HEALTH MONITORING OF COMPLEX STRUCTURE USING TLS AND PHOTOGRAMMETRY

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ABSTRACT:

The demand for high-definition surveys within cultural heritage projects represents one of the main factors which promoted the use of laser scanning technology and photogrammetry. By measuring millions of points within relatively short time periods, terrestrial laser scanners allow to derive complete and detailed 3D models of real objects from acquired point clouds. Despite the wide spread of Terrestrial Laser Scanning (TLS) technology, the use of such systems for stability control is still a research field not much investigated. In the view of in-depth 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, total station (TS) and photogrammetry are being employed to survey the historical building *Olympic Theatre*, in Vicenza. Known as the oldest surviving enclosed theater in the world, this structure was constructed in 1580-1585 by Andrea Palladio, one of the greatest architect of the Italian Renaissance. The main goal of this work is to analyse and verify the stability over the time of this kind of structure by applying the Finite Element Methos (FEM) analysis to a highly detailed 3D model of the Theater. A few surveys of the Theater have been carried out with consumer digital-reflex camera Nikon D200, Leica Laser Scanner HDS 3000 and Leica Total Station TCR 705 in order to derive a complete 3D model.
This paper presents the results obtained from these surveys and highlights issues and difficulties related to the application of laser scanning and photogrammetry to an unusual and complex geometry such as the Olympic Theater in Vicenza.

1. INTRODUCTION

A great number of papers have been so far published about the comparison and the integration between laser scanning and digital photogrammetry as surveying and 3D modeling techniques. Most of the works report about their application to Cultural Heritage. A wide variety of objects - like small and large statues, historical buildings, whole archaeological sites - have been scanned and modeled for different purposes such as preservation, as-built documentation, reconstruction and museum exhibitions. Achieved results have shown that these two technologies can supplement each other in creating high-quality 3D recordings and presentations. Laser scanning can produce the dense 3D point-cloud data that is required to create high-resolution geometric models, while digital photogrammetry is more suited to produce high-resolution textured 3D models representing just the main object structure. In many cases, fusion or integration of both surveying techniques are regarded only as the application of digital images onto the laser scanning-based 3D model and/or the production of orthophotos. However some exceptions to this common approach should be mentioned. For example in (Guidi et al., 2003) and in (Vozikis et al., 2004) the photogrammetric survey is used, with different strategies, to improve the point cloud registration. Digital images have been also used to extract information on edges and linear surface features in order to bridge gaps in the laser scanner data and to add new details to improve the realistic perception of the scene (Alshawabkeh et al., 2004). Despite the wide use of TLS systems in several applications, their employment for stability control is still a research field not much investigated.
In the view of an in-depth investigation on this topic, a three-years project has been established with a twofold objective. First, the generation of a virtual 3D representation of a complex historical structure through the integration of digital close-range photogrammetry and terrestrial laser scanning. Second, the generation of a TLS-based 3D model suited for the application of FEM analysis to the stability control of the building. To this aim the *Olympic Theatre* in Vicenza was fully surveyed with both measuring techniques. In 2004 authors carried out a similar project for the survey of the ancient church of Pozzoveggiani, located in the surrounding of Padua (Italy), which was however featuring a simple geometry composed by both planar and curved surfaces (Guarnieri et al., 2004).
This paper presents the results obtained from these surveys and highlights issues and difficulties related to the application of laser scanning and photogrammetry to an unusual and complex geometry such as the *Olympic Theatre* in Vicenza.

2. THE OLYMPIC THEATRE

The *Olympic Theatre* of Vicenza (northern Italy) represents a majestic and most valuable symbol of the Palladian architectonic art, and it is today the most ancient existing covered theatre in the world. This, together with its unique scene and artistic characteristics, makes it one of the most important Italian and world-wide architectonic jewels.
The Theatre was constructed between 1580 and 1585 and it is recognized as one of the highest masterworks of the Italian Renaissance architect Andrea Palladio.

