Great Statues and Seismic Vulnerability – A Photogrammetric Approach for Early Safeguard

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In recent years, more and more attention has been paid to create safeguard measures in protecting masterpieces, art items, and large statues, from the uncontrollable event of an earthquake [Agbadian et al. 1988]. In this paper a comprehensive analysis of a set of significant statues currently located in the Bargello Museum in Florence (Italy) is proposed. The work includes the geometrical survey of the object, until arriving to measure their seismic safety level. While the correct definition of the shape of the elements is fundamental in this processing, an attention will be given to the phase of the digital survey, here operated using photogrammetry based on Structure from Motion procedures. All the steps of the workflow will be analyzed and described in its main issues, lessons learned, new procedures. A set of different procedures will be compared, a brief method based on a 50 MP resolution camera with high quality optic and highly accurate modeling and its integration with direct measurements and/or 3D Laser Scanner Survey. The results of the procedures will be matched to the results of the simulation analysis, suggesting affordable approaches for any similar conditions about the interpretation of the state of safety of this important cultural heritage.

Key words:
Photogrammetry, Statues, Bargello Museum, Seismic Vulnerability, Resilience.

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INTRODUCTION

This work has been developed within the *RESIMUS* Research Project: *“RESIMUS, un progetto volto alla vulnerabilità sismica delle opere museali”* [Viti 2018]. Its multidisciplinary approach has the goal to combine different knowledges in order to prevent risk to the museum’s collections in case of earthquakes. The same working method, characterized by the collaboration and the comparison between different professions, was applied to Giambologna’s statue of Oceano, now located under the vaults of Bargello National Museum, in Florence and to the homonym fountain in Boboli Garden, where it was originally placed.

The Bargello Museum is an exceptional and privileged case study, both for the importance of the exhibited collections and for the variety of settings used. Even Boboli Garden has similar properties, since it is one of the most important examples of Italian garden in the world and is a real open-air museum, for the architectural-landscape setting and for the collection of sculptures, ranging from antiquity Roman to the 20th Century.

Starting from the application of this method to previous case studies, such as Ammannati’s Juno’s Fountain [Cerri et al. 2017], Donatello’s Marzocco [Mattoni and Tanganelli 2018] and also referring to the first significant contributions in this direction [Lowry et al. 2007; Parisi and Augenti 2013; Wittich et al. 2016; Spyrakos et al. 2017; Gonizzi Barsanti and Guidi 2017; 2018], the work was analyzed in compliance with the guidelines for monumental heritage [BBCC 2010], in order to guarantee its preventive protection in case of seismic events.

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As recent seismic events proved that artistic goods are very vulnerable to earthquakes, research communities are starting to focus their attention on the preservation of museum’s collections. The peculiar vulnerability of freestanding structures, namely statues, were slenderness is the main characteristic, remarks the need to understand their behavior and develop reliable tools to predict their response to seismic loads. Here the first results from this research while it is still ongoing.

THE HISTORICAL RESEARCH

In the middle of 17th century Florence was one of the capitals of the artistic and architectural culture, known all over the world as the capital of Renaissance. In these years, a great work of transformation and embellishment of the city was carried out. The protagonists of this venture were Giorgio Vasari and Bartolomeo Ammannati, under the aegis of Cosimo I de’ Medici. Both architects contributed to the transformation of Palazzo Vecchio and Palazzo Pitti, where Cosimo established the base of his government and life.

In 1565 and 1567 Cosimo I commissioned two large fountains for Boboli Garden, depicting *Nettuno* and *Oceano* to be placed on the main axis of the garden to celebrate his person and Medici dynasty power (Figs.1 and 2). The sequence of the two fountains was certainly not a casual event but perfectly designed to exalt the two components necessary for Cosimo to govern: the warrior and determined temperament, recognizable in the angry *Nettuno* of Stoldo Lorenzi and the ability to dominate the lands conquered with justice and magnanimity, clear in the peaceful *Oceano* by Giambologna, our case study. [Medri 2003; Soldini 1976; Paolozzi Strozzi and Zykos 2006]. At the center stands the statue of *Nettuno*, commonly called *Oceano*, surrounded by lying river gods that represent the Nile, the Ganges and the Euphrates, which symbolically pour their waters into the large basin, which represents the Ocean. The two large fountains occupied their original position until 1590 when they were moved to the current location, because of the transformation of that area of the garden in a stone theater. In the same period, Bartolomeo Ammannati was realizing his Fountain of Neptune in *Piazza della Signoria*. (Fig.3). In 1559, Cosimo I de' Medici launched a competition to design a fountain at a time when a new aqueduct was also being built, the first to bring running water to the city. The plan was for a statue of *Nettuno* as the primary element, in a chariot drawn by sea-horses, symbolizing Florence's command of the Mediterranean. Initially, Baccio Bandinelli was the sculptor chosen, but he died before work began. Sculptor Ammannati was hired to take over and completed the work with assistants and collaborators. The face of *Nettuno* is said to resemble that of the Grand Duke Cosimo.

