COMBINED TECHNIQUES FOR THE STABILITY CONTROL OF HISTORICAL STRUCTURES

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Abstract: The demand for high-definition surveys within cultural heritage-related projects represents one of the main factors which promoted the use of laser scanning technology. By measuring millions of points within relatively short time periods, terrestrial laser scanners allows to derive complete and very detailed 3D models of real objects from acquired point clouds. These features drew in recent years the interest of surveyors, engineers, architects and archaeologists towards the laser scanning technique as an invaluable surveying mean for 3D modeling of sites and artifacts of cultural heritage. A wide variety of objects, e.g., small pieces of pottery, statues, buildings, and large areas of archaeological sites, have been scanned and modeled for various purposes like preservation, reconstruction, study, and museum exhibitions. However, the use of TLS systems for stability control is still a research field not much investigated.

In the view of insight investigation on this topic, a three-years project has been established in order to evaluate the use of multiple surveying techniques for the stability control of a complex historical structure. To this aim, terrestrial laser scanning (TLS), total station (TS), deflectometers and photogrammetry are being employed for a first test on the Anatomy Theatre, one of the oldest, most important and best-known historical "medical" buildings. Located inside the *Palazzo del Bo'*, the building seat of the University of Padua, the Theatre was built in 1594 as first permanent structure of its kind and substituted for the temporary theatres which were set up when necessary. The main goal of this work is to verify the stability over the time of this kind of structure, given the inherent organic decay of the wooden parts.

So far three consecutive surveys of the Theatre have been carried out with a Leica laser scanner (HDS 3000) and a Leica Total Station. In the first one the historical structure has been fully measured in order to derive a complete 3D model suited for FEM analysis; then, according to a six months time span, two further surveys were performed for stability check.

In this paper we present the results obtained from the repeated surveys and highlight issues and difficulties related to the laser scanning of an unusual geometry such as the one provided by the Anatomy Theatre of the University of Padua.

1. INTRODUCTION

The use of high-definition surveying laser scanning for cultural heritage-related projects is one of the "sweet spots" for this technology. Given its capability of measuring millions of points within relatively short time periods, complete and detailed 3D model of objects could be efficiently and easily created from acquired point clouds. These features drew in recent years the interest of surveyors, engineers, architects and archaeologists towards the laser scanning technique as an invaluable surveying mean for 3D modeling of sites and artifacts of cultural heritage. A wide variety of objects, e.g., small pieces of pottery, statues, buildings, and large areas of archaeological sites, have been scanned and modeled for various purposes like preservation, reconstruction, study, and museum exhibitions.

Among various applications, the use of TLS systems for stability control is still a research field not much investigated. In the view of this consideration, we planned a series of laser scanner surveys aimed to assess the effectiveness of TLS when used for stability control of complex historical structures. To this aim, a first test is currently ongoing on the Anatomy Theatre, one of the oldest, most important and best-known historical "medical" buildings. Built in 1594, the Theatre was the first permanent structure of its kind and substituted for the temporary theatres which were set up when necessary. The main goal of this work is to verify the stability over the time of this kind of structure, given the inherent organic decay of the wooden parts. Although this task could be performed with classical surveying methods, we decided to use a long-range terrestrial laser scanner (Leica HDS 3000). This choice was dictated by considering that the presented work is part of a wider project aimed not only at the checking of the structure stability but also at the structural assessment through the use of finite element model.

Just from the beginning, this work seemed to be quite challenging for the application of a TLS for two main reasons: the complexity of the structure's geometry to be surveyed and the need to develop a specific laser data reduction method. Indeed finite element softwares commonly employed require a very limited amount of input data compared with typical laser scanner point clouds, which have therefore to be properly reduced, without loosing too much the information about the object's geometry.

So far four consecutive surveys of the Theatre have been carried out with a Leica laser scanner (HDS 3000) and a Leica Total Station. In the first one the historical structure has been fully measured in order to derive a complete 3D model suited for FEM analysis; then, according to a six months time span, three further surveys were performed for stability check.

In order to evaluate any damage or weakening incurred on the wooden parts due to temperature, moisture changes or presence of termites we have also planned to evaluate the effectiveness of an infrared thermal camera on a few portions of the tiers. Results of this test should be available at the time of the FIG Symposium.