The *Olympic Theatre* is formed of four parts: the cavea, the orchestra, the proscenium, meant as the public square of the Greeks, the agorà, and the fixed scenes (Figure 1).

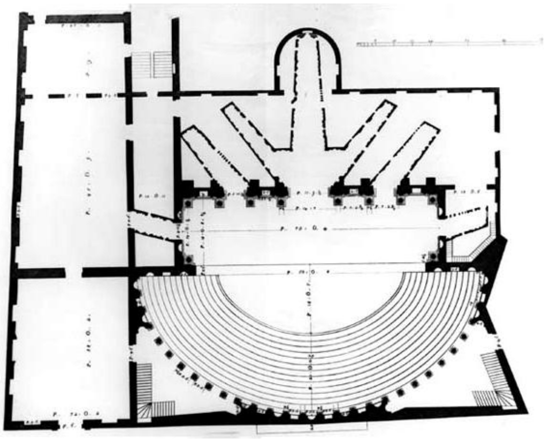

Figure 1. *Olympic Theatre* floor plan.

Palladio, deep connoisseur of ancient texts and their masterpieces, began working on the prestigious site but died in 1580 a short time after the work was entrusted. Despite this setback, the construction continued, with Palladio's sketches and drawings serving as a guide, and Palladio's son, Silla, taking charge of the project.
The front part of the scene forehead opens through the great Arch of Triumph (Figure 2), and beyond the openings it is possible to reach the streets of an imaginary Thebes from very evocative corners. This wonderful scenery was created by another prominent Vicentine architect, Vincenzo Scamozzi, who took over the entire project of Palladio, concluding the work of Silla.

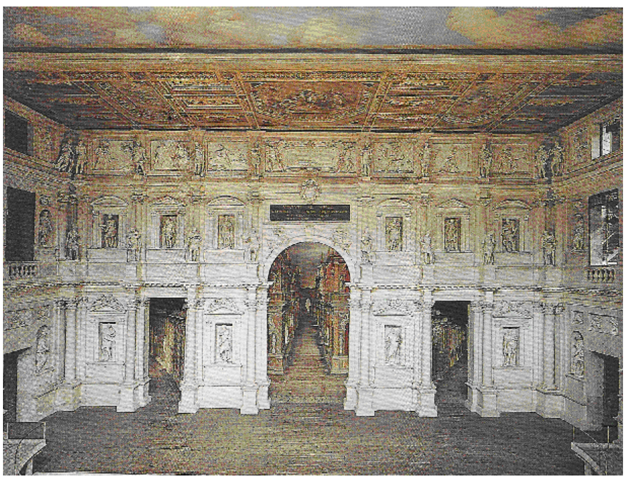

Figure 2. Oly*mpic Theatre* stage-set.

Scamozzi's stage set was the first practical introduction of perspective views into Renaissance theatre. The scenery consists of seven hallways decorated to create the illusion of looking down the streets of a city from classical antiquity. Ancient Thebes, was to be the setting for the first play staged in the theatre. A set of seven extraordinarily realistic *trompe-l'œil* false perspectives provide the illusion of long street views, while actually the sets recede only a few meters (Figure 3). The way in which seats in all parts of the theatre were provided with at least one perspective view can be seen by observing the theatre floorplan (Figure 1) and following the sight lines of audience members in different parts of the theatre.
Since 1994, the *Olympic Theatre*, together with other Palladian buildings in and around Vicenza, has been part of the UNESCO.

Figure 3. Detail of the wood-and-plaster stage scenery designed by Vincenzo Scamozzi.

3. DATA COLLECTION

Considering the twofold objective of this work the *Olympic Theatre*, was surveyed by means of close-range digital photogrammetry and terrestrial laser scanning, as described in the following subsections.

