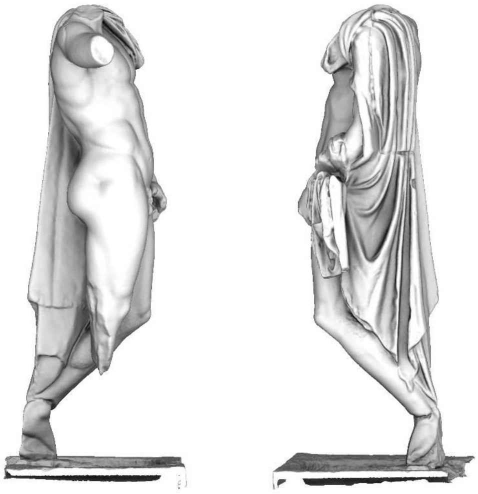


Fig. 3. The complete 3D model of the statue, which resulted from the fusion of image-based and active scanning reconstructions.

For the utilization of the final 3D model for structural analysis purposes, the 3D triangular mesh was further decimated and converted to NURBS surface representations [15].

IV. Finite Element Analysis

The model obtained from the 3D scanning reconstruction was imported with the use of an appropriate format file (.sat file) in the Finite Element Program Abaqus [16]. Though the model was already processed and converted into NURBS surfaces, further optimization in terms of geometrical editing of specific edges and faces had to be made within the FE program before converting it into a unified solid element. Furthermore, additional discretization of the solid element was needed and implemented, in order to obtain the final model for the calculation (Figure 4). Although the process of importing and optimizing a 3D scanned model is a challenging task, the results are quite satisfactory, especially in the case of very complex structures such as the herein discussed statue of Gaios Offelios Feros.

After incorporating into the model the material properties, the boundaries and the loading (static and/or dynamic), results in terms of displacements and stresses can be obtained and evaluated (Figure 5).

The scope of this analysis, which is still ongoing, is to investigate various mechanisms for the support of the statue in order to choose the most appropriate one, which will cause the minimum stresses and the minimum intervention from the aesthetical point of view.

It is noted that, at the initial restoration of the statue performed several years ago, the left leg was connected to the toe and the base through a steel dowel that was inserted into the leg. This method of support proved insufficient, as it caused a long crack at the marble, along the leg. Today, scaffolds are used to secure its stability.

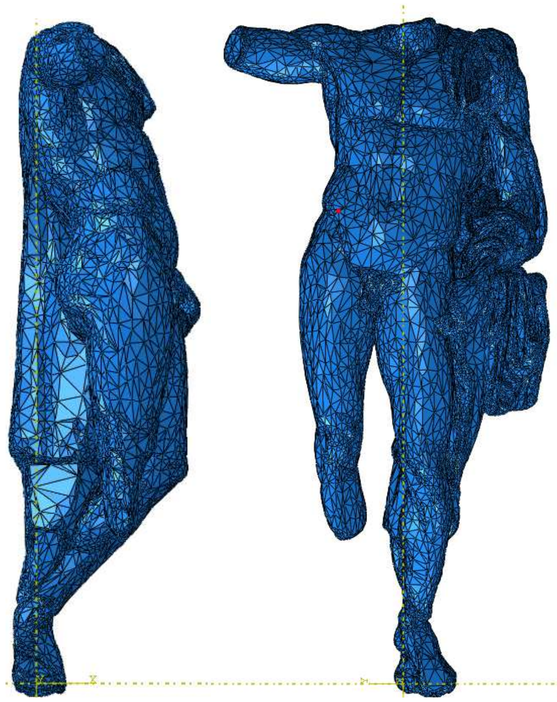


Fig. 4. Meshing of the finite element model.

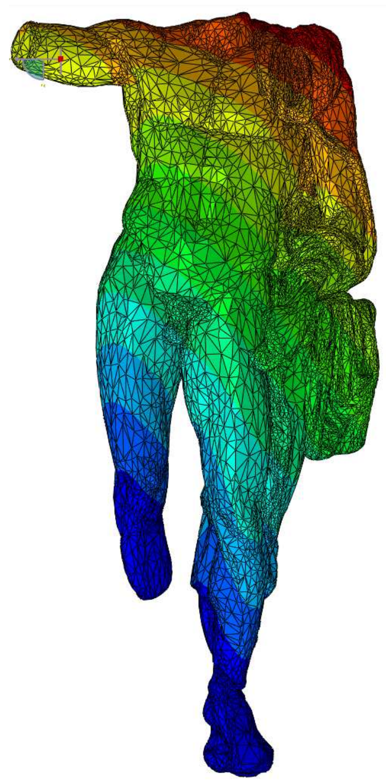


Fig. 5. Displacements caused by a horizontal loading at the top of the statue (colors denote displacement magnitude).

V. CONCLUSIONS

Precise 3D reconstruction has been an active research field for the past decades. One can notice that, lately, there has been a rapid evolution concerning algorithms, hardware and commercial products. While the theoretical aspects of active and mainly passive techniques of 3D reconstruction are always on research peak, the introduction of such methods in the workflow of other engineering field is also essential from a scientific and societal point of view.

ACKNOWLEDGMENT

The work presented herein was performed in the framework of the project: "Investigation of the support of the marble statue of Gaios Offelios Feros in the Archaelogical Museum of Delos" funded by the French School of Athens (École Française d' Athènes). It has also been supported by European Union funds and National funds (GSRT) from Greece and EU under the project 3D ORO: "Efficient and Effective 3D Computer Vision Tools for Improving the Performance of 3D Digitalization".

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