The paper is structured as follows. Section 2 provides a short description of the Anatomy Theatre while section 3 deals with the description of the procedure we adopted to produce a 3D model suited for subsequent finite element analysis. Then in section 4 we report on the preliminary results obtained from the repeated stability checks, highlighting issues and difficulties related to the laser scanning of an unusual geometry such as the one provided by the Anatomy Theatre. Section 5 provides an overview on the use of the infrared thermal camera, while section 6 draws the conclusions.

2. THE ANATOMY THEATRE

The Anatomy Theatre is certainly one of the oldest, most important and best-known historical "medical" buildings. Built in 1594, the Theatre was the first permanent structure of its kind and substituted for the temporary theatres which were set up when necessary. Inspired to the forms of Colosseum and the arena of Verona, using classical antiquity as a model, it intended to hold spectators of anatomy lectures disposed in concentric tiers. The particular shape of the structure resembles an inverted cone set inside a cylinder, both with an elliptical cross-section, and organised in tiers were spectators stand (figure 1).

The structure is comprised of larch beams positioned in "spokes". Curtain panelling is fixed vertically between the beams and air vents are placed in the panelling. The interior of the cone is subdivided in six levels or tiers, which permit a passage of about 35-40 cm (figure 2). The tiers are supported by overhanging corbels and are finished with a parapet of about one meter height consisting of shaped and carved walnut elements on which the handrail rests.

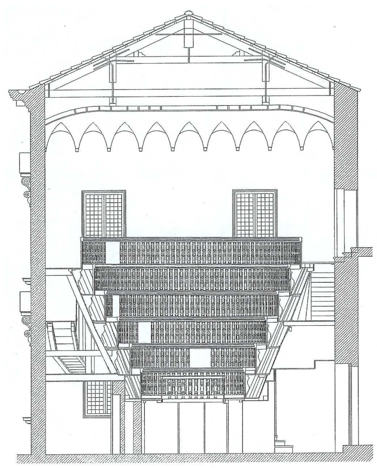


Figure 1 - Cross-section of the Anatomy Theatre

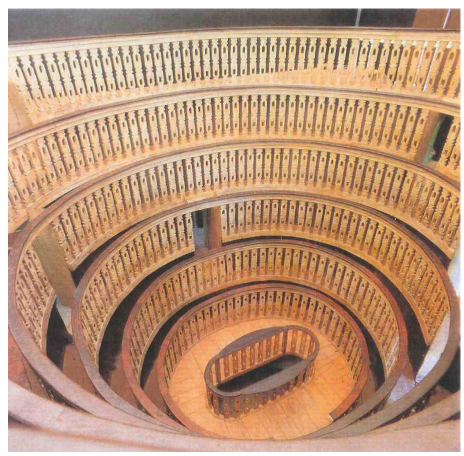


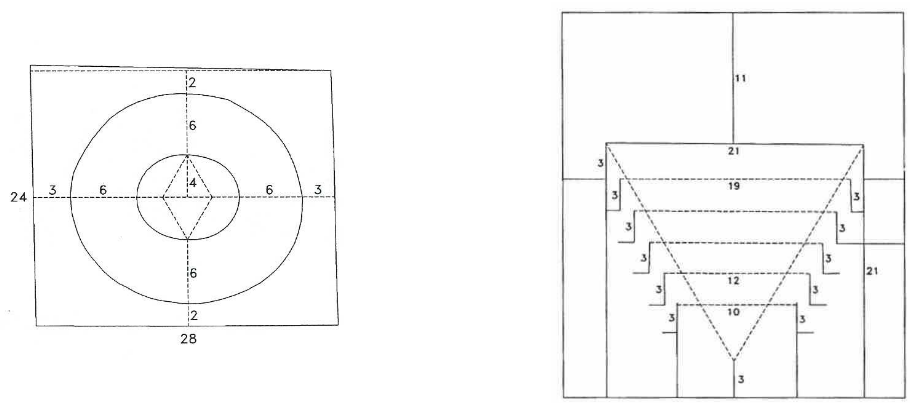
Figure 2 - Top view of the structure

Access to the various levels is by stairs in stone and wood on the outside of the cone (figure 3). In the middle of the floor of the first balcony the structure shows a hole, whose longest axis corresponds to the dissection table which by means of an appropriate mechanism was raised and lowered to the floor underneath, where attendants could easily place the preparations without the need to come upstairs where the demonstrations took place (figure 4). Although the Theatre was in use for almost three centuries it is still well preserved and, apart from a few 18th century modifications, in its original state.