3.1 Photogrammetric data acquisition

High-resolution digital images of the theatre were captured for photogrammetric processing using a *Nikon D200* digital reflex camera. This is a 10.2 Mega pixels CCD camera with a sensor size of 23.6 x 15.8 mm. About 150 images were collected in one day, setting the image resolution at the highest level (3872 x 2592) in order to acquire good quality textures.
Standoff distance ranged between 5m and 40m according to the geometry of the building and the need to get at least an image overlap of 50%.
During photogrammetric data collection, coordinates of 38 ground control points (GCP) were measured with a reflectorless total station (*Leica TCR 705*), as well. These points have been employed both for the photogrammetric processing and for the merging of the laser scanning 3D model with the one produced with the photogrammetric data.

3.2 Laser scanning data acquisition

The survey of the interior of *Olympic Theatre* was performed with the high precision TLS Leica HDS 3000 owned by Cirgeo. This scanning system, based on Time-Of-Flight measuring principle, allows for a large Field of View (360^o H x 270^o V) thanks to the adoption of a dual-window structure. It ensures a low beam divergence (< 6 mm @ 50 m) and a good measuring accuracy (6 mm @ 50 m) at the same time. In addition to the intensity of reflected beam, the Leica HDS 3000 is able to

acquire RGB data at different resolutions (low, mid, high) through the 1 Megapixel built-in CCD camera.
In this work point clouds were acquired with different spatial resolutions ranging from 5 mm (statues, decorations, principal details) to 5 cm (macro-structure, structural elements). These values were chosen as an acceptable compromise between the level of detail of the 3D model and the computing resources needed for data processing. A total number of 35 scans were thoroughly collected in four days, resulting in a 70-million-point dataset. Most of the time was spent for moving the laser scanner between planned station positions: the narrow space (60÷100 cm) inside the scenery behind the proscenium made this operation very difficult.

4. DATA PROCESSING

In the first stage, the data collected from both surveying methods were processed independently resulting in two different 3D models. In the second stage, such models have been properly merged together exploiting the editing capabilities provided by Rhinoceros software, in order to achieve a unique virtual representation of the Theatre.

4.1 The 3D Model from Photogrammetric data

Prior to data capture, the camera interior parameters were recovered using the calibration tool of PhotoModeler Pro 5 software. To this aim 12 images of a predefined calibration grid were acquired from different viewpoints; during this stage 3 photos were captured with the camera rotated at 90^o around its optical axis in order to improve the accuracy of the estimate. Through the automatic recognition of 4 markers placed at the corners of the grid and the application of a Bundle Adjustment (BA) procedure, interior parameters were succesfully computed.
In order to reduce the processing time needed to create the 3D model from the 150 high resolution images (7 MB for each one), the work was subdivided in three different projects: P1 for the stage-set and ceiling decorations, P2 for the tiers (Figure 4), and P3 for the statues and scenes behind the tiers.
For each project, a first minimum set of matching points has been manually selected among adjacent images and the corresponding relative orientation was computed. Subsequently, further geometric features – such as points, lines, corner and cylinders – were added to improve the level of detail of the resulting model. For each group of new added elements, a global BA procedure was applied in order to recompute the relative orientation and to reduce the residual error.

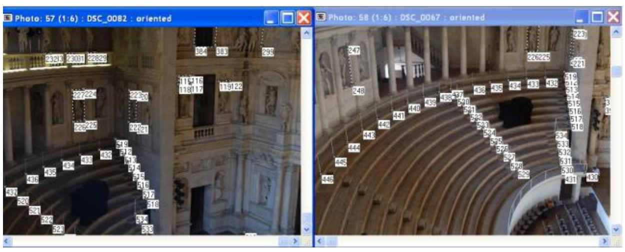

Figure 4. Example of matching point extraction.

Then, the 3 projects were merged together in Photomodeler by selecting a few points evenly distributed among the resulting partial models. Finally, the scale factor and the absolute orientation of the global model were computed using 3 GCPs measured with the Leica total station. Unfortunately, the transformation between the model reference frame and the one defined by the total station survey (absolute reference frame) could be estimated with a limited accuracy, since Photomodeler allows to use only three GCPs.
Figure 5 shows the recovered camera poses, while Figure 6 shows a view of the whole photogrammetric model. As shown in the latter Figure, the Scamozzi's scenery has not been modeled given the extreme complexity of its decorations.

