Terrestrial Laser Scanning and Digital Photogrammetry for Cultural Heritage: an Accuracy Assessment

Timothy NUTTENS, Philippe DE MAEYER, Alain DE WULF, Rudi GOOSSENS, Cornelis STAL, Belgium

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SUMMARY

This paper deals with the high resolution terrestrial laser scanning of the historic site of the ‘Sint-Baafs Abbey’ (Ghent, Belgium) to obtain a geometrically accurate 3D model. The comparison of the accuracy acquired with terrestrial laser scanning on the one hand and digital photogrammetric processing on the other hand, indicates the applicability of laser scanning for recording cultural heritage sites with a high accuracy. Terrestrial laser scanning is already successfully being used in a broad variety of applications where a very dense and highly accurate recording of an object is needed. Furthermore laser scanning is increasingly being used in the field of cultural heritage and archaeology, for 3D geometric information and conservation of historic buildings or excavation sites.

Previous research indicated that for high accuracy applications, which require cm-level accuracy, a sufficiently fine lateral resolution is necessary. An earlier laser scan recording of the Sint-Baafs Abbey did not meet this required high lateral resolution. This high resolution is also required to compare both terrestrial laser scanning and digital photogrammetric mapping. Therefore, the complete setup has been repeated and improved. The recording of the digital stereo couples and the topographical measurements for the photogrammetric restitution have been done simultaneously. Topographical measurements were also performed for a set of control points. The coordinates of these control points function as the 'ground truth' to which the results of the laser scanning and the photogrammetric restitution are compared.

These comparisons show a systematic error in planimetry between the photogrammetric restitution and the topographical control points of 1.04 cm and 1.05 cm between laser scanning and topography. The random error in planimetry between the photogrammetric restitution and the topographical control points is 3.99 cm and 2.31 cm between the laser scanning and the control points. For both the systematic and random errors, the error in Z is higher for the photogrammetric restitution than for the laser scan measurements.

This project focuses on the comparison of the 3D accuracy of terrestrial laser scanning and digital photogrammetric restitution for applications in the field of cultural heritage and archaeology where the 3D geometric accuracy plays a very important role. The results indicate that terrestrial laser scanning meets the feasible accuracy with digital photogrammetry.

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1. INTRODUCTION

Terrestrial laser scanning is a possible solution for the still growing demand for very accurate and dense 3D geometrical data. These 3D data have to be measured or recorded in a short time frame and in different field conditions, depending on the application. In a wide range of applications the high demands for accuracy and measurement time on the field often result in the inadequacy of the traditional surveying techniques and digital photogrammetry. In a lot of projects, high operational time costs for a topographical survey with total station are often a restriction or stumbling block. Depending on the field conditions, it might not even be possible to get close enough to the objects to measure all necessary details. In many cases it is also too dangerous to measure for a couple of hours, for example along busy roads or in quarry (Beraldin *et al.*, 2000; Biosca & Lerma, 2008). Aerial recordings often do not provide the necessary detailed information on vertical object features or facades of buildings. In projects where the circumstances make the use of digital photogrammetry or total station measurements difficult or impossible, high resolution terrestrial laser scanning can be a feasible alternative to record the spatial information fast and accurately (Tao *et al.*, 2001). Furthermore, the combination of laser scanning and high resolution digital images not only results in the acquisition of geometrically accurate 3D data, but also in high resolution texture mapping (Haala & Alshawabkeh, 2006).

The acquisition of accurate 3D models or plans of archaeological sites, cultural heritage sites and monuments is very important. These 2D and 3D deliverables allow a cultural or site management based on correct, complete and geometrically accurate documents. This research specifically focuses on the need for geometrically accurate documents of cultural heritage sites rather than generating 3D models only for visualization. The measurements for this research are made at the historic site of ‘Sint-Baafs Abbey’ in Ghent, Belgium. On the site, there are still remnants of the surrounding walls of the ‘Sint-Baafs Abbey’ which dates originally back to the seventh century AD.