Fig. 1 Stoldo Lorenzi’s Neptune in the Boboli Garden, Florence. (Photo: Marco Giorgi)

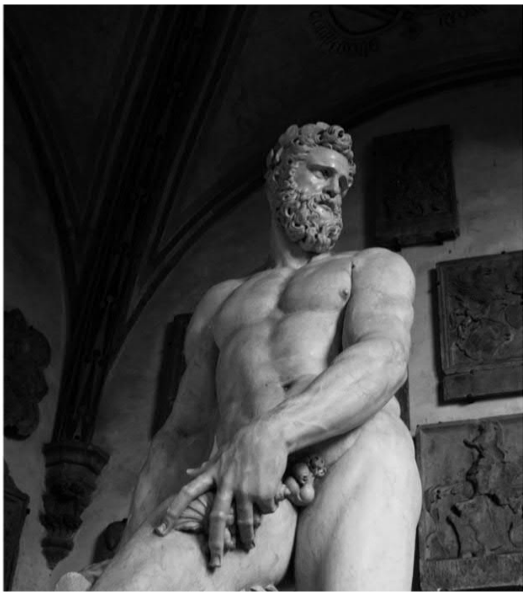

Fig. 2 Giambologna’s Oceano, in the Bargello National Museum, Florence. (Photo: Laboratorio Fotografico di Architettura)

Fig. 3 Bartolomeo Ammannati's Neptune realized from 1560 to 1565, also known as "Biancone" (the big white guy) (Photo: Raffaella Paolucci)

SURVEY METHODOLOGIES AND DIGITAL MODELS

According to the considerations emerging from the RESIMUS project, the seismic assessment of artifacts requires an accurate preliminary representation of the object, because only an accurate representation can provide reliable results in terms of seismic assessment. With the cooperation of the Photographic Laboratory of DIDALABS[1] we made two photogrammetric surveys, respectively of the original Oceano statue, conserved at the Museum of Bargello, and of its copy, within the Fountain in the Palazzo Pitti Garden. For both the statues a 3D laser scanner survey was used to better support the scaling and completion of the photogrammetric operations. In the case of the statue at the Bargello Museum it was used a partial lasergrammetry, previously taken in 2011 during the operation on the digitalization of the "Fontana di Sala Grande" [Verdiani et al. 2012]. For the "Fontana dell 'Isola" a new set of scans was done in October 2018. Finally, different types of seismic analysis were conducted on the two models obtained with the survey campaigns.

PHOTOGRAMMETRIC SURVEY

In line with the procedures of "Structure from Motion/Image Matching" (SfM/IM) [Guidi et al. 2015] software, which is the well-known process of reconstruction of the shape of an object through the collimation of points from a set of photos, the model of the copy of Oceano was obtained using *Agisoft Photoscan*[2]. Instead, for the model of the fountain it was preferred to operate using *Reality Capture*[3]. Although the workflow from the photos to the creation of the final 3D model is substantially the same for both software, the changes introduced by the superior operative speed of RC in all the data processing, made more interesting the use of Reality Capture. A hypothesis about using

[1] Group of several laboratories of the Department of Architecture
[2] https://www.agisoft.com/
[3] https://www.capturingreality.com/

the similar function offered by *Autodesk Recap*[4] was taken into consideration, but it was not completed because of the quite unpractical need of total upload of the picture set to the Autodesk server.

The first step to obtain an effective alignment is the correct image shooting. The SfM/IM software extracts the remarkable points from the photos (that it calls “cameras”), then it derives the photographic parameters and finally crosses the recognizable points on more photos finding the coordinates of the points in the space. Since the minimum number of photos that the SfM/IM can automatically collimate is three, for each point are required at least three offset and stackable images. Subsequently, the alignment of the chambers produces two point-clouds, first a sparse one, then a dense one, with a significantly higher number of points. From the dense cloud a mesh is created and then a UV mapping on which the texture of the object is generated and applied.

For the Oceano model, 140 shots were used from the 152 images taken with a Fujifilm GFX 50S a Mirrorless, Medium Format, with a resolution of 51 MP, mounting a Fujinon GF 32-64mm F4 R LM WR zoom lens and a SONY α7R mirrorless, full frame, with a resolution of 36,4 MP, mounting a Sony FE 24-70mm F4 ZA OSS They generated a sparse cloud of 268.605 points, a dense cloud of 83.000.000 and a polygonal mesh of 16.630.000 triangles (Fig. 4). The main issues in the shooting of this statue were the height of the statue itself. In facts, while it was not allowed to arrange a scaffolding (neither a ladder) around the statue, a high tripod and some “acrobatic” positioning were the only solution to allow a good coverage of the whole statue. For this same reason, having in mind the even higher statue in the Boboli Garden, the photographers preferred to use a lighter camera for the shooting of this second statue.

Then, for the “Fountain of the Island” 437 shots were taken using a Pentax K-1, CMOS Full-Frame, with a resolution of 36.4 MP, mounting a lens SIGMA 35mm, F1.4 DG HSM and a SONY α-7R Mirrorless, Full Frame, with a resolution of 36.4 MP, mounting a Sony FE 24-70mm f/4 ZA OSS zoom lens. These two cameras, despite the excellent lens and sensor quality, offer very good connectivity and allow a full remote control of the shot. Their low weight and easy balance make quite simple to operate them on a pole or a very high tripod. Using a high tripod, extended to its maximal height (2,1 m) and with two operators rising it up, it comes out as a simple and well working solution for all the shooting in the Boboli Garden.