The dimensions of the Theatre, built inside a trapezoid-shaped room, turn out to be rigorous multiplications of the unit length of the time, the "Paduan foot", which corresponds to about 36 cm. According to such unit, the room measures 24 by 28 feet with an estimated height in the center of about 12 m. The internal minimum width of tiers is one foot, the width of some accesses is 2 feet with a height of 5, the minimum width between the walls and balustrade at the top level is 3 feet on the East and West sides, while it is 2 feet on the North and South ones (figure 5a). The most interesting element is the first tier, which shows an elliptical shape with a major axis of 10 feet and whose focuses seem to form an equilateral triangle with respect to the minor axis. The sequence of the upper ellipses does not have coincident focuses going up each level, rather they get closer creating a more centralised form (figure 5b).

Figure 3 - Entrance to the top-most level

Figure 4 - View of the Theatre from the aperture for the dissection table



(a) (b)

Figure 5 - Composition scheme in Paduan feet of the plan (a) and longitudinal section (b)

Optimal use of the Theatre was favoured by its unique form, a reversed "funnel", whose functionality was accentuated by reserving the artificial light just for the "scene", thus emphasizing the type of spectacle which was part of the scientific activity of anatomic operations.

3. DATA ACQUISITION AND MODELING

All the datasets employed for both the 3D modeling and for the stability check of the Theatre were collected with the Leica HDS 3000 laser scanner. This scanning system allows for a larger Field of View (360^o H x 270^o V), ensuring in the same time a low beam divergence and a good measuring accuracy (both ≤ 6 mm @ 50 m). The data acquisition was performed with Cyclone software in three subsequent periods of time: in the first run, we surveyed the whole structure with a point spacing of 1 cm for the wooden elements and 2 mm for black and white non-retroreflective targets (figure 6). The latters were used as artificial matching points in order to avoid possible mistaken during scan registration, given the high symmetry of the structure. Altogether 7 scans were collected resulting in a total amount of 25.850.000 points. Two work days were required to complete this initial stage, most of the time was spent for moving the laser scanner between planned station positions: the narrow space between the tiers (40 cm) made this operation very difficult. The subsequent two surveys were carried out just to collect data for the structure's stability analysis. Due to the shape complexity of the Theatre and the time required to scan the whole environment, we decided to survey only a specific portion of the structure. In such area, 10 retroreflective targets were measured with higher resolution (2 mm) than the surrounding wooden elements (1 cm), both with the laser scanner and with a total station. The latter was employed for the quality assessment of laser measurements on these control points.

3.1. DATA PROCESSING

Acquired point clouds were then registered each other in order to produce the 3D model of the Theatre. Even this operation was carried out in Cyclone software, adopting the well known two-steps procedure consisting in a pairwise scan alignment followed by a global registration, based on the ICP algorithm (Besl et al., 1992; Chen et al., 1992; Bergevin et al., 1996).

The pairwise scan alignment was performed by manual selection of the center of the black & white targets, which could be easily identified by colouring the scans with the intensity data. As shown in figure 7, the average RMS of the global alignment was around 7 mm: this is a quite good result considering that the Leica HDS 3000 is claimed for a single point measurement accuracy of 6 mm. The resulting aligned model is shown in figures 8 and 9.

