STABILITY CONTROL OF AN HISTORICAL STRUCTURE WITH TLS SURVEY

V. Dal Piaz [a] , A. Guarnieri[b], F. Pirotti[b], A. Vettore[b]

[a] DAUR – Department of Architecture, Urban Design and Survey, University of Padua, Italy
e-mail: vittorio.dalpiaz@unipd.it
[b] CIRGEO – Interdepartment Research Center for Geomatics, University of Padua,
viale dell'Università 16, 35020 Legnaro (PD) – Italy
e-mail: cirgeo@unipd.it

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ABSTRACT

In this paper we present the preliminary results of a study aimed to assess the stability of a complex historical structure such as the Anatomy Theatre. The construction occupies the two upper floors on the north west side of *Palazzo del Bo'*, the building seat of the University of Padua. 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. 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, a long-range terrestrial laser scanner (Leica HDS 3000) was employed. This choice was dictated by considering the numerous measurement benefits offered by TLSs, such as three-dimensional data capture, remote and noncontact (i.e. targetless) operation and dense data acquisition. 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.
In the paper we will present the preliminary results obtained from the repeated checks 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 apllications, 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 three consecutive surveys of the Theatre have been carried out with the Leica laser scanner. In the first one the historical structure has been fully measured in order to get its complete 3D model; then, according to a six months time span, two further surveys were performed for stability check.

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 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. Then section 5 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. Access to the various levels is by stairs in stone and wood on the outside of the cone (see 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. 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.
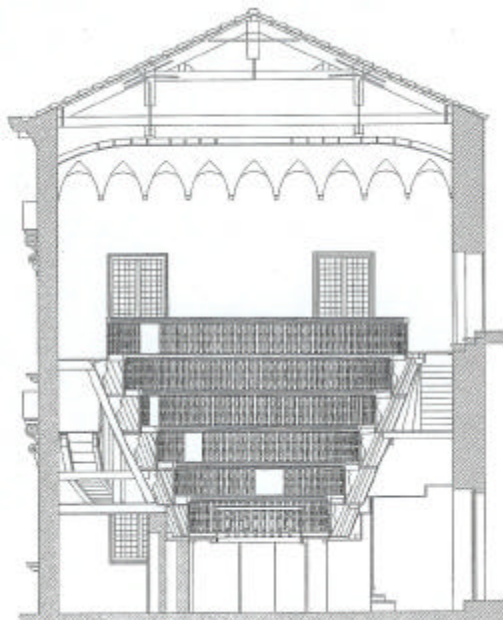

Figure 3: Entrance to the topmost level

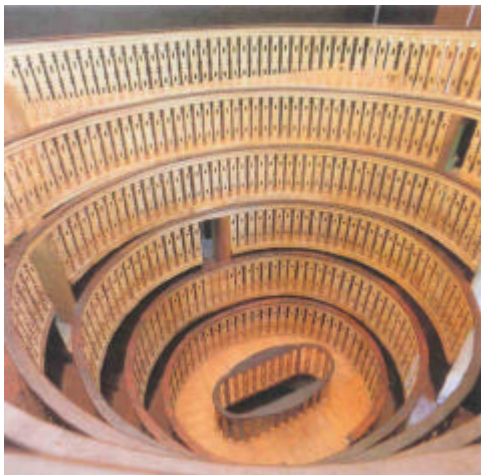Figure 1: Cross-section of the Anatomy Theatre


Figure 4: View of the Theatre from the aperture for the dissection table.

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 (see figure 5b).

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.

Figure 2: Top view of the structure
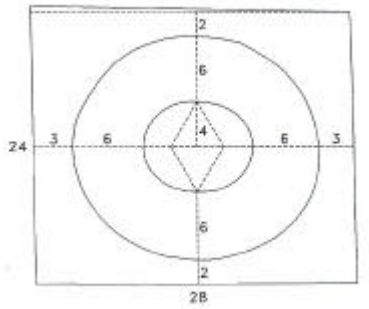
(a)
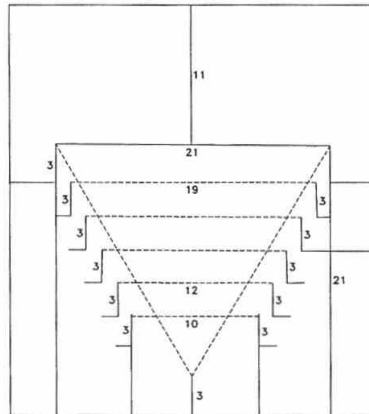
(b)