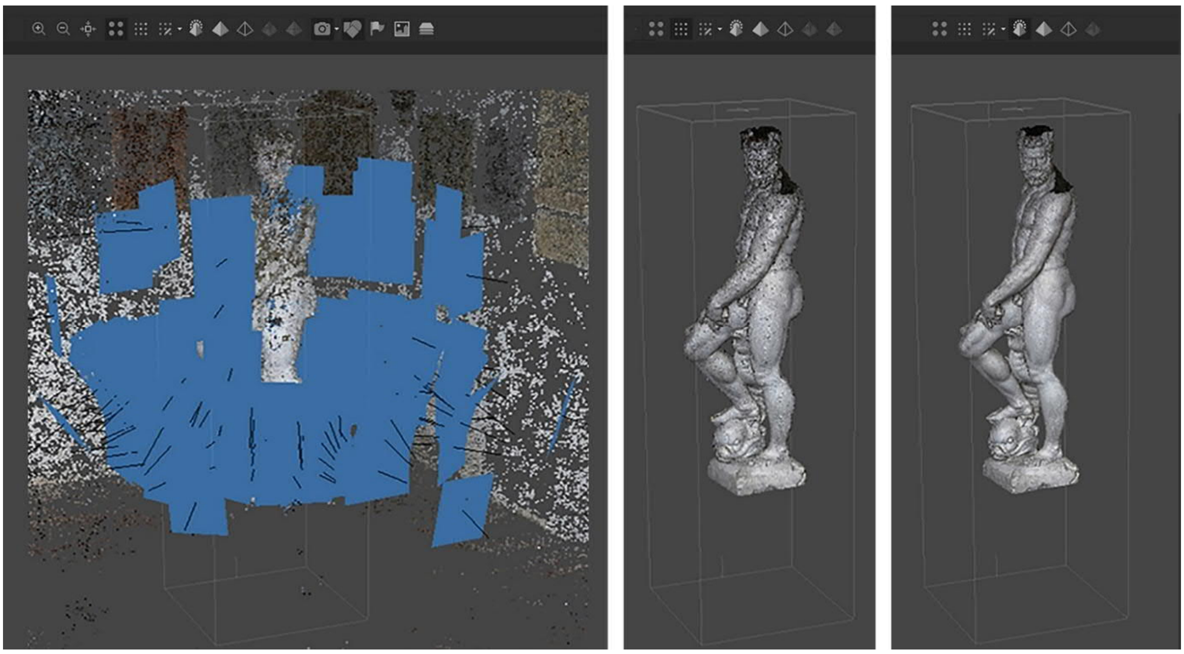

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Fig. 4. Elaboration of the model in Agisoft Photoscan: a) spare cloud with cameras; b) dense cloud; c) mesh model