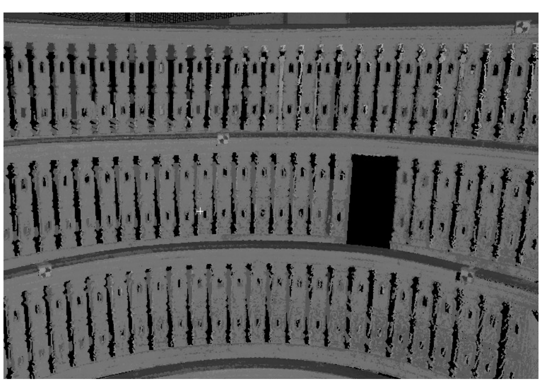


Figure 6 - Close-up view of the B&W targets

ScanWorld	ScanWorld	Status	Weight	Error Vector
Scw_01	Scw_06	On	1.0000	aligned [0.007 m]
Scw_01	Scw_02	On	1.0000	aligned [0.008 m]
Scw_01	Scw_03	On	1.0000	aligned [0.008 m]
Scw_01	Scw_04	On	1.0000	aligned [0.007 m]
Scw_02	Scw_05	On	1.0000	aligned [0.005 m]
Scw_02	Scw_07	On	1.0000	aligned [0.005 m]
Scw_02	Scw_03	On	1.0000	aligned [0.005 m]
Scw_03	Scw_05	On	1.0000	aligned [0.005 m]
Scw_04	Scw_03	On	1.0000	aligned [0.009 m]
Scw_05	Scw_01	On	1.0000	aligned [0.011 m]
Scw_05	Scw_04	On	1.0000	aligned [0.007 m]
Scw_05	Scw_06	On	1.0000	aligned [0.010 m]
Scw_06	Scw_04	On	1.0000	aligned [0.007 m]
Scw_07	Scw_03	On	1.0000	aligned [0.005 m]
Scw_07	Scw_04	On	1.0000	aligned [0.007 m]

Figure 7 - Registration results

Figure 8 - Side view of the aligned model

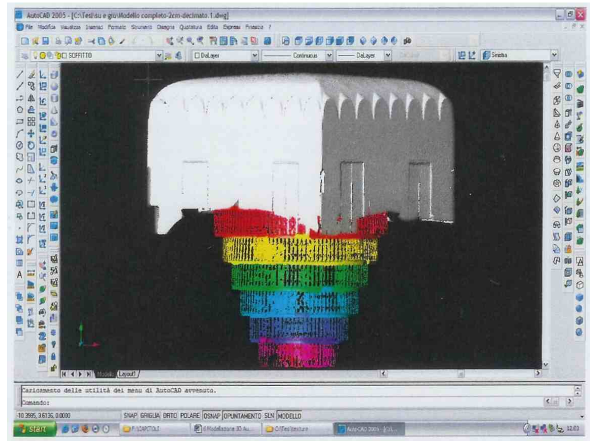


Figure 9 - Segmentation of the meshed model

3.2. 3D MODEL TEXTURING AND SIMPLIFICATION

After registration, the resulting point cloud was subsampled with different settings for the ceiling and the tiers: such strategy was adopted in order to find a good compromise between level of detail and computational complexity. Indeed the 3D model of the Theatre should have to be used as primary dataset to conduct a finite element analysis on the structure. As softwares currently available on the market for this application are not optimized to manage large amount of points, such as those typically obtained from TLS surveys, data reduction was a necessary step. Several trials were performed prior to find the best value combination, i.e. 5 cm for the ceiling and 2 cm for the tiers. Then the resulting model was furtherly segmented in its componing parts, the ceiling and the 6 tiers, which were separately triangulated with the same step as used for the subsampling (figure 9). In this way it was more easy to import the whole dataset in Autocad, for further model editing .

Here, the various components of the structure were properly modeled according to a procedure applied in a previous work (Guarnieri et al., 2006). Basically, a few representative objects of the balustrades, the handrails and other minor elements were selected and profiles were extracted from the corresponding laser points. Such profiles were then used as guidelines to reconstruct the corresponding original 3D geometry: for each object the resulting replica was substitued in place of the laser points. An example of the profile extraction procedure is shown in figures 10 and 11.

As final step of the 3D modeling of the Anatomy Theatre, the mesh edited in Autocad was imported in 3D Studio Max for the texturing and for the generation of a video (figure 12). The rendering of the scenes was done with the Raytracing technique. An example of the textured 3D model is shown in figure 13.

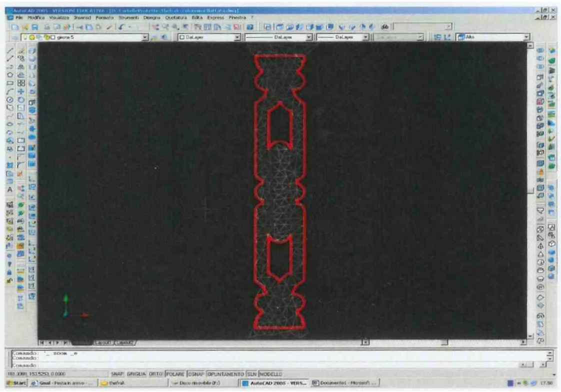


Figure 10 - Example of the profile extraction procedure applied to an element the balustrades.

