EXPERIMENTS ON DEFORMATION MEASUREMENTS OF “HELSINKI DESIGN WEEK 2005” INFO PAVILION

Petri Rönnholm[a], Petteri Pöntinen[a], Milka Nuikka[a], Antti Suominen[a], Hannu Hyyppä[a],
Harri Kaartinen[b], Ilmari Absetz[a], Hannu Hirsi[a], and Juha Hyyppä[b]

[a] Helsinki University of Technology, P.O. Box 1200, FI-02015 TKK, Finland – first.lastname@tkk.fi
[b] Finnish Geodetic Institute, Geodeetinrinne 2, P.O. Box 15, FI-02431 Masala, Finland – first.lastname@fgi.fi

Commission V

KEY WORDS: terrestrial laser scanning, close-range photogrammetry, construction quality, deformation, CAD/CAM, load test

ABSTRACT:

The ”Helsinki Design Week” info pavilion is an example of a challenging mass customisation based industrial construction planned with CAD techniques. The final pavilion was modelled using both close-range photogrammetric methods and terrestrial laser scanning. The as-built model was compared to the design model revealing the maximum difference of 0.035 m. Two load tests (20 and 100 kg) were arranged to simulate low and moderate snow loads on a roof structure and to arrange two different loads versus deformation cases for measurements. Both modelling methods yielded similar result indicating that the 20 kg load did not cause significant deformations to the pavilion. In the case of 100 kg load, the rim arcs kept their shapes well, but some deformations was found from the shell structures. The results from photogrammetry and laser scanning were compared and both methods had some advantages and disadvantages. The strength of photogrammetry was more accurate alignment when corners were measured and the strength of the laser scanning was the more complete surface model. In our case, the photogrammetric models were measured from free-network image blocks. One model appeared to have some distortion along the z-axes. The disadvantages with laser data included difficulties to measure accurate corner points and the strong deformation of reference spheres in moist conditions.

1. INTRODUCTION

The “Helsinki Design Week 2005” (HDW) info pavilion is an example of a complex structure using the advantages of glass and plywood (Figure 1). The glass surface consists of 135 glass triangles enchased with plywood ribs. The glass functions as a stressed skin; the triangles of plywood prevent the glass from bending and the free-shaped rim arcs supply the load to the base (Lehto and Seppänen, 2005).

Figure 1. “Helsinki Design Week 2005” info pavilion.

The HDW Info Pavilion is a miniature of a challenging mass customisation based industrial construction. Every single glass triangle and plywood rib of the pavilion is unique. All of the parts have been modelled three dimensionally in the CAD model of the structure. Each part has been manufactured with an automated CNC-machining (computer numerical control) device controlled by the data from the CAD model and the whole design-manufacturing-process was highly automated. One point of interest was acquiring as-built information from the pavilion and to compare the realized structure to the design model.

As a natural hygroscopic material, wood is apt to deformations in shape and dimensions due to changes in humidity. Also exterior loads such as snow, wind and service loads cause deformations in building structures. Wood is a common material for load carrying building frame-structures as well as in interior and exterior surface-structures. Glass is also used frequently, especially in facades. The HDW pavilion has these two materials in a relatively complex and challenging form.

Another point of our interests of this portable structure was, how rigid the shape of the HDW is and how to detect the deformations when different loads were attached to the pavilion. For this task two measuring methods were selected: close-range photogrammetry and terrestrial laser scanning.

Close-range photogrammetry is a well-accepted tool for 3D measurements and commonly used in various tasks such as for cultural heritage documentation (Gruen et al., 2002), building restoration (Cardenal et al., 2005), deformation monitoring (Hampel and Maas, 2003; Gordon et al., 2004), and reconstruction tasks (Grussenmeyer and Yasmine, 2003; Harun and Ahmad, 2003; Schindler et al., 2003; Valiev, 1999). In the most advanced applications, the 3D-model can be created from an image sequence with a minor human interaction (Werner et al., 2001; Pollefeys et al., 2000). Currently, it is easy to get off-the-shelf digital cameras, calibrate them and use existing photogrammetric software for actual measurements.

