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From TLS data to FE model: a workflow for studying the dynamic behavior of the Pulpit by Giovanni Pisano in Pistoia (Italy)

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Abstract

This paper discusses the first results of an ongoing two-year research activity aimed to identify the actual dynamic behavior of the Pulpit of Giovanni Pisano in Pistoia in order to design a long-term structural health monitoring system. First steps of the research have foreseen a Photogrammetric and Terrestrial Laser Scanner (TLS) survey of the structure in order to build a refined digital three-dimensional geometric model of the Pulpit to be employed for both documentation and structural assessment. The paper reports the main outcomes of the TLS survey together with the procedure employed to obtain a reliable finite element model of the Pulpit. An original workflow for direct transfer of high accuracy TLS-based three-dimensional model to a finite element model is proposed and discussed.

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Keywords: Terrestrial Laser Scanning (TLS); Cultural Heritage (CH); Finite Element (FE) modelling; Structural analysis.

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1. Introduction

The marble pulpit inside the church of Sant'Andrea in Pistoia (Italy), one of the greatest sculptural masterpieces of the Western art, was realised by Giovanni Pisano between 1298 and 1301at the time of the parish priest Arnoldo, as reported by a Latin inscription along the bottom band of the figured panels. It consists of a raised hexagonal platform, enclosed by a parapet decorated with sculptures and bas-reliefs representing scenes from the Gospel and other biblical characters and symbols. The arches which bear the platform are supported by seven slender red marble columns with Corinthian capitals (six at the corners and one in the center, Fig. 1). Each column has a different height, as three columns stand on bases and four are resting on sculptures. The pulpit is about 4 meters high and the diameter of the hexagon is about 2 meters.

The pulpit is currently located in the fifth intercolumn on the left side of the main nave of the church, but it was originally positioned in front of the presbytery near the penultimate column on the right side, from where it was removed in accordance with the indications of the Council of Trent (perhaps around 1619), at the time of the parish priest Bartolomeo Cellesi (Carli 1986).

In the new location, the pulpit was mounted differently, to adapt it to a different use and to a different relationship with the believers. These modifications involved, among other things, the relocation of some corner groups of the parapet and the elimination of two lecterns. The Gospel lectern depicting the Eagle, symbol of St. John, is now in the Metropolitan Museum in New York (a cast was placed on the pulpit in 2001), that of the Epistle with Christ at mercy between two angels has been identified, albeit not unanimously, in that of a similar subject now kept in the State Museums in Berlin.

Fig. 1. Point cloud of the pulpit.

The investigations and archival research carried out to date attest that the pulpit of Sant'Andrea in Pistoia has been the object of a series of restorations and interventions over the last two centuries, only partially documented and ascertained in their extent, but which testify to a persistent attention to the conditions of conservation of the plastic elements and of the stability of the architectural structure. For example, as early as 1836, injuries to the pulpit panels, which were restored by the sculptor Stefano Ricci, were reported. More recently, over the last decade, attention and investigations have been carried out, in particular for the presence of "cracks" and "crevices", which have led to partly discordant reports and evaluations. In 2007 the "Opificio delle Pietre Dure" started a series of investigations and studies on the pulpit: morphometric survey; analysis of the constituent materials (stone material, finishes and gilding applied on the marble, glass inlays, mortars for the bedding of the marble slabs); geological and geomechanical analyses to define the conditions of the foundations; endoscopic analyses; geophysical ultrasound surveys; georadar surveys, to verify any soil anomalies; gammagraphic survey on columns and arches above. The studies, and the results obtained, have been published (Aldrovandi et al. 2011) and have led to the operational possibility of a complete disassembly of the pulpit.

This paper, which move from these studies, presents the first results of an ongoing two-year research activity aimed to identify the actual dynamic behavior of the pulpit in order to design a long-term structural health monitoring system. The Terrestrial Laser Scanner survey provides a refined and detailed representation of the actual geometry which includes, among other aspects, the tilt of the columns and the mass distribution in the bas-reliefs of the panels. The exact knowledge of both these aspects is fundamental in order to build a reliable numerical model capable to reproduce, and estimate, the current dynamic behavior of the structure. In a first part, the paper reports the main outcomes of the Terrestrial Laser Scanner survey, while in a second part the procedure employed to build a finite element numerical model of the pulpit is proposed and discussed. In particular, an original workflow for direct transfer of high accuracy Terrestrial Laser Scanner-based three-dimensional model to a finite element analysis software is discussed.

2. The 3-D survey of the pulpit

2.1. Aims and previous campaigns

It was considered essential to carry out a digital survey and 3-D modelling of the artwork, in order to obtain a digital model suitable for building the numerical model of the construction. During previous researches (Aldrovandi et al. 2011), a laser scanner survey of the pulpit had already been done, however, digital data are not available and only 2-D publications and outputs can be accessed. In addition, the reference system of the previous survey is not clearly identifiable, so it is not possible to verify any deformations that may have occurred between the two campaigns.