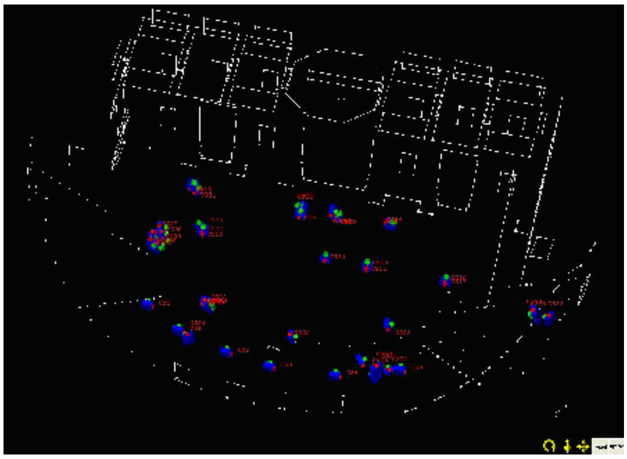

Figure 5. Recovered camera poses.

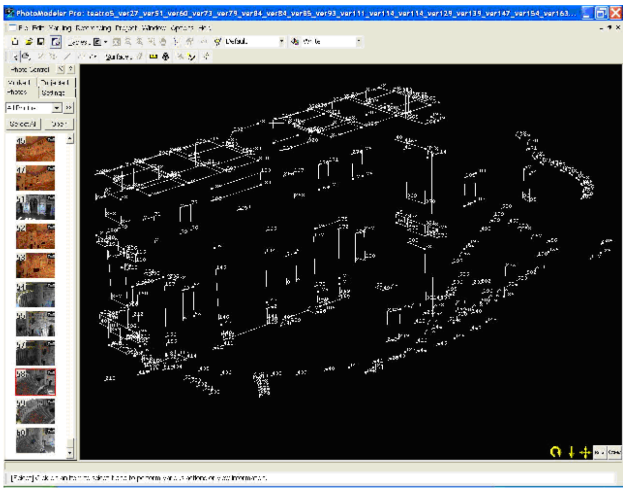

Figure 6. View of the photogrammetric model.

4.2 The 3D Model from laser point clouds

In order to produce a polygonal model, the Leica software Cyclone was used to align and merge the range data. The registration of all scans was performed according to a two-steps approach. First the range data were aligned pair by pair with manual selection of the matching points between two or more scans (Figure 7), then an ICP-based global alignment was applied to the whole dataset. The latter procedure allows for a more uniform distribution of the residual registration error across the scans with respect to a simple pairwise approach, as described in several works (Besl et al., 1992; Bergevin et al. 1996; Pulli, 1999). At the end of this processing stage, a residual RMS error of about 7 mm has been obtained. 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 3D model is shown in Figure 8.

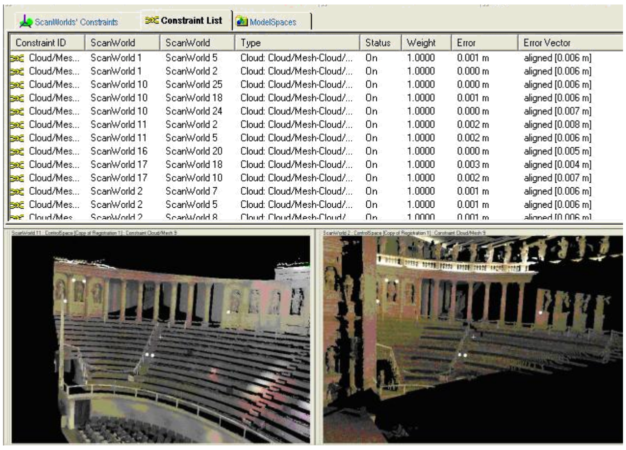

Figure 7. Pairwise scan alignment.