In addition to the photogrammetric methods, terrestrial laser scanning has become an established tool for acquiring 3D models. Reported examples of applications include cultural heritage recording (Alshawabkeh and Haala, 2004), architectural modelling (El-Hakim et al., 2005; Schuhmacher and Böhm, 2005), building reconstruction (Lee and Choi, 2004), as-built documentation (Sternberg et al., 2004), forest modelling (Thies and Spiecker, 2004), and structural engineering (Guarnieri et al., 2005; Lindenbergh et al., 2005). With terrestrial laser scanners, the accuracy of individual sample points (eg. ±2 - ±5 mm) are lower than photogrammetrically acquired ones, but the model of a surface is much more accurate because of the dense point cloud (Gordon et al., 2004). The potential of combining close range photogrammetry and terrestrial laser scanning is to optimise the geometric accuracy and the visual quality of 3D data capture of scenes (Alshawabkeh and Haala, 2002).

The main objectives of this research included comparison of CAD plans with as-built models, measuring the temporal deformations of wooden structures of the HDW pavilion as a function of various sizes of loads and comparison of results obtained by terrestrial laser scanning with those obtained by close-range photogrammetric measurements.

The long-term scenario of this project is to develop and adapt modern ICT based 3D measurement techniques to model and verify the quality of construction projects and also measure the deformations in building structures.

2. MATERIAL

During the data acquisition, the HDW pavilion was situated in Lahti city. The main focus of observations was on interior parts, because the outer cover of the HDW pavilion was completely made from glass. Operating through the glass was expected to cause too much uncertainty for distance measurements and therefore outer cover was not included.

The applied terrestrial laser scanner was FARO LS 880 HE80, which is based on phase measurements providing high-speed data acquisition. Technical parameters of the scanner include maximum measurement rate of 120000 pulses/s, wavelength of 785 nm, vertical field of view 320° and horizontal field of view 360°, and linearity error of 0.003 m (at 25 m and 84 % reflectivity), see also www.faro.com. Accuracies and performances of various types of laser scanners have been reported earlier e.g. by Fröhlich and Mettenleiter (2004). Laser scanning was done from two positions using the half resolution for each three cases. The laser scanning data was post-processed with the Faro Scene 3.0 and the Geomagic Studio 8. The comparison between the CAD model and the photogrammetric model was done in the AutoCAD.

During the laserscanning, the weather conditions were not ideal. The temperature was only a few degrees above zero (Celsius) and the air humidity was high. During some scans, it was slightly raining. Similar weather conditions can be expected to be reality, when working on construction sites. Therefore, this example was a good experiment revealing some unexpected behaviour of the FARO laser scanner. These experiences are described more in detail in chapter 3.

The camera applied was Nikon D100 and the applied image size was 2240 by 1488 pixels. The camera was calibrated using calibration targets provided by the iWitness (Fraser and Hanley, 2004). One image block was acquired at each step of the load tests. The photogrammetric blocks were free-networks, leaving the possibility of scale deformations. In addition, the measured targets were natural such as corners. The interpretation problems of natural targets cause inaccuracies. Also the image block geometry was not optimal, because all images were taken close to same height level. However, the accuracy indicators after block adjustment were not alarming.

The borders of four triangles in the corners (Figure 2) from inside of the HDW pavilion were measured with a measuring tape in order to get an approximate scale for the photogrammetric model.

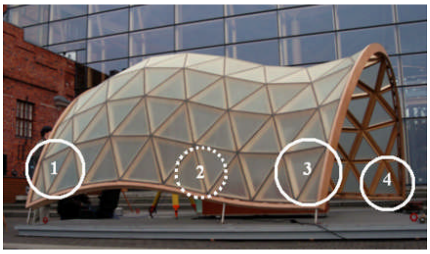

Figure 2. The dimensions of four corner triangles of the pavilion were measured in order to get approximate scale for the photogrammetric model.

