3D SURVEYING FOR STRUCTURAL ANALYSIS APPLICATIONS

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Abstract

The plenty of works presented in last two years about the use of 3D models in the field of Cultural Heritage witness the great interest of surveyors, engineers, architects and archaeologists towards the laser scanning technique as an invaluable surveying mean for as-built documentation, digital archiving and restoration of important elements belonging to our historical and cultural heritage. Usually, the end products are represented by VR models (Vrml, Flash), suited to be shared among different user across the Internet, stunning movies (Avi, Mpeg, Divx), showing the 3D geometry of various objects, even phisically located in remote sites, embedded in a unique virtual environment, textured DSMs (Digital Surface Models) of both large and small size artistical pieces (e.g. churches, ancient buildings, statues, basrelieves, etc.) and orthophotos. Such wide variety of applications demonstrate that 3D models allow the user to retrieve different information contents from a unique digital representation of the reality, what is a topic not yet fully investigated.
In the context of information retrivial from laser scanning data, this paper focuses on the use of TLS-based 3D models for structural analysis applications. To this aim an historical building, located in the city of Padua (Italy), was surveyed with the Leica HDS 3000 laser scanner for the generation of a complete 3D model of the object. Acquired point clouds were then registered in Polyworks and corresponding results were compared with the ones obtained by the application of Procustes Analysis algorithms, in order to verify the effectiveness of such registration method. Afterthat a few cross sections have been extracted from a building's wall, presenting a few visible crackings, and employed for a FEM based structural analysis.

Keywords: 3D model, TOF Laser scanner, FEM analysis.

1. Introduction

Since early '90s terrestrial laser scanners (TLS) have been increasingly spreading out on the market as an efficient alternative 3D measurement system with respect to photogrammetry and/or geodetic methods. Given their 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 allowed laser scanning technology to start to dominate the market in a variety of applications such as automotive and mining industry, mechanical engineering, as-built documentation for both industrial plants and historical buildings, archaeology and architecture. In this context, 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 has increased remarkably in recent years. 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 such purposes as preservation, reconstruction, study, and museum exhibitions.
However, in most of the works presented in last two years about the use of 3D models in the field of Cultural Heritage, the end products have been limited to visually pleasant representations of surveyed objects, while only few ones addressed the problem of a metric analysis of such models. In this sense we can account for papers reporting the generation of VR models (Vrml, Flash), suited to be shared among different user across the Internet, stunning movies (Avi, Mpeg, Divx), showing the 3D geometry of various objects, even phisically located in remote sites, embedded in a unique virtual environment, textured DSMs (Digital Surface Models) of both large and small size artistical pieces (e.g. churches, ancient buildings, statues, basrelieves, etc.) and orthophotos. Such wide variety of applications demonstrate that 3D models allow the user to retrieve different information contents from a unique digital representation of the reality, what is a topic not yet fully investigated.
As contribute to the topic of information retrivial from laser scanning-based 3D models, in this paper the use of a TLS-based 3D model for structural analysis applications will be discussed. To this aim, an old venetian villa located in the city of Padua, Villa Giovanelli (Fig. 1), has been surveyed with a Leica HDS 3000 laser scanner for the generation of a 3D model of the whole building. Acquired point clouds were then registered with Polyworks software and the results of this modeling stage were compared with the ones obtained by the application of Procustes Analysis algorithms, in order to verify the effectiveness of such registration method when applied to TLS-based 3D models. Afterthat a few cross sections have been extracted from a wall of the villa, where the outer surface is affected by a a few cracks, in order to investigate and evaluate the use of TLS data to perform a FEM- based structural analysis.

Figure 1: View of the front side of Villa Giovanelli

The paper is structured as follows. Section 2 provides a short description of the data collection step while focuses more on the results of the scan global alignment, performed both with Polyworks software and with the Procrustes Analysis. In section 3 preliminary results of the FEM-based structural analysis are presented and finally conclusions are discussed in section 5.