An accuracy assessment is an important criterion in the research on the geometrically accurate recording of cultural heritage sites. This accuracy assessment is also important for the optimal use of different recording and measurement techniques in different applications and on various heritage sites. The authors focus on the comparison of the 3D accuracy between measurements with terrestrial high resolution laser scanning and digital photogrammetry. The obtained coordinates with both techniques are compared with total station measurements, which will be considered as the ‘ground truth’.
As the results of the previous stage of the project indicated (Nuttens *et al.*, 2009), the lateral resolution of the laser scanning has to be high enough to be able to firmly compare both

terrestrial laser scanning and digital photogrammetric mapping. Therefore, the previous setup has been improved and repeated. In the new setup, a different type of laser scanner and a higher resolution are being used.

2. DIFFERENT TECHNIQUES FOR RECORDING THE 'SINT-BAAFS ABBEY'

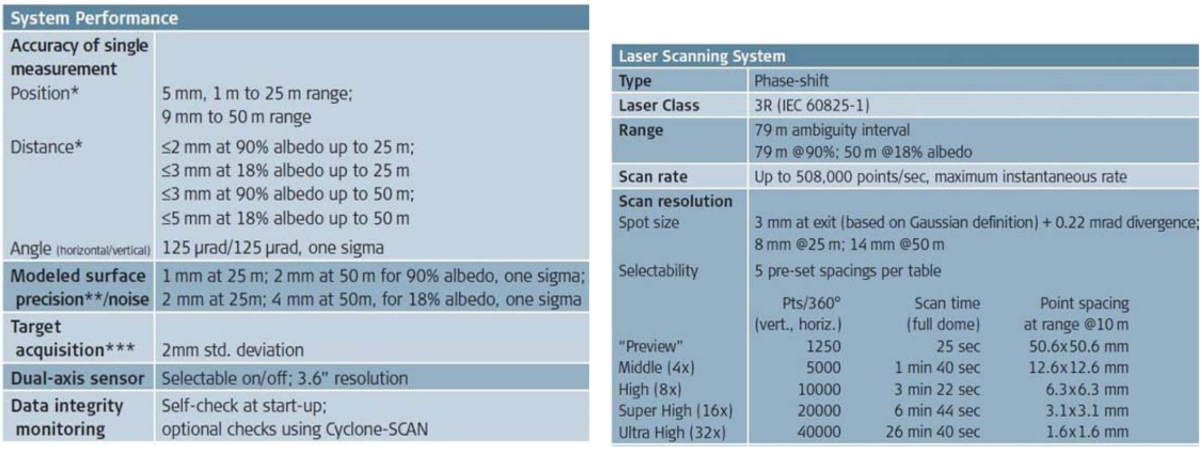
2.1 Measurements with terrestrial laser scanning

Since 2008, the important historical buildings in the city centre of Ghent are being recorded with terrestrial laser scanning, in collaboration with the City of Ghent ('Ghent 3D'). The facades of these historical buildings and the most important interiors are being scanned. During these measurements different types of laser scanners are tested, such as Leica HDS3000, Leica ScanStation2, Leica HDS6100 (Figure 1) and Trimble GX.

Figure 1: Laser scanner setup (Leica HDS 6100) at 'Sint-Baafs Abbey' (Gent, Belgium) (2010)

The site of the 'Sint-Baafs Abbey' is one of the cultural heritage sites in Gent which are recorded with laser scanning. The remnants of the walls on this site are the topic of this research project to assess the possible 3D accuracies not only with terrestrial laser scanning but also with digital photogrammetry. In an earlier stage of the project, the site was scanned with a laser scanner Leica ScanStation2 (time-of-flight scanner). The project's setup at that time defined a lateral scanning resolution of 3 to 4 cm. In that earlier stage, a first comparison was made between the 3D accuracies of terrestrial laser scanning and digital photogrammetry. One of the findings was that the scanning resolution of 3 to 4 cm was not sufficient enough to achieve an equal accuracy with laser scanning compared to digital photogrammetry. In the most recent stage of the project, the walls of the abbey are scanned with the phase-based laser scanner Leica HDS6100 (Figure 2) with an average resolution of 0.5 cm. The horizontal and vertical angle increment of the resolution level was 0.018°, which represents a point spacing of 7.9 mm at a distance of 25 meter. The maximal range for the measurements of the abbey was approximately 15 meter. The higher scanning resolution allows to investigate whether this higher resolution improves the results of the previous project stage.