3. METHODS

The initial state of the HDW pavilion was captured by the photogrammetric image block and by making two laser scans. The structure was loaded with a sand-filled sack lifted on the top of the pavilion (Figure 3, left). For another test a load of weights was hanged to the rim arc (Figure 3, right). The weights were 20 kg and 100 kg, respectively. After adding the loads, similar data acquisition as for initial measurements was carried out in order to get a comparable set of data.

Figure 3. Left: The HDW pavilion was stressed by lifting a 20 kg sand-filled sack on the top of the structure. Right: Another load test included 100 kg of weights hanging from one rim of the pavilion.

Image observations were added to the least squares block adjustment for solving image orientations. The adjustment was calculated using the iWitness software. An approximate scale of the model was defined using distances from measuring tape measurements. Later the scale difference between laser scanning data and photogrammetric point cloud was solved by the least squares method. The mathematical model was the 7-parametric transformation:

$$X_T = \frac{1}{\lambda} R(X - X_S)\,, \tag{1}$$

where X_T is the transformed 3D point, λ is a scale factor, R is a 3D rotation matrix, X_S is shift and X is the original 3D point. The scale was eliminated from the adjustment when comparing data sets from different load test phases in order to prevent deformations to adjust in the scale. 3D point clouds were not registered to the ground truth. Therefore, difference bars in Figures 11-14 are relatively correct, but they can include some uniform shifts.

The inner corners of plywood triangles (Figure 4) were observed from 3 to 8 images. In addition, the free-shaped rim arcs from the sides were measured. Overall RMS errors (1-sigma) for image measurements were 0.408 mm (initial state), 0.616 mm (the 20 kg load) and 0.575 mm (the 100 kg load). All photogrammetric blocks were free-networks without any reference points.

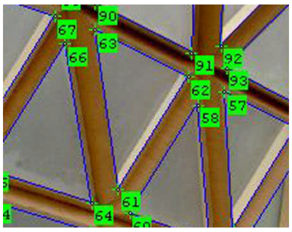

Figure 4. Detail of photogrammetric measurements.

Corresponding points, compared to 3D points from photogrammetric block, were extracted manually from laser scanning data (Figure 5). The corners of triangles appeared to be too uncertain for using breakline detection algorithms and planes were too narrow, noisy or badly oriented preventing automatic methods for accurate corner detection. Therefore, the small area close to a corner was selected and then the mean point was calculated. It would have been possible to adjust 3D points interactively at more accurate locations, but the time for the measurements would have increased significantly. It was assumed, if all points from laser data were chosen in the similar way, they would be comparable. The corner points were selected manually using the Faro Scene software.

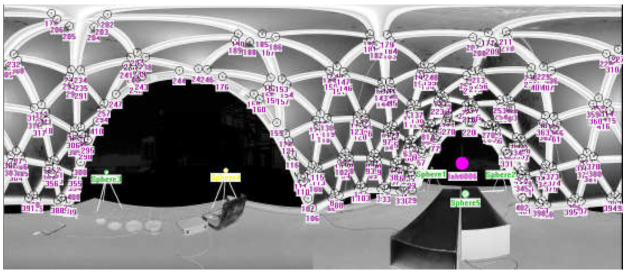

Figure 5. Corresponding points to photogrammetric measurements were selected from laser point cloud using the Faro Scene program.

An approximate registration of two laser scans was calculated using target spheres (Figure 6). The spheres under open sky were covered with humidity. This caused unexpected phenomena when the spheres were heavily distorted (Figure 6). Only very narrow belts of the correct surfaces of the spheres remained. The automatic fitting of spheres in the Faro Scene software failed to be accurate because of the distorted target spheres. Therefore, the registration was considered to be only an approximation. The displacement of registration was tested selecting small sample areas from two different scans. These laser data sets were imported in the Geomagic Studio 8. The point clouds were then transformed to surfaces. Finally, two surfaces were registered together revealing the mean shift of 0.012 m. The final registration was, however, calculated using common points extracted from laser data sets.