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

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° H x 270° V) thanks to the adoption of a dual-window, ensuring in the same time a low beam divergence (< 6 mm @ 50 m) and a good measuring accuracy (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 matching points for the registration step in order to overcome issues which could arise during point correspondence search 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 being spent for switching the station position: the narrow space between the tiers (40 cm) made, indeed, very difficult to move and correctly set up the laser scanner. The second and third 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 limit these surveys just to a specific portion of the structure. In such area, 10 retroreflective targets (not yet available in the first run) were placed and 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 in order to assess the quality of laser measurements on the control points (i.e. the targets). For each survey, just one scan of the interesting area was acquired.
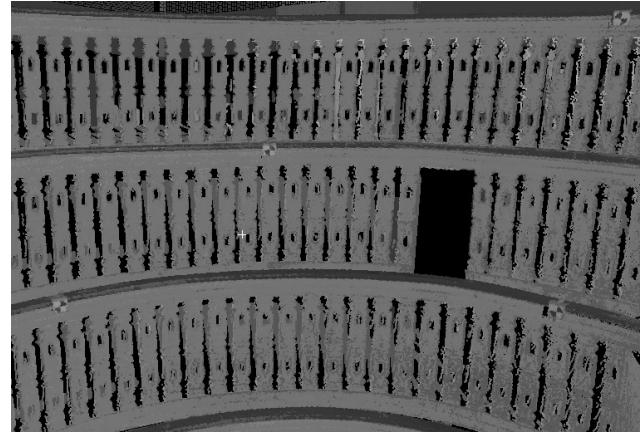

Figure 6: Close-up view of the Black & White targets

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 alignment was performed in several steps, changing at each run the value of some cloud constraint parameters (number of iterations, percentage of points to be considered and max search distance). The initial point matching operation was done by manually selecting the center of the black & white targets: the use of the intensity data, rendered in gray scale, instead of the RGB colors provided by the built-in ccd camera greatly helped the operator in this stage. 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.

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

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. In this way it was more easy to import the whole dataset in Autocad, for further model editing (figure 8).

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 9 and 10.
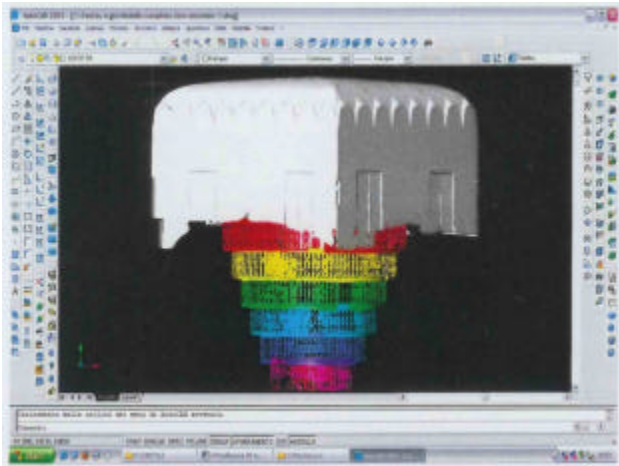

Figure 10: Extraction of the profile of a whole handrail.

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 11). The rendering of the scenes was done with the Raytracing technique. An example of the textured 3D model is shown in figure 12.

Figure 8: The 3D model of the Anatomy Theatre imported in Autocad as separate layers.
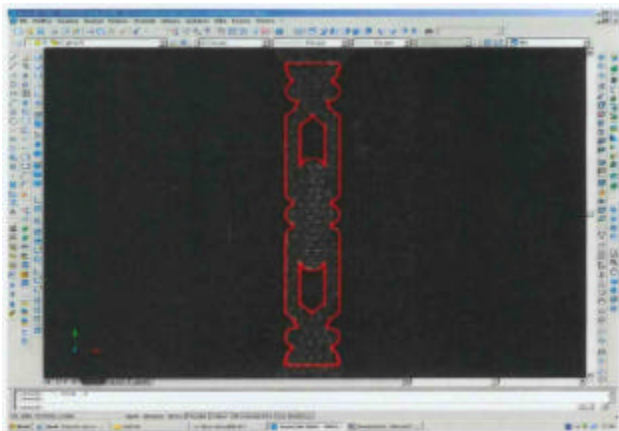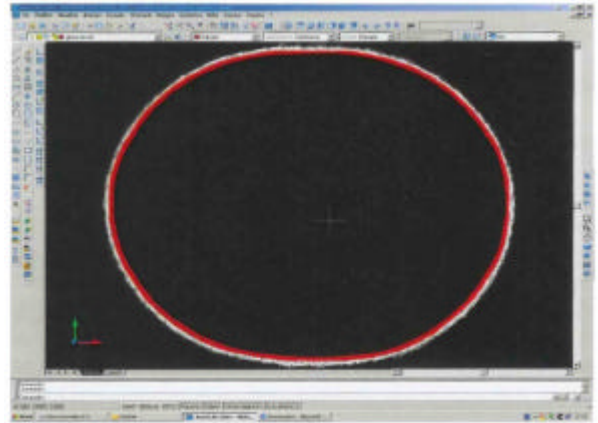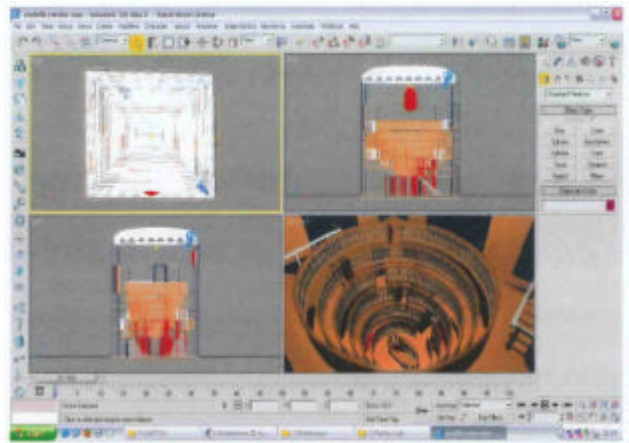