The point clouds measured with the Leica ScanStation2 contain for each point an RGB value, based on digital photographs taken with the built-in digital camera (Figure 3). On the contrary, the point clouds recorded with the Leica HDS 6100 do not have an added RGB-value. These point data contain merely the intensity value of the reflection of the laser beam on the object. The main advantages of the phase-based laser scanner are the much shorter recording time of the whole site, the much higher resolution within this time frame and the higher accuracy on the short distances in this case (maximum 15 meter).



System Performance	
Accuracy of single measurement	
Position*	5 mm, 1 m to 25 m range; 9 mm to 50 m range
Distance*	≤2 mm at 90% albedo up to 25 m; ≤3 mm at 18% albedo up to 25 m ≤3 mm at 90% albedo up to 50 m; ≤5 mm at 18% albedo up to 50 m
Angle (horizontal/vertical)	125 µrad/125 µrad, one sigma
Modeled surface precision/noise**	1 mm at 25 m; 2 mm at 50 m for 90% albedo, one sigma; 2 mm at 25m; 4 mm at 50m, for 18% albedo, one sigma
Target acquisition***	2mm std. deviation
Dual-axis sensor	Selectable on/off; 3.6" resolution
Data integrity monitoring	Self-check at start-up; optional checks using Cyclone-SCAN

Laser Scanning System			
Type	Phase-shift		
Laser Class	3R (IEC 60825-1)		
Range	79 m ambiguity interval 79 m @90%; 50 m @18% albedo		
Scan rate	Up to 508,000 points/sec, maximum instantaneous rate		
Scan resolution			
Spot size	3 mm at exit (based on Gaussian definition) + 0.22 mrad divergence; 8 mm @25 m; 14 mm @50 m		
Selectability	5 pre-set spacings per table		
	Pts/360° (vert., horiz.)	Scan time (full dome)	Point spacing at range @10 m
"Preview"	1250	25 sec	50.6x50.6 mm
Middle (4x)	5000	1 min 40 sec	12.6x12.6 mm
High (8x)	10000	3 min 22 sec	6.3x6.3 mm
Super High (16x)	20000	6 min 44 sec	3.1x3.1 mm
Ultra High (32x)	40000	26 min 40 sec	1.6x1.6 mm

Figure 2: Leica HDS 6100 – Specifications (http://hds.leica-geosystems.com) (2010)

Multiple scanning positions are necessary for the complete recording of the site of 'Sint-Baafs Abbey'. During the whole project until now, more than thirty scanning positions have been used to record the whole site. For the latest measurements with the Leica HDS 6100, fourteen scanning positions were defined to cover the whole area of interest. The different point clouds resulting from the scanning positions are linked based on so-called 'targets'. Targets are reference points, in this case blue-white discs, which are spread over the measurement site. Based on at least three common targets between different scanning positions, these scanning positions can be linked together.

To georeference the total point cloud, the coordinates of the targets are measured in the Belgian Lambert72 coordinate system. Based on the known Lambert72 coordinates of the targets, the laser scan point cloud can be georeferenced in this same coordinate system. The Lambert72 coordinates are measured with a Trimble R8 GNSS receiver, based on a RTK network solution of the 'Flemish Positioning Service' with an achievable accuracy of 1 to 2 cm (AGIV, 2008).

Figure 3: RGB colored point cloud of ‘Sint-Baafs Abbey’ derived from measurements with Leica ScanStation2 (own research, 2009)

2.2 Recording with digital photogrammetry

For the photogrammetric restitution of the walls of the abbey, topographical measurements were executed and digital photographs were recorded. The final products of this photogrammetric process are digital elevation models of the walls of the abbey and orthorectified images.