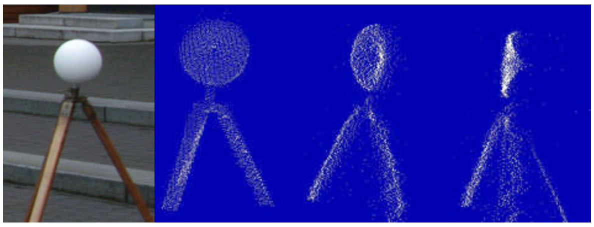

Figure 6. Moisture on the surfaces of the reference spheres caused the distance measurements to fail. The spheres were heavily distorted and the automatic adjustment of sphere object failed.

4. RESULTS

Totally six 3D models were measured from the HDW pavilion: three with photogrammetric methods and three with laser scanning. The first models with both methods were from the original shape of the pavilion and the next models, respectively, were with load on the structures. In Figure 7, examples of the models before load test are presented.

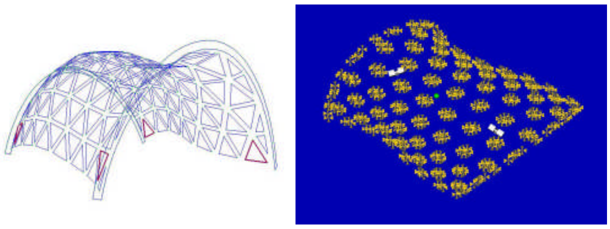

Figure 7. Left: Photogrammetric model of the pavilion. Right: Corresponding points extracted from laser scanning data. The locations of two laser scanner positions are visible. Both models are acquired before the load test.

The 3D point cloud from photogrammetric measurements was compared with the design model. The point clouds were registered using the least squares method. The photogrammetric model and corresponding CAD design model were visualized in the AutoCAD (Figure 8). The maximum difference was 0.035 m, the mean was difference 0.014 m and the standard deviation was 0.0065 m.

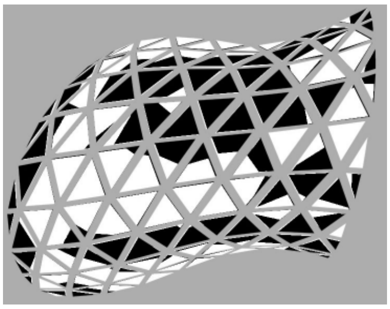

Figure 8. Visualization of aligned design (CAD, white) and as-built (photogrammetric, black) models.

Extracted 3D points from the laser scans were compared with the photogrammetric point clouds. After the registration, the behaviour of the residuals acted as expected. The locations of laser-derived corners were shifted, but very regularly according to the corner orientation (Figure 9). The results of all comparisons are gathered in Table 1. It must be noted that the laser scanner represents surfaces more accurately and the shifts were partly caused by difficulties to define accurate breaklines and corners from laser data.

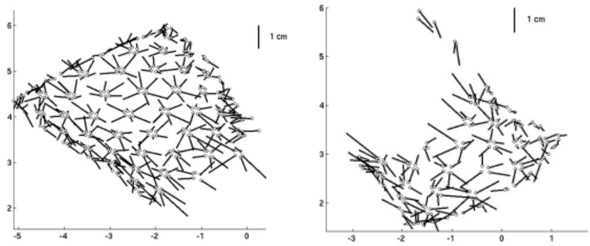

Figure 9. Perspective views of residuals from above of the pavilion Extracted 3D points from two different laser scans were compared with the photogrammetric point clouds. The residuals acted regularly according the corner orientation.

When two scans were registered together, no regular behaviour of residual vectors according to the corner orientation could be found anymore (figure 10). For the registration, common points were selected from two laser data sets. The mean residual vector length was 0.0057 m, the standard deviation was 0.0025 m and the maximum value was 0.012 m.

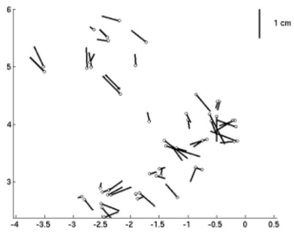

Figure 10. The residual vectors of common corners are acting randomly when two laser scan are adjusted. Residuals are multiplied with 50 in order to ensure visibility.