[4] https://www.autodesk.com/products/recap/overview

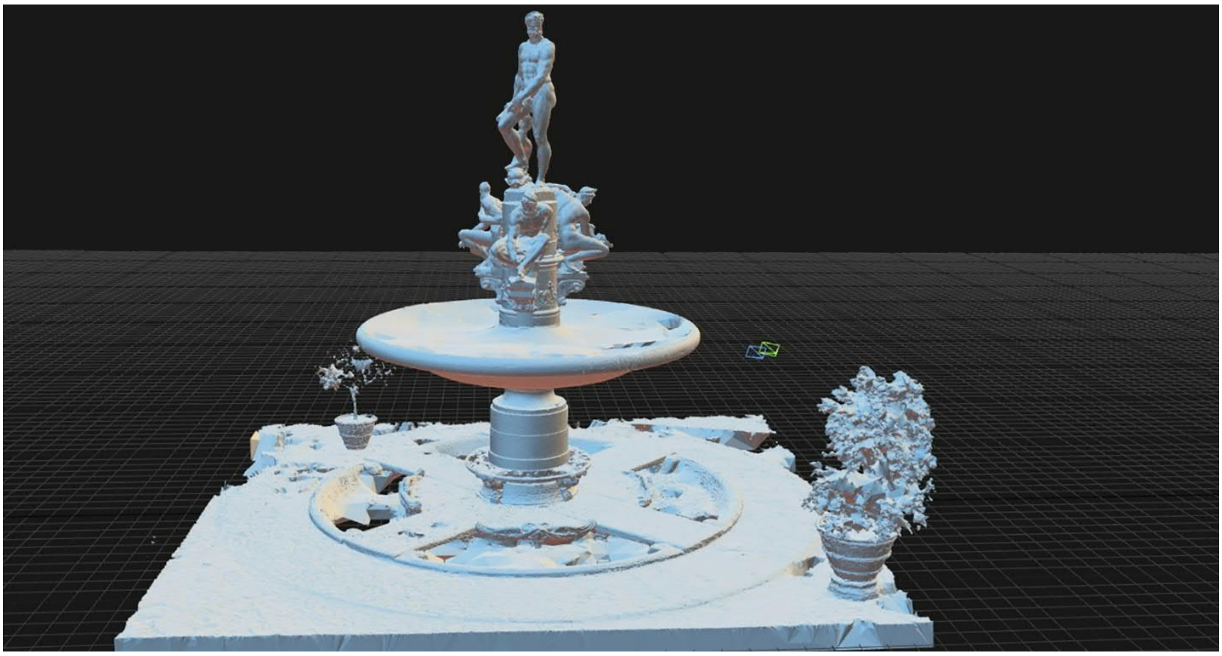

Fig. 5. Surface model of the Oceano's Fountain obtained in Reality Capture

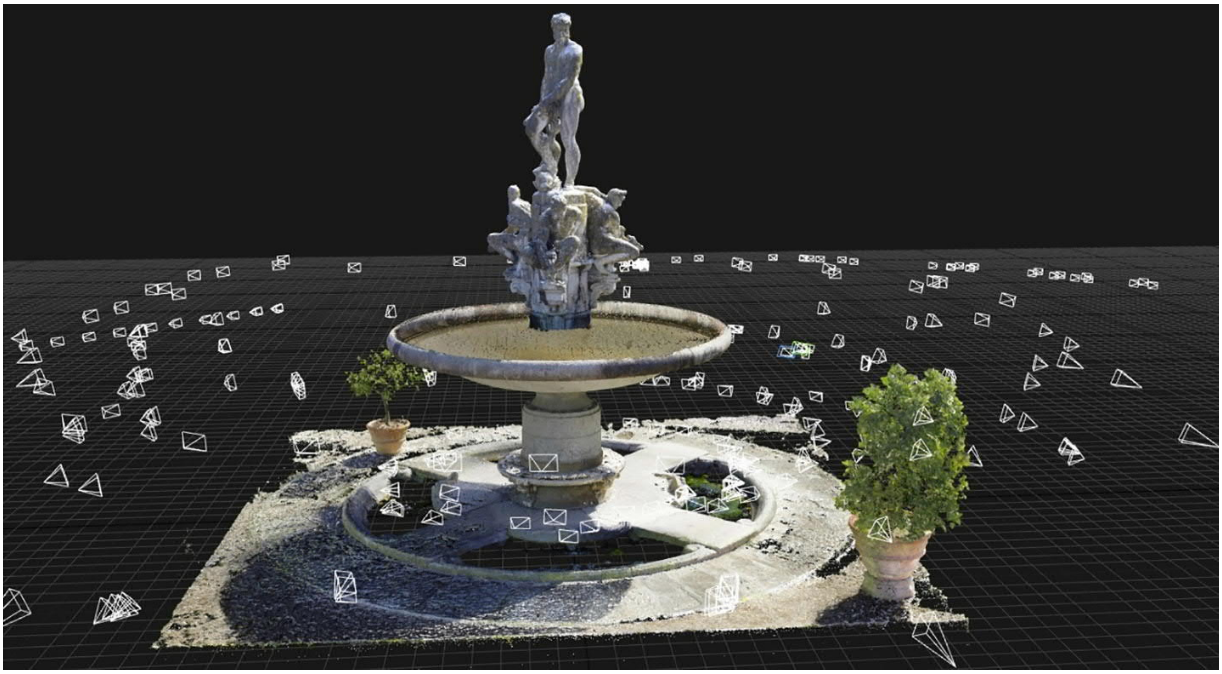

Fig. 6. Textured model of the Oceano's Fountain with cameras, generated in Reality Capture

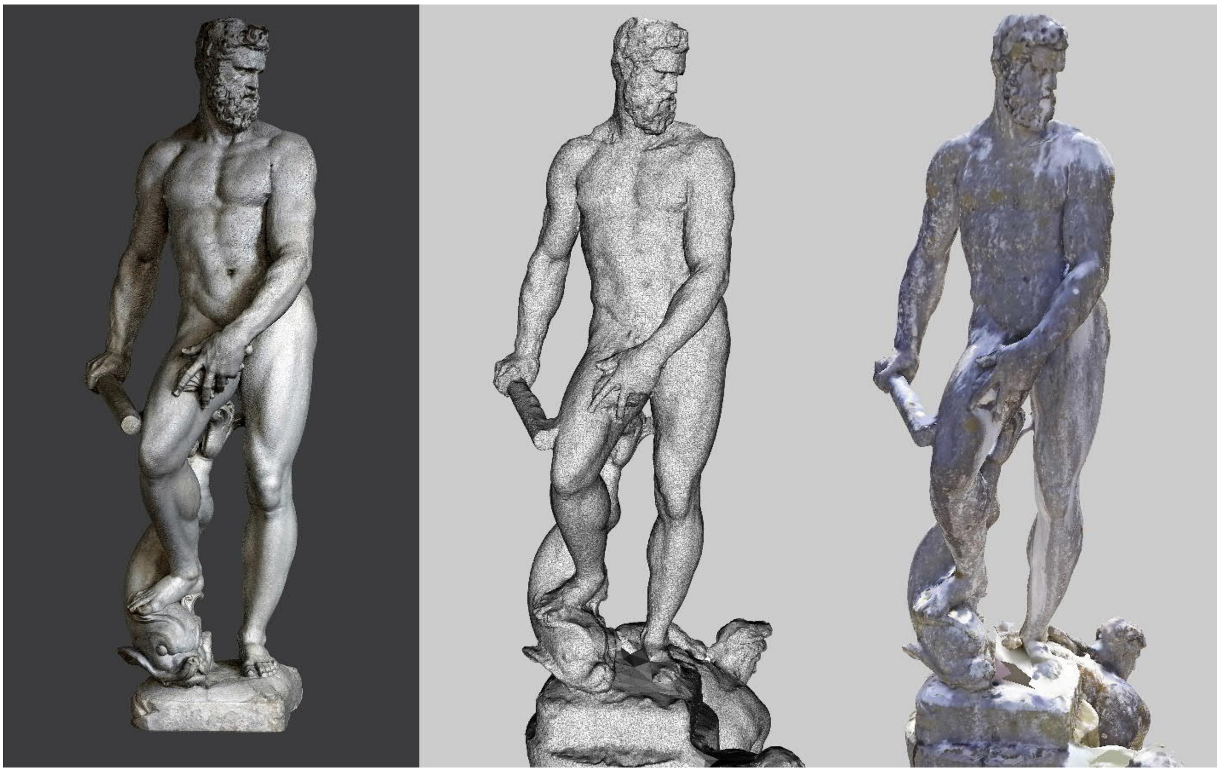

Fig. 7. Comparison between Oceano's original copy and its copy on the fountain

In a couple of hours, the whole work was done. From a sub-selection of the shots (402) the photogrammetric processing generated a cloud of 2.429.000 points and a polygonal mesh of 159.000.000 triangles (Figs.5 and 6). Since at the time of the survey campaign the fountain basin was full of water, its internal profile was rebuilt with the *Mcneel Rhinoceros 6 software*[5], making assumptions about its hypothetical geometry shape.