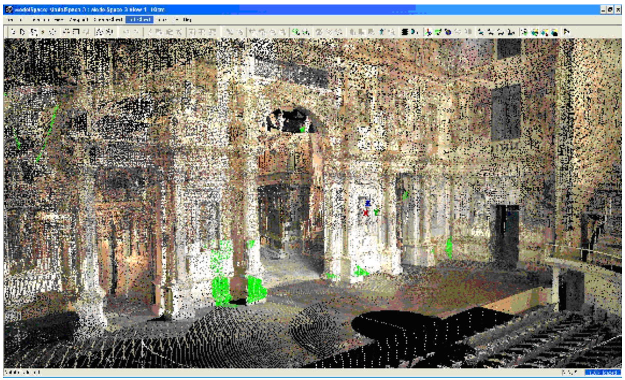

Figure 8. The laser scanner 3D model.

5. DATA FUSION

In most published works the concept of "integration" or "combination" of 3D models derived from photogrammetry and laser scanning is regarded basically in two ways: as texture mapping of the meshed TLS model or, conversely, as production of orthophotos using the aligned and triangulated point clouds as a DEM.

Here data fusion is aimed to create a unique 3D virtual representation where photogrammetric and laser scanning data are merged together so that the final product can be seamlessly explored. With this approach the 3D modeling applied to Cultural Heritage can benefits of the use of both surveying techniques. For example, in the case of historical buildings, such as the *Olympic Theatre*, 3D information about enough regular portions of the structure can be derived from photogrammetry, while more interesting architectural details and areas with higher surface curvature (statues, Scamozzi's scenery, etc.) can be reconstructed from laser scanning data.

In order to properly combine the two models in one product, a common reference frame was defined using the total station measurements. The photogrammetric and the TLS 3D models were georeferenced in this common frame according to a method developed in a previous work (Guarnieri et al., 2004). Basically the transformation parameters were estimated using the quaternion representation applied to 8 GCPs measured with the total station. The same points were also identified on the photogrammetric and on the laser scanner 3D model. The unified model was then imported in Rhinoceros and edited in order to create or rebuild those parts of the building which could not be properly imaged or surveyed with the laser scanner given their geometry and position with respect to the data capture stations.

6. FEM ANALYSIS

The second objective of this work was to perform a stability control for the *Olympic Theatre* through FEM analysis. To this end the laser scanner 3D model was subsampled with a 5 cm decimation step. This data reduction was a necessary step because FEM softwares currently available on the market are not optimized to manage large amounts of points, such those typically obtained from TLS surveys.

After that the 3D model was triangulated in Geomagic software, getting a mesh of about 1.944.200 triangles (Figure 9) and then imported in Strauss, for FEM analysis.

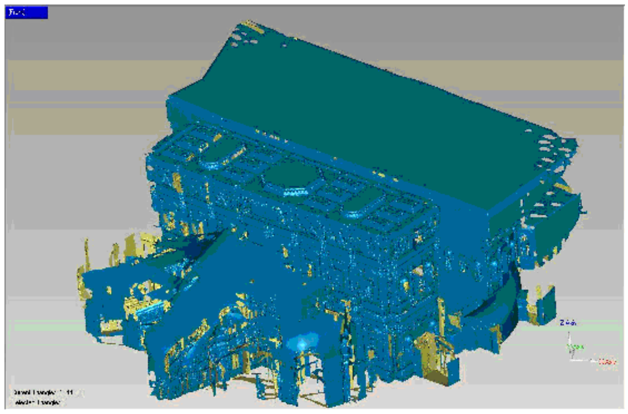

Figure 9. 3D model triangulated in Geomagic software.