Table 1. The results of all comparisons.

	Total (mm)			z-direction (mm)		
	mean	std	max	mean	std	max
Laser init. – image init.	6.5	2.9	15.5	3.3	3.7	12.6
Image init. – Image 20 kg	2.7	1.5	8.9	1.2	1.1	7.9
Laser init. – laser 20 kg	3.6	2.1	10.4	1.7	1.5	7.8
Image init. – Image 100 kg	5.1	2.6	14.7	3.0	2.3	13.6
Laser init. – laser 100 kg	4.0	2.2	11.4	1.9	1.5	7.3

Photogrammetric and laser scanning measurements were compared also in z-direction. As expected, corner orientations and incident angles were visible from the residuals. On the upper parts of the pavilion, all corners are located nearly on the plane that is perpendicular to the z-axis. Therefore, the interpretation error had no significant affect to the z-residuals. However, on the vertical sides the corner orientation is significant. Residuals on horizontal corners were smaller than on vertical ones (Figure 11).

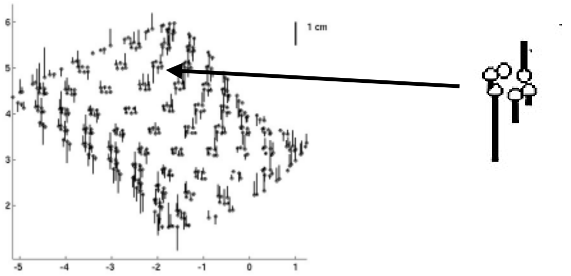

Figure 11. Residuals in z-direction when laser data and photogrammetric data were compared. Corner orientations are visible on residual pattern.

The photogrammetric observations and laser data were compared separately before and after the load test. The results are shown in Table 1. The residuals in z-direction are visualized in Figure 12. The photogrammetric inspection of the 20 kg load test case did not reveal significant deformation on the HDW pavilion. Neither the laser scanning showed clear deformations. The variation of differences can be explained with less accurate interpretation with the laser scanning data.

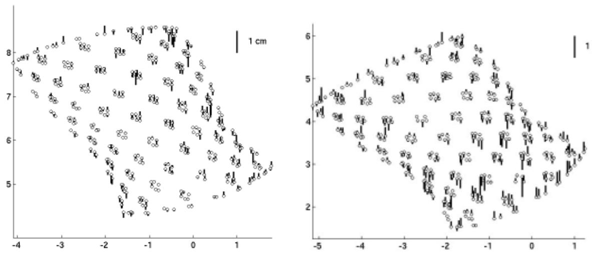

Figure 12. Left: Photogrammetic data after applying the 20 kg load on the top of the pavilion was compared with photogrammetric initial state data. Right: Corresponding comparison between laser data sets. Note that the coordinate systems were different with photogrammetry and laser scanning.

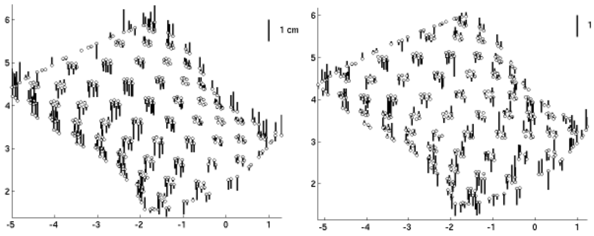

Figure 13. Left: Photogrammetric results when the 100 kg load was placed to hang from the rim. Right: Laser scanning comparison.

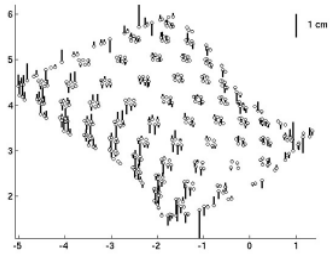

Figure 14. The photogrametric comparison of Figure 13 (left) is recalculated with a separate scale factor in z-direction. The

differences are much closer to the laser scanning case (Figure 13, right) than the original comparison (Figure 13, left) was.