2. Data collection & registration

The survey of outer walls of the venetian villa was performed with the newest high precision Leica HDS family product (Fig. 2), i.e. the Leica HDS 3000 laser scanner, currently owned by Cirgeo. 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), as in previous laser system (formerly Cyrax) 2500. Furthermore, beside intensity of reflected beam the HDS 3000 is able to acquire RGB data at different user selectable pixel resolutions (low, mid, high), through the 1 Megapixel built-in CCD camera.
Point clouds were acquired with a spatial resolution of 1 cm, this value was chosen as an acceptable compromise between level of detail of the final 3D model and computing resources needed for data processing. Thoroughly 26 scans were collected in different days, resulting in a 30 million points aligned 3D model, whose partial view is shown in figure 2.
The scans were processed in Polyworks software according to the following scheme: in the first step range data were aligned pair by pair, then a ICP-based global alignment was applied to the whole dataset. The latter procedure was required in order to distribute the residual registration error more uniformly across the scans, respect with a simple pairwise approach, as described in several works (Besl et al., 1992; Bergevin et al. 1996; Pulli, 1999).

Figure 2: Aligned 3D model of Villa Giovanelli

Beside the several approaches currently adopted for range data global registration, like the ICP algorithm (Besl and McKay, 1992) and its multiple variants or the least squares 3D surface matching (Gruen et al., 2004), an alternative procedure is represented by the Procrustes Analysis, PA, (Beinat et al., 2001). This method avoids the linearisation of equation systems and large matrix inversions through the use of singular value decomposition (SVD) of matrices of order 3 x 3, thus determining a fast and easy software implementation. Moreover, no prior information is requested for the geometrical relationship existing among the different model objects components, which can be expressed independently into their own reference system; only identical corresponding points are needed for the alignment. The method lacks of reliability criterium to detect blunders and gross errors but it can handle global and simultaneous registrations (Generalised Procrustes Analysis) and not only simple pairwise registrations. The Extended Orthogonal Procrustes (EOPA) algorithm, adopted in this work, is an extension of the least square method originally developed by (Schoenemann, 1966) for the estimate of the rotation between two datasets, called Orthogonal Procrustes Analysis (OPA). This generalization, firstly given by Schoenemann and Carroll (1970), allows to compute pairwise in a least square sense not only the unknown rotation, but also the translation and scale factor. In order to verify the effectiveness of the Procrustes Analysis for the alignment of terrestrial laser scanning data, a preliminary test was undertaken by comparing the results of the pairwise registration performed in Polyworks with the ones obtained from the EOPA method, applied to a few scans of the walls of Villa Giovanelli. As shown in Table 1, only 4 scans were used for this test and for each scan pair about 10 matching points were manually selected. The difference between the RMS results can be explained considering that the registration algorithm implemented in Polyworks is based on a ICP variant, therefore it uses not only a first set of matching points selected by the user but all of the overlapping points existing between the two datasets, while the EOPA method works just on the first point set. Though both methods adopt a least square approach, the capability provided by Polyworks to increase the number of initial correspondences, exploiting the overlap areas, allows for stronger reduction of matching errors wrt. to the EOPA method.

Table 1: Comparison results

N. of scans	N. of selected matching points	RMS - Polyworks	RMS - EOPA
4	30	8 mm	14 mm

3. 3D model structural analysis

As mentioned at the beginning of this paper, 3D models of cultural heritage objects have been mainly considered so far in terms of data sources for as-built documentation, archiving and restoration purposes. However in our opinion, they comprise a larger information content, allowing them to be profitably used in a wider number of application fields. In order to demonstrate the validity of this assertion, in this section we report the preliminary results of a FEM-based structural analysis performed on a wall of the east side of the villa, on which a few crackings are visible at short distance (Fig. 3 and 4).
The advantage of the use of a laser scanner-based 3D model for structural analysis investigations is mainly represented by the availability of a highly detailed representation of the object's geometry, which allows for a better estimate of the stressing states. Tipically, structural investigation tools can be related to the following two main groups: traditional static analysis and Finite Element Methods (FEM). The latter seems to be more suited for complex structures, as it provides several advantages, among which we recall the option to work in a 3D space, to perform different kind of analysis (linear, non-linear, dynamic, etc.) and to test specific features of the structure with a stepwise approach. On the other hand FEM analysis doesn't allow to estimate the plausible response in the case of elements that are non-stressing resistant.