Figure 11: Model texturing and rendering in 3D Studio Max.

Figure 9: Example of the profile extraction procedure applied to an element of the balustrades.
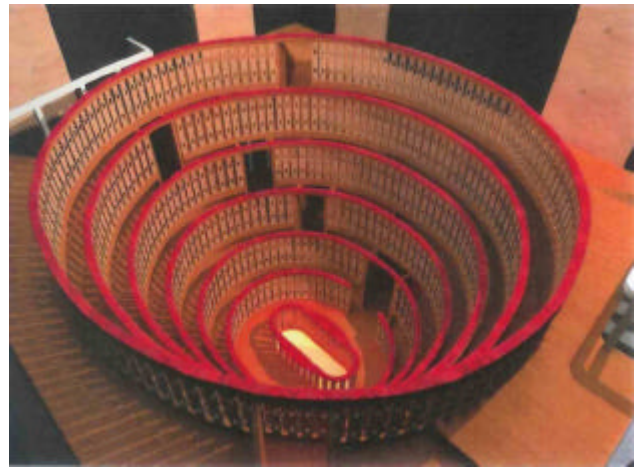

Figure 12: A perspective view of the rendered 3D model.

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 13) 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 refernce 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. Figure 14 shows the vertical displacements as derived from both the Leica HDS 3000 (green squares) and the Total station (red squares). In such figure, the Z coordinate of the center targets 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. Values obtained for the vertical displacements are also reported in table 1 for reader's convenience.
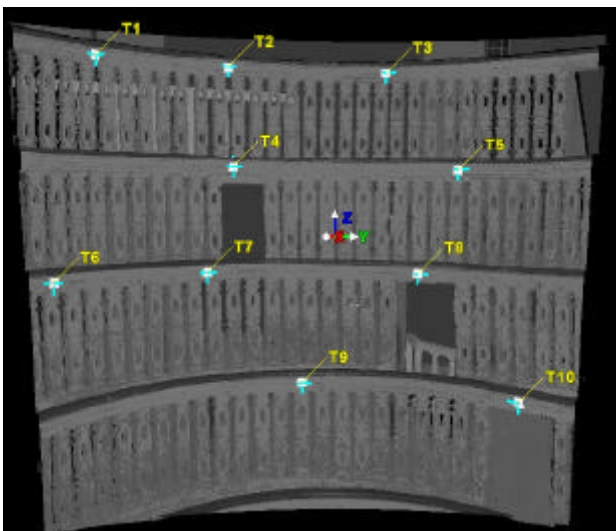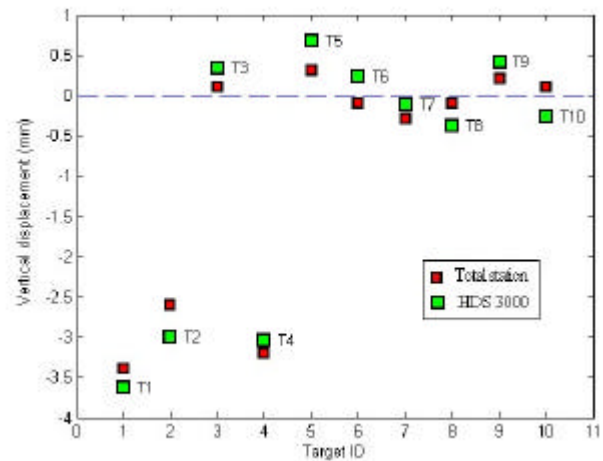

Figure 14: Vertical displacements computed by TLS and Total station measurements between survey 1 and 2.

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.

Table 1: Comparison between the vertical displacements derived by TLS and Total station measurerments

Target ID	Vertical displacements (mm)		Delta (mm) (TLS – Tot Stat)
	HDS 3000	Total station	
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

On second survey, performed for stability checking after six months, we placed a pair of deflectometers below the floor of the first level, in order to detect likely movements ranging between 0.01 and 0.1 mm, i.e at a level not detectable with laser scanner measurements (figure 15).

Figure 13: Location of the 10 targets used for stability control.

(a)

(b)

Figure 15: The deflectometers placed below the first floor.

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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5. 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