When the 100 kg weights were attached to the HDW pavilion, both methods revealed more differences than with the 20 kg case (Table 1). The photogrammetric results (Figure 13, left) were behaving unexpectedly compared to laser scanning results (Figure 13, right). The shape and distribution of differences indicated that some scale problems might have occurred between coordinate axes, especially in z-direction. In Figure 14, the registration was calculated leaving also the z-scale as a free parameter resulting the mean residual vector length of 0.0042 m, the standard deviation of 0.0023 m and the maximum value of 0.0136 m. If these values and visual plot (Figure 14) were compared with laser scanning results (Table 1) (Figure 13, right), the similarity was pronounced. However, leaving the z-scale as a free parameter also part of the true deformation were expected to be compensated in adjustment. Therefore, this result was only suggestive and not verified without additional control, such as tacheometer measurements.

In the Geomagic Studio 8, two surfaces can be compared in 3D. In Figure 15, one scan before load tests and one after the 100 kg test were compared. This examination showed, in which parts of the HDW pavilion the deformations have occurred. One example of the rendered surface model can be seen in Figure 16.

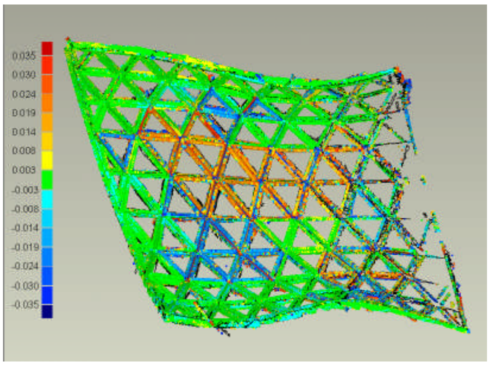

Figure 15. The comparison of scans before load tests and after the 100 kg test. The 100 kg weight was attached to the left rim of the pavilion. Note: Result is not comparable to other difference images on this paper. The pavilion is now looked from below, unlike in the other difference examinations in this paper.

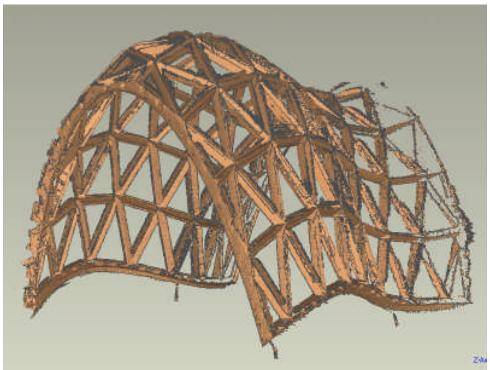

Figure 16. Rendered surface model from a single laser scan. The glass parts were eliminated, because laser scanning could not record them accurately.

5. CONCLUSIONS

The measurements revealed that the HDW pavilion meets relatively closely the original design plans. The mean difference was only 0.014 m and the maximum difference was 0.035 m.

The 20 kg load on the top of the HDW pavilion did not cause such distortion that could have been verified from both photogrammetic measurements and laser scanning data. The longer residuals from laser data were expected, because of the difficulties to identify corners accurately.

The 100 kg load on the rim arc of the pavilion did cause observable variation on corresponding point differences. Both methods revealed similar trends, however, the residuals in laser data were not as regular as in photogrammetic data. The length and regularity of residuals in photogrammetric data gave reason for suspecting scale deformation within the image block. According the both methods the side rims kept their shapes very well. A cross-section along the rib revealed very minor deformations.

Both photogrammetry and laser scanning gave similar results. In this examination, only the main node points were extracted or measured. This method was not optimal for laser scanning data, because it is difficult to mark a corner accurately. Photogrammetric model after applying the 100 kg load test was suspected to have scale distortion in z-direction. It is recommended to use some reference targets for preventing the possible deformations of the free image block.

The strength of laser scanning was the amount of the data representing the detailed 3D shape of the HDW pavilion. On the other hand, the huge amount of the data caused high requirements for post-processing. The post-processing time with both methods was, as expected, significantly longer than the data acquisition.