A few cross-sections extracted from the 3D model of the wall were imported as DXF in the Straus software, considering a 40 cm section depth, subdivided according to a series of 4-node elements (Plate) of 10 cm each. A linear static analysis was performed on such cross-sections, aimed to study the response of the wall structure to the different effects of the weight and the off-plumb line. Corresponding results related to a cross-section sample are shown in figures 5 and 6 respectively.

Figure 3: Partial vew of the east wall

Figure 4: close-up view of the cracking marked by the red circle on the left

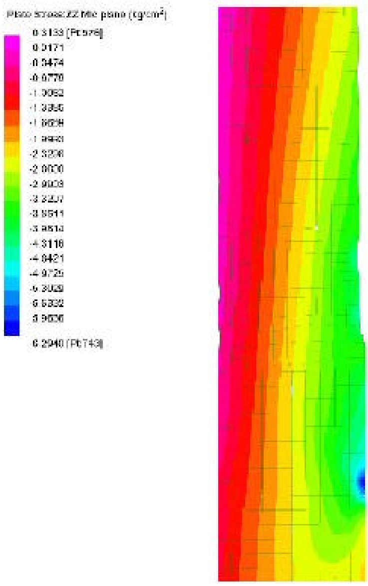

Figure 5: Effects of the weight

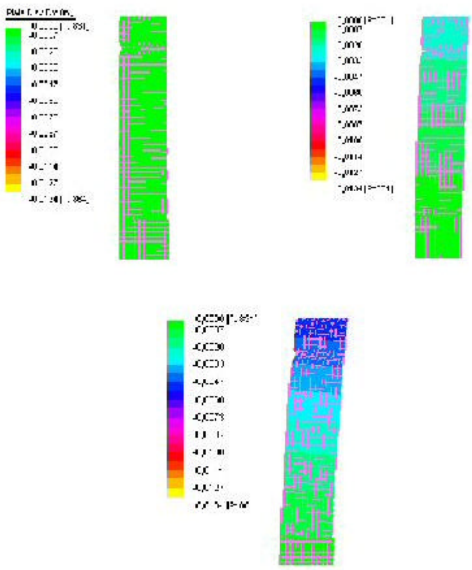

Figure 6: Effects of the off-plumb line

5 Conclusions

In this paper a work related to 3D model-based structural analysis on a structure belonging to the Cultural Heritage has been presented. Namely, the outer walls of Villa Giovanelli, an old venetian villa located in Padua, was surveyed with an high precision terrestrial laser scanner. During the modeling stage, a global alignment of acquired scans was performed employing two different methods: through the registration tool provided by Polyworks modeling software and by application of the Procrustes Analysis algorithm. Different results obtained in terms of RMS can be ascribed to the alignment procedure implemented in Polyworks, which uses not only the initial matching points, provided by the user, but also all of the point belonging to the overlapping areas. Preliminary results related to the structural analysis of the east-side wall of the villa have been presented, as well. The study is current under development and it is aimed to detect the areas of the wall requiring most important consolidation works due to the presence of a few differently sized cracks.

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References

Beinat, A., Crosilla, F., 2001. *Generalized Procrustes analysis for size and shape 3-D object reconstructions*. In: Gruen, A., Kahmen, H. (Eds.), Optical 3-D Measurements Techniques V, Vienna, pp. 345-353.

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.

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.

Gruen A., Akca D., 2004. Least squares 3D surface matching. *Int. Arch. of Photogrammetry and Remote Sensing*, Vol. 34(5/W16), Dresden, Germany.

Leica Geosystems, 2004. The HDS 3000 technical specifications. http://www.leicageosystems.com.

Lissitz R.W., Schoenemann P.H., Lingoes J.C., 1976. A solution to the weighted Procrustes problem in which the transformation is in agreement with the loss function. *Psychometrika,* 41(4), pp. 547-550.

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

Schoenemann, P.H., Carroll, R., 1970. Fitting one matrix to another under choice of a central dilation and a rigid motion. *Psychometrika*, 35(2), pp. 245-255.