3D LASER SCANNER SURVEY

To integrate and complete the photogrammetry of both the statues it was preferred to use a specific lasergrammetry. The scans of the *Oceano* from the Bargello Museum were recovered from a previous survey, made in 2011 and covering a large part of this statue. (Fig.10). The subject of the scanning was the group of statues belonging to the “Fontana di Sala Grande” by Bartolomeo Ammannati, but the use of a full panoramic Scanner, produced the secondary gathering of a large part of Neptune, just at one bay of distance. The scanner used at that time, a Cam/2 Faro Photon using phase shift measurement technology, was a good solution, probably not the best on marble, but efficient enough to produce a full usable contribution for the scaling of the photogrammetry of the statue.

In the case of the “Fontana dell’Isola” the lasergrammetry was operated using a Cam/2 Faro X330 Phase shift model, a quite interesting unit, with a measuring range up to 330 meters. With such a range it was possible to take the measurement of the whole fountain and of all its surroundings.

The creation of such a large model when working on a statue is due to the intention of having some elements in more for evaluating the general design and asset of the island, the real section of the ground and the relationships between nearby trees, open spaces (all interesting data for studying the effective exposition to the weather and to the wind of this monument). In a certain sense a set of data for further study were put apart.

The scan of the fountain was done in 24 scans, 8 taken from a distance of about 10 meters from the fountains; 8 taken from a distance of about 20 meters, 4 at close range, from low points around the base and 4 from a distance of about 50 meters.

[5] https://www.mcneel.com/it/products

Fig. 9. 3D Laser scanner survey of the "Fountain of the island" in the Boboli Garden

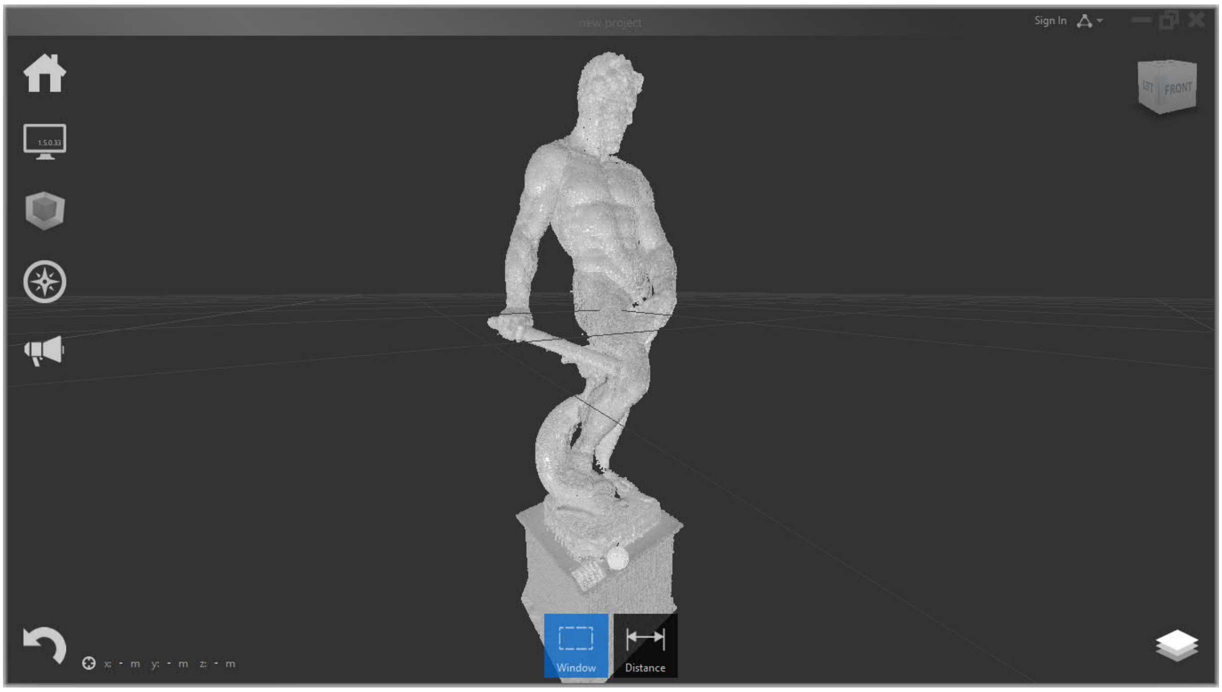

Fig. 10. 3D Laser scanner point cloud of Oceano recovered from 2011 survey in the Bargello Museum, Florence