It was also planned to use the 3-D model for segmenting the pulpit into its constituent elements (as a further contribution to structural investigations), to document the individual parts of the work and to make virtual reconstructions and simulations of its original state. It was decided that the overall survey of the geometry should be carried out by laser scanning and to use photogrammetry for more detailed documentation of the single elements, the materials and the state of conservation.

2.2. Open issues on marble acquisition with terrestrial laser scanner

This paper deals with 3-D acquisition and modelling carried out with terrestrial laser scanning (TLS). With this technique, a surface is sampled by measuring the distance from the instrument, calculated according to the time-of-flight spent by a laser beam or the phase-shift between the waveforms of the original and reflected signals.

TLS technology enables the optimal acquisition of opaque surfaces with lambertian reflectance (such as those of many materials used in cultural heritage and buildings), but the acquisition with TLS of translucent or transparent surfaces or material with a specular reflectance or a high refractive index is still challenging.

Since the first studies on laser scanner survey for cultural heritage (Tucci et al. 2017), several scholars (Lichti & Harvey 2002, Tsakiri et al. 2003, Voetgle & Wakaluk 2009, Callieri et al. 2009) stressed the issues related to the acquisition of marble, widely used in cultural heritage but with a translucent and anisotropic surface. The laser beam penetrates and scatters beyond the marble surface, causing unpredictable depth measurement and noise errors (García Fernández 2016) which are influenced by the material properties (color, anisotropy, translucency, refraction index, etc.), by the instrument characteristics (laser frequency, beam intensity, laser spot size, echo-reception threshold, etc.) and by the reciprocal position between instrument and object (distance, angle of incidence, etc.).

Giovanni Pisano's pulpit is mostly made of white marble (coming from several quarries in the Apuan Alps and therefore with variable characteristics, Aldrovandi et al. 2011), except for the columns which are in red marble. Its morphology is extremely complex; therefore, each element is inevitably acquired at variable distances and angles of incidence. Consequently, the only parameter that can be selected is the kind of instrument. For this reason, some tests have been carried out with several scanners. The selected instrument is a time-of-flight scanner with a wavelength of 532 nm (green).

2.3. The survey workflow

Scans were done with a resolution of 6 mm @ 10 m, also acquiring the RGB value with the integrated camera. Point clouds with RGB information and vertex-colour meshes are useful for segmenting the different parts, but for a more realistic and communication-oriented visualization will be used photogrammetric 3-D models which have a better colour quality.

A total of 28 scans were performed. Scans were taken for each face and edge of the hexagon at about two meters, in some cases the closeness of the nave columns and walls forced to modify this acquisition pattern. As the bas-reliefs are very elaborate, in order to minimise the lack of data between the figures, scans have been acquired from different heights at every scan position. In addition, three scans were made between the columns under the platform and two above it. Finally, a few overall scans were taken from a greater distance.

As known, a topographic network reduces the potential misalignment between scans and drift. For this reason, a topographic surveying network measured with total station was created. The four vertices of the network have been permanently marked with nails to define a local reference system both for laser scanner and photogrammetric surveys; moreover, this could also allow further integrations and monitoring over time. Currently, seven targets have been measured from the vertices of the network for the alignment of the scans.

2.4. Determining the axes of the columns

A significant aspect for the structural evaluation of the pulpit is the determination of the axes of the columns, each of them tilted with a different direction and slope. The challenge is to find the axes despite the noise of the scans. For this aim, the portions relating to the columns were segmented from the point cloud. For each column, at least seven horizontal slices have been extracted at a regular distance.

Therefore, the best fitting circumference has been determined from each of them. In fact, since the inclination is small, slices are cut according to planes almost orthogonal to the axis, so, even if the sections are actually elliptical, they have a very small eccentricity and can be approximated with a circumference. Finally, the axis of the columns resulted as the best fit line of the centres of the circumferences (Fig. 2).

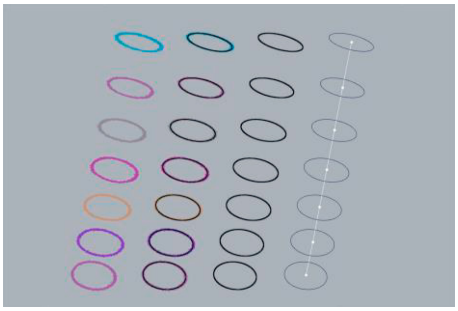


Fig. 2. Determination of the axis of a column. From left: point cloud slices, best fit circumferences, circumferences, centres best fit line.