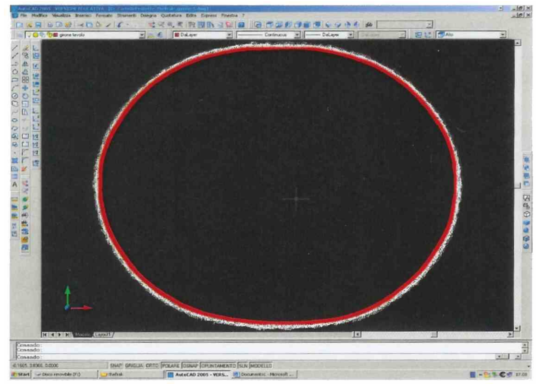


Figure 11 -: Extraction of the profile of a whole handrail.

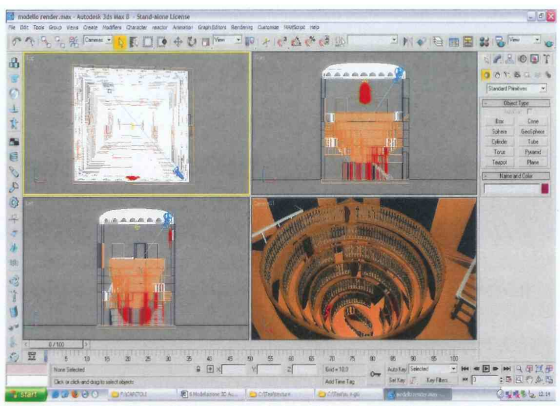


Figure 12 - Model texturing and rendering in 3D Studio Max

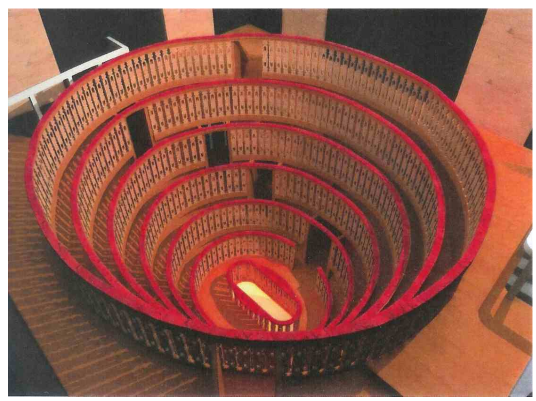


Figure 13 - A perspective view of the rendered 3D model

4. STABILITY CONTROL

Beside the generation of a 3D model of the Anatomy Theatre to be used both for FEM-based analysis and for multimedia presentations, a further objective of this project dealt with the investigation on the capability of our laser scanner to acquire reliable 3D data for the stability control of historical structures.

To this aim, 3” by 3” square Leica HDS retroreflective targets were employed as reference points for the data processing. Namely, 10 targets were placed on the handrails of a portion of the Theatre (figure 14) and used to detect the displacements, while 6 targets were attached on the surrounding walls, considered fixed with the rest of the building (see figure 1): these markers are used just to align the various scans acquired over the time. So far 2 surveys have been performed, measuring such targets with both the Leica HDS 3000 and a Leica total station. In order to make TLS measurements comparable with geodetic ones, the target centers have been detected with the same method described in (Valanis and Tsakiri, 2004). Firstly, four scans with a 2 mm point spacing are collected for each target, then the corresponding point clouds are merged together and the points are grouped into three classes based on their reflectance. One class contains the point with high reflectance, the second class consists of points with love reflectance and the third class consists of the points of medium reflectance. After classification the target center coordinates are obtained by calculating the mean position of the two clusters with largest mean reflectivity values. As demonstrated in (Valanis and Tsakiri, 2004) this approach provides a better accuracy (0.1 mm) with respect to that achievable using the automatic target identification tool implemented in Cyclone software (1.5 mm).

As we are interested in relative target center displacements, we did not apply any transformation between the laser scanner and total station reference frames, rather we just computed the differences in X, Y, Z coordinates from laser scanner measurements at each survey epoch and compared them with the corresponding differences obtained from the geodetic surveys. Values obtained for the vertical displacements (along the Z coordinate) are reported in table 1. Here, the Z coordinate of each target center computed after the first survey is assumed to be zero (i.e. null displacement). Both instruments were properly levelled, making the respective Z axis parallel each other.

Differences between TLS and total station displacements are in the order of 0.2 – 0.4 mm, which is the same range of variation found between the target center X, Y, Z coordinates measured by the instruments.