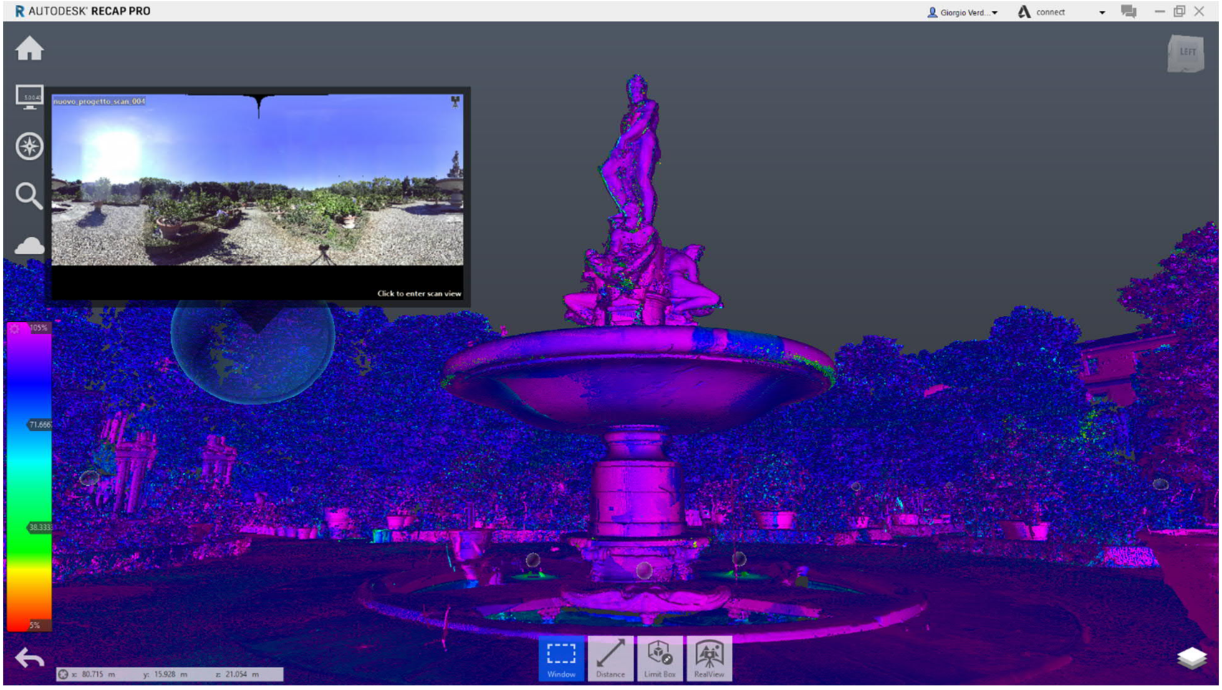

Fig. 11. View of the aligned point cloud (colours based on reflectance values)

The scanning resolution was set to “1/4” (the points are taken with a distance of 6mm at 10 meters of distance) for all the scan except for the four taken nearby the basement, taken with the resolution set at “1/5” (the points are taken with a distance of 8mm at 10 meters distance) and an accuracy with a 4x redundancy. The alignment was done using Autodesk Recap.

Fig. 12. View of the aligned point cloud (greyscale based on reflectance values)

MODELING AND SEISMIC ANALYSIS

The modeling and analysis part illustrated below refers to the original copy of Ocean statue preserved inside the Bargello National Museum. The same considerations and evaluations were made on the fountain in Boboli Garden.

Starting from the model obtained with the surveying instruments, the “finite element method” (FEM) model used for structural analysis was obtained by simplifying the initial model to make it suitable for a numerical analysis. At first step, the number of polygons was reduced through the *Quadratic Edge Collapse Decimation* procedure in *MeshLab software* [Cignoni et al. 2008], after which, it was implemented and transformed from a surface model into a volume model with *Strauss 7* (Fig. 13). According to simplified methodologies and approaches for the evaluation of the vulnerability of artistic artifacts [Liberatore et al. 2000; Ciampoli and Augusti 2000], a preliminary qualitative evaluation of the object was carried out. The case study belongs to a typological category *T3* (STAT-statue, sculpture and large vases), in particular A2 (object resting on a flat surface or pedestal), with consequent category of behavior A, specifically R4, or oscillatory response mode with overturning as a mechanism of associated damage.

The structural analysis was performed on a FEM model consisting of 125.600 four-nodes tetrahedral isoperimetric elements with the software Straus7. The sculpture is made in marble, with an Elastic Module of 50.000 MPa, a Poisson coefficient of 0,2 and a density equal to 2.700 kg/m³, while the pedestal is made in concrete, with an Elastic Module of 28.000 MPa, a Poisson coefficient of 0,2 and a density equal to 2.400 kg/m³. The statue and pedestal system were assumed as a single continuous body. At the lower face of the pedestal the X, Y and Z displacements were locked to simulate a joint at the base. This hypothesis allows us to evaluate the effects produced in the linear elastic field by seismic actions in terms of displacement and stress.