6. REFERENCES

Alshawabkeh, Y. and N. Haala, 2004. Integration of Digital Photogrammetry and Laser Scanning for Heritage Documentation. XXth ISPRS Congress, Istanbul, July 2004, IAPRS, Vol. XXXV, Part B. In: http://www.isprs.org/ istanbul2004/comm5/papers/590.pdf (visited 28.6.2006).

Cardenal J., E. Mataa M. Ramos, J. Delgadoa, M.A. Hernandeza, J.L. Pereza, P. Castroa, and M. Torresa, 2005. Low cost digital photogrammetric techniques for 3D modelization in restoration works. A case study: St. Domingo de Silos' church (XIVth century, Alcala la Real, Spain), CIPA 2005 XX International Symposium, 26 September – 01 October, 2005, Torino, Italy. In: http://cipa.icomos.org/ fileadmin/papers/Torino2005/722.pdf (visited 27.6.2006).

El-Hakim, S., E. Whiting, L. Gonzo, and S. Girardi. S. 2005. 3D Reconstruction of Complex Architectures from Multiple Data. Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH 2005: "Virtual Reconstruction and Visualization of Complex Architectures" Mestre-Venice, Italy, 22-24 August, 2005. Volume XXXVI, Part 5/W17 ISSN 1682-1777. In: http://www.commission5.isprs.org/3darch05/pdf/1.pdf (visited 28.6.2006).

Fraser, C.S and H.B. Hanley, 2004. Developments in close-range photogrammetry for 3D modelling: the iWitness example, International Workshop: Processing & Visualization using High-Resolution Imagery, Pitsanulok, Thailand, 18-20 Nov. In: http://www.photogrammetry.ethz.ch/pitsanulok_workshop/papers/09.pdf (visited 27.6.2006).

Fröhlich, C. and M. Mettenleiter, 2004. Terrestrial Laser-Scanning - New Perspectives in 3D-Surveying. Proceedings of the ISPRS working group VIII/2 'Laser-Scanners for Forest and Landscape Assessment' Freiburg, Germany 03-06 October 2004. ISSN 1682-1750 VOLUME XXXVI, PART 8/W2. In: http://www.isprs.org/commission8/workshop_laser_forest/FROEHLICH.pdf (visited 27.6.2006).

Gordon, S., D. Lichti, J. Franke, and M. Stewart, 2004. Measurement of Structural Deformation using Terrestrial Laser Scanners. 1st FIG International Symposium on Engineering Surveys for Construction Works and Structural Engineering Nottingham, United Kingdom, 28 June – 1 July 2004. In: http://www.fig.net/nottingham/proc/ts_03_2_gordon_etal.pdf (visited 27.6.2006).

Gruen, A., F. Remondino and L. Zhang, 2002. Reconstruction of the Great Buddha of Bamiyan, Afghanistan. In: International Archives of Photogrammetry and Remote Sensing, Vol. XXXIV, part 5, Corfu, Greece, pp. 363-368.

Grussenmeyer, P. and Yasmine, J., 2003. The Restoration of Beaufort Castle (South-Lebanon): A 3D Restitution According to Historical Documentation. In XIXth CIPA International Symposium, Antalya, Turquey. Sept. 30th. Oct 4th, 2003. IAPRS, Vol. XXXIV-5/C15 ISSN 1682-1750 pp. 322-327.

Guarnieri, A., F. Pirotti, M. Pontin. and A. Vettore, 2005. Combined 3D surveying techniques for structural analysis applications. Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH 2005: "Virtual Reconstruction and Visualization of Complex Architectures" Mestre-Venice, Italy, 22-24 August, 2005. Volume XXXVI, Part 5/W17 ISSN 1682-1777. In: http://www.commission5.isprs.org/3darch05/pdf/28.pdf (visited 27.6.2006).