The digital photographs were taken with a non-metric Canon EOS 1Ds (11 Megapixel) high-end full-frame digital single lens reflex camera. The topographical measurements with a reflectorless total station were made to determine the coordinates of the ground control points in the Belgian Lambert72 coordinate system. The location of the topographical measurements in the Belgian Lambert72 coordinate system is based on the same GNSS coordinates as the georeferencing of the laser scan point cloud. The ground control points allow us to perform an absolute orientation in the photogrammetric process, so that the digital elevation model and the orthophoto are georeferenced in the Lambert72 coordinate system.

The photographs for the stereo models were taken with a minimum overlap of 80 %. Places or areas on the object with direct sunlight and places with little or no contrast were avoided by taking into account the changing sunlight direction during the day. The digital photogrammetric restitution of the stereo couples was performed in the VirtuoZo^{TM} software.

The processing of the stereo models is performed in a non-metric way. The non-metric processing, due to the use of a non-metric camera, means that there is no internal orientation of the images. An internal orientation uses a camera calibration file to correct the camera- and lens distortions based on fiducial marks recorded onto the image. The relative orientation of both images of the stereo model is a half-automated step in the photogrammetric process. The software searches automatically for homological points between both images but the operator has to check all homological points for possible errors. He has to confirm that the homological points indicate the same points on both images and that the error of the relative orientation does not exceed the limit of 1/5th of a pixel. At least 100 to 150 homological points have to be selected and confirmed.

The quality of the result of the image matching is largely influenced by the total number of homological points and by the spread of these points over the overlapping area of the stereo model. Furthermore, the quality of the image matching is of great importance for the quality of the resulting digital elevation model and the orthophoto (Figure 4).

Figure 4: Sint-Baafs Abbey – Orthophoto of a part of the wall (2010)

By indentifying the topographically measured ground control points in the stereo model, this stereo model can be georeferenced. This is called the absolute orientation. The known coordinates of these ground control points locate and orientate the stereo model, the digital elevation model and the orthophoto in the Belgian Lambert72 coordinate system. For each stereo couple, twelve to fifteen ground control points were measured. The maximum allowed error on the absolute orientation for the processed stereo couples in this project was 1 cm in X-, Y- and Z-direction.

2.3 Control points with total station

Spread over the walls of the abbey which were measured with laser scanning and recorded with digital photogrammetry, an independent test set of 100 points was measured with the total station. This test set consists of highly distinguishable points on the walls of the abbey such as corners of stones and details on ornaments. These control points were topographically measured with a reflectorless total station and georeferenced in the Belgian Lambert72 coordinate system. The measurements with total station are considered to yield to 'true' coordinate values of these selected control points and so these coordinates serve as the 'ground truth' to which the other measurement techniques are compared. The coordinates of this set of selected control points are also determined in the laser scan point cloud and in the results of the photogrammetric restitution.

3. RESULTS

The coordinates of the set of control points determined in the laser scan point cloud and the photogrammetric results were compared with the topographically measured coordinates of these points. For each point, the difference in X-, Y- and Z-coordinate was calculated. Outliers in the data set were eliminated.

First, the differences between the coordinates from the digital photogrammetry and the topographical measurements are calculated. These differences are averaged to calculate the systematic error of the digital photogrammetry results compared to the measurements with the total station. Next, the absolute values of these differences are averaged to calculate the random error of the digital photogrammetry results. Analogue calculations are performed for the coordinates from the laser scanning compared to the topographical measurements with total station. Also the differences between the photogrammetric results compared to the laser scanning coordinates are determined. Based on these differences, the systematic and random errors between the digital photogrammetry and the laser scanning results are calculated. The following tables give an overview of these calculated systematic and random errors.

Comparison of systematic errors in the position of the control points using laser scanning and photogrammetry compared to total station measurements			
	Systematic error (cm) (Average of algebraic error values)		
	X	**Y**	**Z**
Photogrammetry vs. Total station	-1.00	-0.30	-1.57
Laser scanning vs. Total station	0.90	-0.53	0.27
Photogrammetry vs. Laser scanning	-1.90	0.20	-1.83

Table 1: Systematic errors - overview

Table 1 shows the systematic errors of respectively the photogrammetric results and the laser scanning results compared to the total station measurements. The table also displays the errors of the photogrammetric results compared to the laser scanning results. All errors are calculated for the X-, Y- and Z-direction.