In this environment, all the triangular surfaces (*plates*) were assigned the same physical-mechanical properties: continuous and homogeneous stonework structure of 30 cm thickness for the Theatre walls, continuous and homogeneous marble structure of 5 cm thickness for statues and parapets, continuous and homogeneous larch structure featuring a 3 cm thickness for tiers, stage set and Scamozzi's scenery.

Regarding the degrees of freedom (DOF), the structure has been considered fixed to the ground, by removing all the DOFs of the nodes (triangle vertices) placed at the bottom of the model, as shown in figure 10 (violet points). A force of 2.5 N/m^2, acting along the vertical Z axis, was then applied to each plate of the 3D model shingle in order to simulate the effect of snow accidental weight (green arrows).

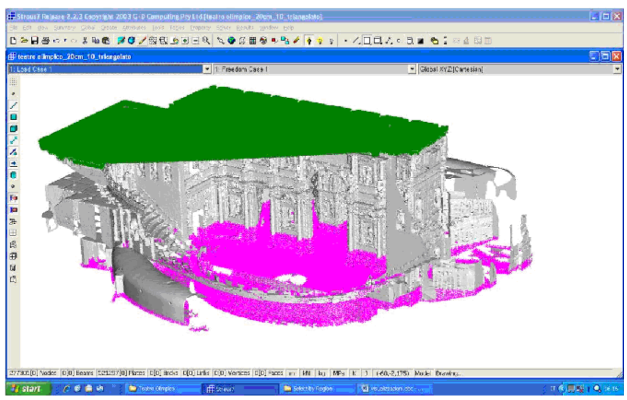

Figure 10. Degrees of freedom (violet point) of the 3D model and forces applied on shingle (green arrows).

According to Italian regulations and to the assigned load, two different kinds of analysis were carried out:

1. *Static Analysis*, from which charts for Stress Plate and for Plate Moments have been derived. This analysis is performed in Strauss through following steps: *Model Linear Static Analysis*, *Model Linear Buckling Analysis*, *Non Linear Static Analysis*. All these computations were done considering the structure own weight and the snow accidental weight.

2. *Dynamic Analysis*, which simulates the effects on the structure of an earthquake, taking into accounts structure and snow accidental weights and wind effect. As the city of Vicenza belongs to the earthquake zone 4 (low seismic probability), we applied a quake with higher seismic degree (seismic zone 3).

The results of the *Static Analysis* are presented in Figure 11, while deformation results of the *Dynamic Analysis* were evaluated through animated videos.

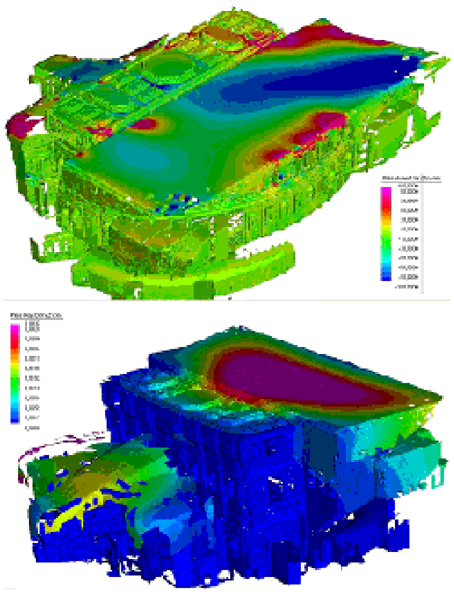

Figure 11. Results of the *Static Analysis* applied to the laser scanner 3D model of the *Olympic Theatre.*

7. CONCLUSIONS

This paper presents the results of the combination of digital photogrammetry and terrestrial laser scanning for the generation of a 3D model of a complex historical building. These models were use for a twofold goal: the generation of a textured model to be used in virtual reality applications, and the application of FEM analysis for the stability control of the building.
To this aim the Olympic Theatre in Vicenza was surveyed with a high resolution Nikon D200 prosumer digital camera and with a Leica HDS 3000 terrestrial laser scanner. Concerning the virtual representation of the Theatre, a proper data acquisition procedure was adopted in order to better exploit the surveying capabilities provided by both surveying techniques: the main structure of the building was determined by image-based method while fine details (statues, marble parapets and more complex scenes) were modeled by range data. Conversely, the FEM analysis was carried out just on the laser scanning data. As discussed, the corresponding 3D model needed specific processing in order to obtain a suited dataset for the stability control.