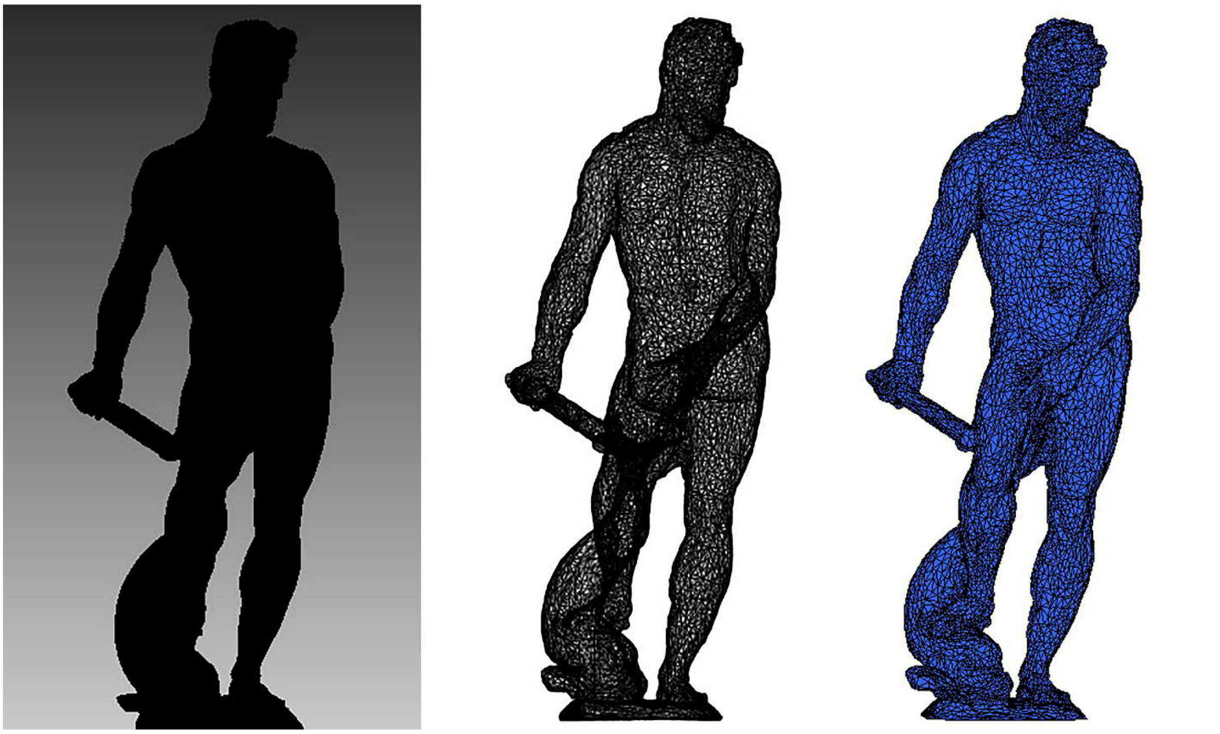

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Fig. 13. FEM analysis on the 3D model of the Oceano's with differently simplified versions of the mesh: a) 2.000.000 triangular faces b) 23.200 triangular faces c) 103.300 solid tetrahedral elements

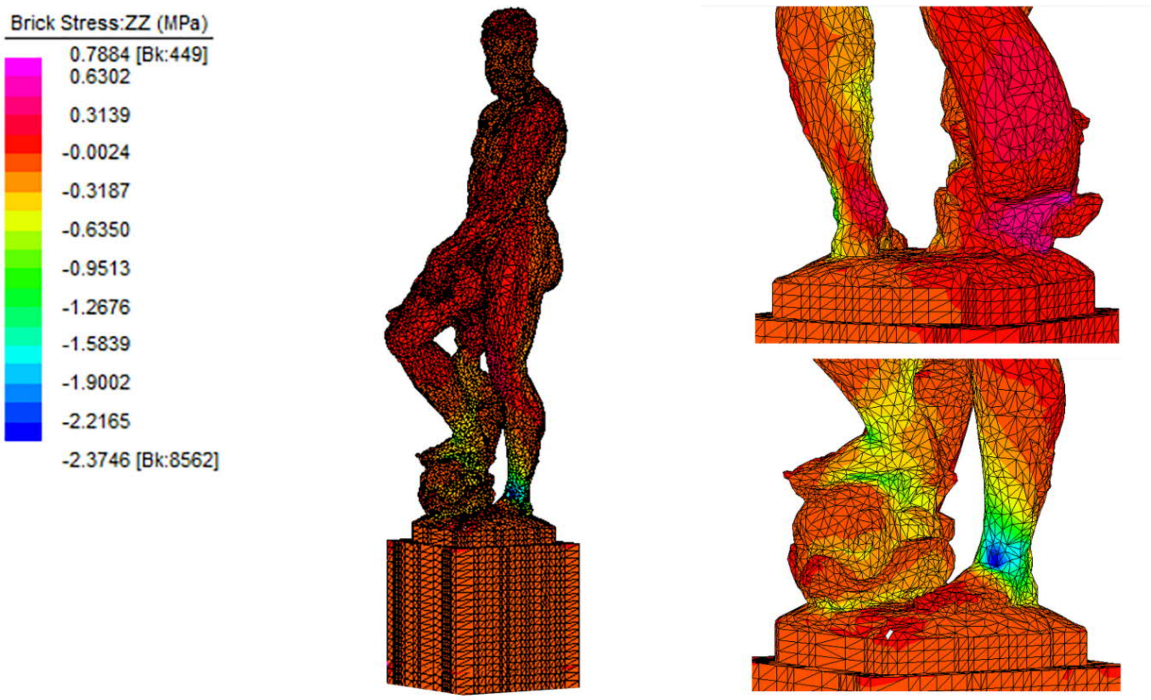

Fig. 14. Static analysis for vertical loads, views of the stress states ZZ

Fig. 14 shows the results provided by the analysis by considering only the proper weight as loading condition. In line with the position of the statue, there is a concentration of stress at the ankles, specifically, 2,3 MPa of compression in the front and 0,5 MPa of traction in the back. However, the compression and tensile values do not reach the resistance limits of the material.