2.5. Building a 3-D mesh model of the pulpit

From the overall point model, a surface model (mesh) was also obtained for further processing. The creation of a mesh model from a point cloud required several steps. The first one concerned the selection and cleaning of the area that includes the pulpit, obtaining a point cloud of about 126 million of points. Then, the point cloud has been decimated and a mesh has been created with the Surface Reconstruction Poisson algorithm (Kazhdan et al. 2006). The mesh, initially consisting of about 32 million triangles, has been reduced to about 16 million faces for documentation and communication and to about 2 million faces for structural evaluation models, balancing the conflicting requirements of high resolution and usability.

3. The structural model

One of the goals of the ongoing two-year research activity is to derive a reliable numerical model to be employed inside the static and seismic vulnerability assessment workflow (Ruggieri et al. 2018, Galassi et al. 2020). Specifically, the numerical approach within the Finite Element (FE) method context could be adopted as one of the most reliable and used for structural analysis purposes. Previous experiences (Pieraccini et al. 2017) have brought attention to the topic of studying the behavior of cultural heritage objects using TLS surveys as an informative basis. On the one hand it is possible to re-build a Voxel-based model derived directly from the point cloud (Castellazzi et al. 2015, Bitelli et al. 2016), on the other hand it is possible to "re-interpret" the geometrical mesh that can be built after the laser scanner results elaboration (Freytag et al. 2011). The different approaches (point cloud derivation of the structural model and intermediate geometrical meshing) can be used at different scales: the first one does not need further elaboration of the geometrical model, because it is directly derived from the point cloud (Korumaz et al. 2017), the second one needs an intermediate geometrical step, but can be easily adapted for the extremely complex geometries which characterize statues and highly decorated objects.

(1)	(2)	(3)	(4)
Boundary surface	Boundary surface	Boundary surface	Boundary surface
1149652 elements	*391816 elements*	*230530 elements*	*81458 elements*
Mean dimension	Mean dimension	Mean dimension	Mean dimension
10.6659 mm	*17.8576 mm*	*23.3765 mm*	*36.2711 mm*
Volume	Volume	Volume	Volume
7057827 elements	*1318370 elements*	*646342 elements*	*189010 elements*

Fig. 3. FEM boundary mesh for different decimation of the original point cloud.

3.1. The geometrical transformation

Given the high complexity of the Pisano's pulpit (Figs. 1 and 3), the most suitable operation seems to be the geometrical derivation of the model as a surface mesh element for the volumetric domain of the structural and non-structural parts. In this case the focus is moved on the validity of the geometrical shapes that must be used for the purpose of building a numerical model with a robust technique (Hamri et al. 2010). Specifically, an acceptable "skin" mesh for the volume must be defined in terms of the correct representativity of the physical geometry and in terms of avoiding poor quality, defined by the introduction of large angles inside the polygonal elements, which are one of the main causes of interpolation and gradient interpolation errors.

The polygonal mesh obtained from the point cloud is the starting point for the transformation towards a FE model of the geometrical shape, to be subsequently employed for structural purposes, as described in the previous section. The starting mesh is obtained by the reduction of the original one, derived from a 126 million point cloud, into a boundary mesh surface containing around 2.5 million of faces: a further optimization is then applied, with the cut of the boundary on the level of the column/statue base, with around 1.15 million of faces. This mesh is then used to obtain a tessellated neutral mesh surface (in STL format), mainly used in the field of rapid prototyping (Grimm 2004), with 4 different levels of optimization and decimation (Fig. 3). While the first 3 models are obtained increasing the decimation size (and therefore the roughness of the mesh), the fourth is created by a shape re-wrapping of the original one and a smoother re-meshing.

3.2. The finite element model and the performed analyses

For the aim of the structural assessment, different types of conditions could be implemented inside the FE model, depending on the type of analysis to be performed. In this case two simple type of analysis (static and dynamic) have been performed to check the reliability of the model. The FE code employed to build the numerical model was code_aster, an open source FE code (Betti et al. 2012). On the one hand the standard linear elastic analysis was employed for simple static evaluations (in order to inspect detailed results in specific parts of the model); on the other hand the linear modal analysis, performed with the Sorensen method (Sorensen 1992), was considered in order to obtain a global output from the model (the frequencies of each mode shape).

(1) Volumetric 3D FE-Model **(5)** Reduced FE-Model

Fig. 4. Volumetric and reduced FE-Model.

Within this context, it is mainly necessary to define: (i) the material mechanical properties, (ii) the boundary conditions, with external restraints, (iii) the loads, such as the self-weight, (iv) the internal connectivity of the structural elements. While no non-linearities have not yet been implemented, both in the mechanical behavior characterization and the geometrical one (big displacements), the latter aspect (internal connectivity) will be here only introduced for future implementation. More specifically, a reduced model will be defined to insert the column elements of the pulpit as 1D finite elements (with the previously discussed geometrical description of the axis and the varying diameter), separately from the more refined 3D volumetric elements, in order to be able to handle the level of connectivity between these elements (Fig. 4).