S. N. Harun and A. G. Ahmad, 2003, The Restoration of Suffolk House, Penang, Malaysia, CIPA 2003 XIXth International Symposium, 30 September – 04 October, 2003, Antalya, Turkey. In: http://cipa.icomos.org/fileadmin/papers/antalya/25.pdf (visited 27.6.2006).

Lee I. and Y. Choi, 2004. Fusion of Terrestrial Laser Scanner Data and Images for Building Reconstruction. XXth ISPRS Congress, Istanbul, July 2004, IAPRS, Vol. XXXV, Commission V. In: http://www.isprs.org/istanbul2004/comm5/papers/189.pdf (visited 27.6.2006).

Lehto, A. and T. Seppänen, 2005. HDW Info Pavilion, Puu-Wood-Holz-Bois, No. 4, p. 26.

Lindenbergh, R., N. Pfeifer and T. Rabbani, 2005. Accuracy analysis of the leica HDS3000 and feasibility of tunnel deformation monitoring. ISPRS WG III/3, III/4, V/3 Workshop "Laser scanning 2005", Enschede, the Netherlands, September 12-14, 2005. pp. 24-29.

Hampel, U. and H.-G. Maas, 2003. Application of digital photogrammetry for measuring deformation and cracks during load tests in civil engineering material testing. In: 6th Conference on Optical 3-D Measurement Techniques. Prof. A. Grün, Institute of Geodesy and Photogrammetry, Swiss Federal Institute of Technology, Zürich, 22-25.9.2003, Vol. II, pp. 80-88.

Pollefeys, M., M. Vergauwen and L. Van Gool, 2000. Automatic 3D modeling from image sequences, invited presentation, IAPRS, Vol. XXXIII, Part B5, pp. 619-626.

Schindler, K. and J. Bauer, 2003. A Model-Based Method For Building Reconstruction. IEEE 1st International Workshop on Higher-Level Knowledge in 3D Modeling and Motion Analysis (HLK 2003), 17 October 2003, Nice, France, Proceedings. IEEE Computer Society 2003, ISBN 0-7695-2049-9. In: http://lear.inrialpes.fr/people/triggs/events/iccv03/cdrom/hlk03/schindler.pdf (visited 27.6.2006).

Schuhmacher S. and J. Böhm, 2005. Georeferencing of terrestrial laserscanner data for applications in architectural modelling. Proceedings of the ISPRS Working Group V/4 Workshop 3D-ARCH 2005: "Virtual Reconstruction and Visualization of Complex Architectures" Mestre-Venice, Italy, 22-24 August, 2005. Volume XXXVI, Part 5/W17 ISSN 1682-1777. In: http://www.commission5.isprs.org/3darch05/pdf/15.pdf (visited 27.6.2006).

Sternberg, H,. Th. Kersten, I. Jahn, and R. Kinzel, R. 2004. Terrestrial 3D laser scanning – data acquisition and object modelling for industrial as-built documentation and architectural applications. XXth ISPRS Congress, Istanbul, July 2004, IAPRS, Vol. XXXV, Commission VII, Part B2, pp. 942-947.

Thies, M. and H. Spiecker, 2004. Evaluation and future prospects of terrestrial laser scanning for standardized forest inventories. IAPRS, Vol. XXXVI, part 8/W2, pp. 192-197.

Valiev, I. 1999. 3D Reconstruction of Architectural Objects from Photos. The 9-th International Conference on Computer Graphics and Vision, Moscow, Russia, August 26 - September 1, 1999 In: http://www.integra.jp/eng/papers/reno_art.pdf (visited 28.6.2006).

Werner, T., F. Schaffalizky and A. Zisserman, 2001. Automated Architecture Reconstruction from Close-range Photogrammetry. Proc. on CIPA 2001 International Symposium: Surveying and Documentation of Historic Buildings -- Monuments -- Sites, Traditional and Modern Methods (2001), p. 54-63.

7. ACKNOWLEDGEMENTS

The financial support of the Academy of Finland (projects 121053 and 211476) and Ministry of the Environment for the project *"the use of ICT 3D measurement techniques for high-quality construction"* is gratefully acknowledged.