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REFERENCES

Alshawabkeh Y., Haala N., 2004. Integration of Digital Photogrammetry and Laser Scanning for Heritage Documentation. Proc. of *XXth ISPRS Congress***,** *Volume 35, Part B***, I**stanbul, Turkey.

Beraldin J. A., 2004. Integration of Laser Scanning and Close-Range Photogrammetry - The Last Decade and Beyond. *Proc. of XXth ISPRS Congress***, Is**tanbul, Turkey.

Bergevin R., Soucy M., Gagnon H. and Laurendeau D., 1996. Towards a general multi-view registration technique. *IEEE Trans. Patt. Anal. Machine Intell.*, 18(5):540–547.

Besl P. J., McKay N. D., 1992. A method for registration of 3-D shapes. *IEEE Trans. Patt. Anal. Machine Intell.*, 4(2): 239–256.

El-Hakim S., Beraldin A., Picard M., 2002. Detailed 3D reconstruction of monuments using multiple techniques. In *ISPRS/CIPA International Workshop on Scanning for Cultural Heritage Recording*, Corfu, Greece, pp.58-64.

Fraser, C.S., Riedel, B., 2000. Monitoring the thermal deformation of steel beams via vision metrology *Journal of Photogrammetry and remote Sensing*, 55, 268-76.

Guarnieri A., Remondino F., Vettore A., 2004. Photogrammetry and Ground-based Laser Scanning: Assessment of Metric Accuracy of the 3D Model of Pozzoveggiani Church. *Proc. of FIG Working week 2004, “The Olympic Spirit in Surveying”,* Athens, Greece.

Guarnieri A., Remondino F., Vettore A., 2006. Digital photogrammetry and TLS data fusion applied to Cultural Heritage 3D modeling. In *Proc. of ISPRS Comm. V Symposium “Image Engineering and Vision Metrology”,* Dresden, Germany.

Guarnieri A., Milan N., Vettore A., 2008. Combined tecniques for the stability control of historical structures. *13th FIG International Symposium on deformation measurement and Analysis*, Lisboa, Portugal.

Guidi G., Beraldin J.-A., Ciofi S., Atzeni C., 2003. Fusion of range camera and photogrammetry: a systematic procedure for improving 3D models metric accuracy. *IEEE Trans. on Systems, Man, and Cybernetics*.

Pulli K., 1999. Multiview registration for large data sets. *Proceedings of 3DIM 99*.

Remondino F., Guarnieri A., Vettore A., 2005. 3D modeling of close-range objects: Photogrammetry or Laser Scanning ? *Proc. Of IS&T/SPIE 17th Annual Symposium, Electronic Imaging,* San Josè, California.

Remondino F., Fraser C., 2006. Digital camera calibration methods: considerations and comparisons. *Proc. of ISPRS Commission V Symposium,* Dresden 2006.

Valzano V., Bandiera A., Beraldin J.-A., Picard M., El-Hakim S., Godin G., Paquet E., Rioux M., 2005. Fusion of 3D Information for Efficient Modeling of Cultural Heritage Sites with Objects. In *CIPA 2005 XXth International Symposium: Cooperation to Save the World's Cultural Heritage*, Torino, Italy.

Vozikis G., Haring A., Evangelos Vozikis E., Kraus K., 2004. Laser Scanning: A New Method for Recording and Documentation in Archaeology. *Proc. of FIG Working week 2004, "The Olympic Spirit in Surveying"*, Athens, Greece.

Raindrop Geomagic, http://www.raindrop.com (accessed on 31/03/2010).

Strauss, http://www.hsh.info (accessed on 31/03/2010).