Table 1. Computational performance of the different Finite Element models.

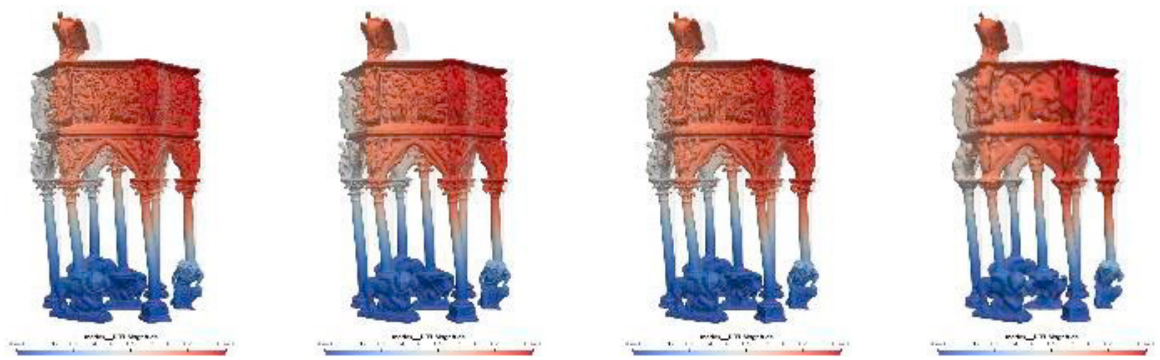
Model	Nodes	Computation time [s]
(1) Volumetric 3D	1242835	7862.72
(2) Volumetric 3D	313716	671.21
(3) Volumetric 3D	164088	256.98
(4) Volumetric 3D	52255	51.94
(5) Reduced 3D-1D	112143	176.55

As reported in Table 1, the four different discretized models (Fig. 3) and the reduced one (Fig. 4), are used to perform the analyses, consisting in the self-weight of the structure (linear static analysis) and the calculation of the first frequency. It is highlighted how the required computation time increases greatly with the increase of the number of nodes and the subsequent amount of degrees of freedom.

3.3. Results comparison

The results obtained from the analyses are here compared in order to have a qualitative identification of the main quantities of interest. Specifically, the stress distribution in the model and the mode shapes and frequencies are obtained for each model. The results show how some of the columns seem to be more interested by local intensification of stresses, particularly the one above the statues.

Based on the results, and the fields produced from the analyses, it is possible to extrapolate the quantities of interest from any part of the object. Specifically, a section cut is produced on a pre-determined height (around 1000 mm from the base), in order to check the stress distribution on the column sections. In this extraction some caution is necessary, as the quantity of interest (i) is obtained from a projection of the stresses on the nodes and (ii) the interpolation over the section cut is executed outside the Finite Element code, as it is performed within the Paraview context. This introduces a potential double source of error, as a first interpolation is performed with averaged values and not on the “real” solution of the computational problem, and a further interpolation is introduced because of the different meshes adopted inside the model. It is however not possible to completely avoid these sources of error, as the standard methods of extraction of the quantities of interest rely on these interpolation procedures, and different meshes are unavoidable in defining models with different decimation/approximation (Giaccone et al. 2020).



(1) (2) (3) (4)

Fig. 5. 1st mode shape with different mesh refinements.

An assessment of the mesh influence on the finite element results is verified by comparing the general outputs reported in Fig. 5 where it is possible to qualitatively compare the deformed shape of the first vibration mode as obtained with the different models: some minor differences are highlighted. In Table 2, to provide a global picture, the base reaction and the main frequency obtained with the different models are reported. Sensitivity of the first frequency is reported assuming as reference the frequency value provided by the finest model.

Table 2. Base reactions and modal frequencies obtained with the different models.

Model	Base reaction [MN]	1st frequency ratio [-]
(1) Volumetric 3D	59,2501	1.000
(2) Volumetric 3D	59,0551	1.022
(3) Volumetric 3D	59,1509	1.039
(4) Volumetric 3D	57,4200	1.030
(5) Reduced 3D-1D	59,0700	1.033

4. Conclusive remarks

The results obtained from the numerical analyses performed with different level of discretization of the pulpit, starting from an extremely refined geometrical model, show how both local and global outputs can be influenced by the discretization level, pre-determined with the adoption of a geometrical surface boundary derived from the TLS point cloud data. On the one hand, it is clear and confirmed that a rough, or even a stylized, representation of the geometry will introduce errors in the computation and evaluation of the outputs. On the other hand, a certain level of approximation can be considered acceptable, depending on the quantities of interest: this level of approximation has to be established case by case and further investigations are needed to generally address the problem.

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