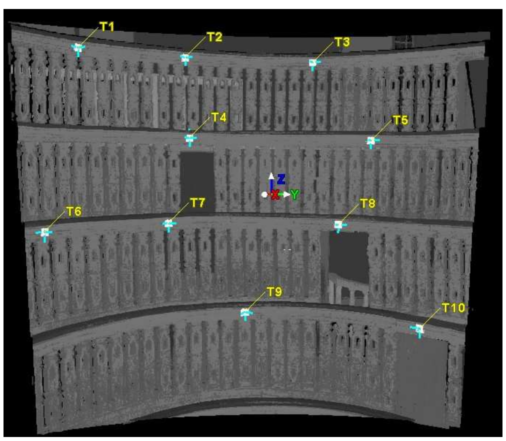


Figure 14 - Location of the 10 targets used for the stability control

Target ID	Vertical displacements (mm)		Delta (mm)
	HDS 3000	Total station	(TLS – Tot Stat)
1	-3.6	-3.4	-0.2
2	-3.0	-2.6	-0.4
3	0.3	0.1	0.2
4	-3.0	-3.2	0.2
5	0.7	0.3	0.4
6	0.2	-0.1	0.3
7	-0.1	-0.3	0.2
8	-0.4	-0.1	0.3
9	0.4	0.2	0.2
10	-0.2	0.1	-0.3

Table 1- Comparison between the vertical displacements derived by TLS and TS measurerments

5. FUTURE DEVELOPMENTS

In order to evaluate any damage or weakening incurred on the wooden parts due to temperature, moisture changes or presence of termites we have planned to evaluate the effectiveness of an infrared thermal camera on a few portions of the tiers.

Infrared thermography measures the thermal radiation emitted by an object in the infrared band of the electromagnetic spectrum and renders the image of the surface area in colours or in grey scale, in relation to a temperature scale. Depending upon the type of thermal imager, measurement of object temperature is also possible. Thermography represents a non-destructive testing and evaluation technique which is applied on the materials and structures in order to assess the physicochemical behaviour of conservation treatments such as stone cleaning, stone consolidation, as well as to disclose any substrate features, such as tesserae on plastered mosaic surfaces, to detect buried defects and inhomogeneity, to monitor hidden structure and moisture content, to analyze corrosions and to check the quality of welding and reinforcements elements. Hidden structure identification, adhesion of frescoes checking, cracks mapping and air flows studies are among the most important applications for conservators and restorers. Modern IR imagers resolve surface temperature differences of 0.1ºC or less. This high sensitivity allows for the evaluation of subtle thermal phenomena, which are only revealed in the form of slight temperature gradients.

Regarding wooden structures, useful application of IR termography relies on the detection and analysis of damages caused by termites. Indeed, when termites have concentrations of activity or nesting within wooden materials, the thermal camera can detect the heat caused by that activity. However this task is not always successfull, because if the infestation is not concentrated enough to alter the surface temperature of the material being scanned, the area will not appear hotter in the thermal camera. If the infestation is not active at the time of the inspection, or areas of the infestation are not active, then little may be detected with the thermal camera.

The thermographic system which will be used in this test is the ThermaCAM B2 (by FLYR Systems), shown in figure 15. The IR detector is a Focal Plane Array (FPA), uncooled microbolometer 160 x 120 pixels, featuring a field of view of 19° x 14° and a minimum focus distance of 0.3m (with 17 mm lens). The temperature range is lying between -20°C and +100°C, with an accuracy of ±2°C (±2%) and a repeatability ±1°C (±1%).

Figure 15 - The IR thermal camera ThermaCAM B2

6. CONCLUSIONS

In this paper we have presented an example of twofold employment of a terrestrial laser scanner on the same object. Namely, a Leica HDS 3000 laser scanner was used to survey a complex historical structure, the Anatomy Theatre in Padua, both to generate a full 3D model for multimedia presentations and to produce a dataset suited for FEM-based structural analysis. Furthermore, laser measurements have been collected for stability control of the structure. To this aim, the Theatre will be continously monitored over three years, by performing surveys on a six month time span basis. As part of an ongoing project, preliminary results showed that vertical displacements derived from the laser scanner data are in quite good agreement with total station measurements, the latter instrument being used to validate the TLS results. To detect the displacements of a portion of the Theatre, a number of Leica HDS retroreflective targets were employed and the respective center coordinates were computed with an accuracy of about 0.5 mm by applying a classification algorithm based on fuzzy logic, instead of the automatic identification tool implemented in Cyclone software.

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