A modal analysis has even been performed; it provided the natural frequencies of the main modes of vibration and it has been used also useful for quantifying the alpha and beta coefficients, according to the classical formulation proposed by Rayleigh [Chopra 1995] to be used in the dynamic analysis over time.

Figure 15 shows dynamic analysis performed in order to evaluate the possible response of the statue-pedestal as a single set. The seismic input was obtained through the Itaca [2008] from 7 accelerograms of real seismic events, compatible with the elastic spectrum proposed by the Italian code [NTC 2018] for the site of Florence, with a soil type B and a return period of 1950 years. The dynamic analysis provided results both in terms of displacement and of stress states. For all analysis, no significant displacements are ever achieved in the three main directions. The maximum value of stress achieved along the Z direction is equal to 3,7 MPa in case of traction and to 6,7 MPa in case of compression. The tensile stress value is very close to the assumed limit of the material.

Linear analyzes allow to highlight the areas in which the highest stress conditions are reached. In all analyzes carried out, it emerges that stress levels are concentrated in the area of the ankles. The obtained results allow a first evaluation of the elastic behavior of the statue; further modeling will be performed considering the non-linear behavior of the materials and inserting the effect of non-linearity produced by the pedestal statue contact surface.

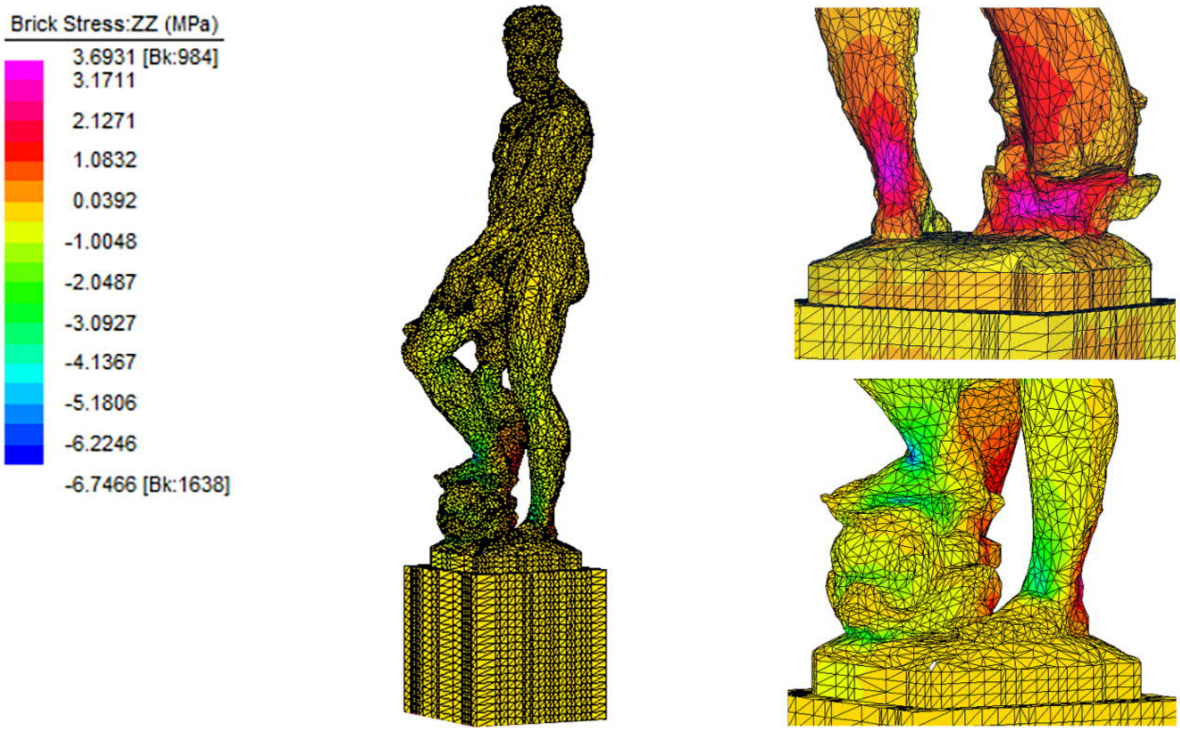

Fig. 15. Dynamic analysis, views of the stress states ZZ at 2,04 s for GMN earthquake

CONCLUSIONS

Italy hosts a great quantity of fundamental cultural heritage masterpieces; their protection from natural events and disasters plays an important role in the cultural and economic asset of the Country. The assessment of the seismic safety of art goods, such as marble statues, requires a complex series of procedures, which involve different research field. The quality of the geometrical representation of the objects is a required starting point for a reliable assessment.

The analysis performed on Nettuno/Oceano evidenced the importance of adopting the most recent technologies for performing the digital survey and to provide the geometrical data to use for analysis. An accurate polygonal mesh is at the base of advanced seismic analysis and, as shown in this paper, it can give clear indications about the weakness and the potential risk in the possible evolutions/events which can possible afflict the statue.

It should be noted that, even if in this work very professional tools have been used, similar analyses, despite less accurate and trustable in the results, could be performed by using mobile photography and cheaper cameras.

This “democracy” in the production of 3D models, if correctly exploited, may produce in the next years, a great resource for the analysis of our outstanding patrimony of statues and monuments.

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Fig. 16. The poster presented to CHNT Conference, November 2018

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