The systematic error in planimetry for the digital photogrammetry compared to the total station measurements is 1.04 cm ($\sqrt{(\text{error in X})^2 + (\text{error in Y})^2}$). For the laser scanning compared to the total station measurements this systematic error in planimetry is 1.05 cm. The results indicate a comparable systematic error in planimetry for both the digital photogrammetric restitution and the laser scanning, based on an average scanning resolution of 0.5 cm. By contrast, the systematic error in altimetry is approximately five times higher for the photogrammetric results than for the laser scanning.

Comparison of random errors in the position of the control points using laser scanning and photogrammetry compared to total station measurements			
	Random error (cm) (Average of absolute error values)		
	X	**Y**	**Z**
Photogrammetry vs. Total station	2.73	2.90	3.07
Laser scanning vs. Total station	1.53	1.73	1.30
Photogrammetry vs. Laser scanning	3.03	3.63	3.20

Table 2: Random errors - overview

In Table 2, the random errors between respectively the photogrammetric results and the laser scanning results compared to the total station measurements are given. Table 2 also shows the photogrammetric results compared to the laser scanning results. All errors are given for the X-, Y- and Z-direction.
For the digital photogrammetry compared to the total station measurements, the random error in planimetry is 3.99 cm. For the laser scanning compared to the total station measurements this random error in planimetry is 2.31 cm. Based on these results, we can assume that the random errors with terrestrial laser scanning with an average resolution of 0.5 cm are two times smaller than the results of the photogrammetric restitution with the VirtuoZo^{TM} software package. The random error in height is also approximately two times smaller for the laser scanning results than for the digital photogrammetry.

These results lead to the conclusion that the lateral resolution of 0.5 cm largely improves the possible accuracies of terrestrial laser scanning compared with digital photogrammetry. As concluded from the earlier stage of the project, the scanning resolution of 3 to 4 cm used in that stage was too coarse. A finer resolution, in this case 0.5 cm, enables us to equal and even exceed the accuracy of digital photogrammetry in this test-case with lines of sight of 5 till 15 meter.

4. CONCLUSION

Terrestrial laser scanning is increasingly being used in a broad range of applications,

including cultural heritage and archaeology. The results of this project show important possibilities for a wide range of future developments and improvements in the recording of archaeological and cultural heritage sites with terrestrial laser scanning.
To perform an accuracy assessment of digital photogrammetry and terrestrial laser scanning, the site ‘Sint-Baafs Abbey’ was recorded with both techniques. A set of independent control points was measured with a total station. This data set is assumed to yield the ‘true’ coordinates of the control points. The comparisons show an equal systematic error in planimetry for the photogrammetric restitution and the laser scanning compared to the topographical control points. The random error in planimetry for the photogrammetric restitution is approximately two times as large as the random error for the laser scanning compared to the topographical control points. For both the systematic and random errors, the error in Z is higher for the photogrammetric restitution than for the laser scan measurements.

In the previous stage of the project the same site was scanned with a lateral resolution of 3 to 4 cm. The results in that stage of the project indicated that a finer scanning resolution was advisable to equal or exceed the accuracy of digital photogrammetry for this test case. The further field measurements with a finer resolution in this stage of the project validate this conclusion. The calculated errors of digital photogrammetry and terrestrial laser scanning compared to the topographical measurements of an independent test set of 100 points confirm the potential of terrestrial laser scanning for high accuracy applications in cultural heritage an archaeology. An important factor is the selection of a sufficiently fine lateral scanning resolution for the terrestrial laser scanning.

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CONTACTS

MSc. Timothy Nuttens
Ghent University – Department of Geography
Krijgslaan 281, Building S8
9000 Ghent
BELGIUM
Tel. +32 9 264 46 56
Fax +32 9 264 49 85
Email: Timothy.Nuttens@ugent.be
Web site: http://geoweb.ugent.be/data-acquisition-3d