Application of laser scanning for deformation measurements: a comparison between different types of scanning instruments.

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Key words: Terrestrial laser scanning, tunnels, deformation measurements, comparison

SUMMARY

High resolution terrestrial laser scanning is more and more being applied for measuring and monitoring geometric deformations of civil technical constructions. At Ghent University (Department of Geography), research is being performed on the deformation measurements of newly built concrete tunnels, by terrestrial laser scanning. In the most recent project ('Liefkenshoek Railway Connection', Antwerp, Belgium) two side-by-side tunnels with a length of approximately six kilometers are being monitored. For each tunnel, the deformations of fourteen sections in are measured by means of terrestrial laser scanning during the first three months after ring erection.

To meet the project's requirements for the measurement accuracy, a phase-based laser scanner, Leica HDS6100, is being used for these measurements. Furthermore, this type of laser scanner allows performing the measurements in a limited time frame. Based on previous experiments, an experimental standard deviation of 0.4 mm is reached with this type of laser scanner under these tunnel measurement conditions (short distances < 6 m). The choice for one specific type of scanning instrument does not only depend on the project's requirements but also on the technical developments and possibilities at the beginning of the project. Because of the fast and high-level developments in scanning technology, a constant comparison and testing of different types of instruments is advisable to choose the most suited instrument.

Based on earlier research, an accuracy assessment of the results with a phase-based laser scanner Leica HDS6100, a pulse-based Leica ScanStation2 and a Trimble robotic total station S6 (2" DR300+) with scanning function was possible. Recently, a series of tunnel measurements were carried out with the pulse-based Leica C10 laser scanner and the Trimble VX robotic total station. Both sets of test measurements are based on the same experimental set-up and processing workflow which makes a completion of and a comparison with the earlier results possible and justified. This accuracy assessment, together with other parameters such as scanning speed, performance of the user interface and the possibility to collect non-geometric data (color and intensity) allow for comparison of the different scanner types not only for tunnel deformation measurements but also for other civil engineering applications with similar requirements and field conditions.

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1. INTRODUCTION

High resolution terrestrial laser scanning is more and more being applied for measuring and monitoring geometric deformations of civil technical constructions. This technique delivers millions of very accurate 3D points in a short time frame, which makes it a valuable alternative or complementary technique for classical topographical measurements with total station or digital photogrammetry (Delaloye *et al.*, 2011; Gumus & Erkaya, 2011; Lerones *et al.*, 2010). Not only in civil technical applications, but also in cultural heritage or archaeological projects, terrestrial laser scanning offers a non-invasive solution for the need for mm-level accurate 3D data in a short time frame and in difficult field conditions (Beraldin *et al.*, 2000; Biosca & Lerma, 2008). This data recording leads to an accurate 3D model which offers a point based representation of the object or site or a complete data set ready for archiving and detailed processing in the future with possibly more powerful processing techniques (Pesci *et al.*, 2011; Rüther *et al.*, 2009). Notwithstanding the fact that terrestrial laser scanning can be used to measure in specific situations where other measurement equipment is not practically usable, the cost of the equipment and the limited automatic processing possibilities of the large point clouds still cause some constraints (Hesse & Stramm, 2004).

At Ghent University (Department of Geography), research is being performed on the deformation measurements of newly built concrete tunnels with terrestrial laser scanning. For these specific tunnel measurements, the main advantage of laser scanning is the speed in which the tunnel surface of interest can be measured. This is an important advantage in comparison with a total station, which can only measure a limited number of points on that tunnel surface at a much slower measurement rate. Moreover, the possibility of laser scanning to measure under difficult light conditions in a limited space offers important advantages in comparison with digital photogrammetry. The research presented in this paper is based on the experience and the results of two recent ovalisation measurement projects in newly built tunnels in Belgium: 'Diabolo Project' (Zaventem, April 2009 – January 2010) and 'Liefkenshoek Rail Link Project' (Antwerp, March 2010 – October 2011). These two projects are the first in Belgium in which terrestrial laser scanning is used to measure and monitor the ovalisation of the constructed tunnels starting from immediately after placement of the tunnel rings until three months after placement. The use of terrestrial laser scanning for this application and the processing of the data has been tested and implemented during the construction of two railway tunnels under Brussels Airport ('Diabolo', Zaventem). The experience from this project has been used to optimize the data collection and processing workflows for the 'Liefkenshoek Rail Link Project'.

The ‘Liefkenshoek Rail Link Project’ creates a new railway connection in the Port of Antwerp, connecting the left and right bank of the River Scheldt. The total length of this new railway connection is approximately 16 km, of which 6 km is constructed with a new tunnel to cross two waterways. The new bored tunnel part consists of two side-by-side tunnels, with an outside diameter of 8.10 m, an inside diameter of 7.30 m and each concrete tunnel ring has a width (along the longitudinal axis) of 1.80 m. Each constructed ring is made of seven concrete elements and one key stone. Two Tunnel Boring Machines (TBM) of the ‘mix-shield’ type are used to drill the tunnels. The deformations of fourteen sections in each tunnel are measured with terrestrial laser scanning in the first three months after placement.

During both projects, different laser scanning instruments have been tested and compared. Based on the test measurements during the ‘Diabolo Project’, a phase-based laser scanner (i.c. Leica HDS6100) gave the best results in both accuracy and measurement time. The choice for this specific type of scanning instrument does not only depend on the project’s requirements for accuracy and measurement time but also on the availability of instruments, user-friendliness, costs and the technical developments and possibilities at the beginning of the project. Because of the fast and high-level developments in scanning technology, a constant comparison and testing of different types of measurement instruments is advisable to choose the most suited instrument for a specific application. This is why this part of the research focuses on the comparison of different scanning instruments for tunnel deformation measurements, focusing on the achievable experimental standard deviation of the instruments in tunnel measurement conditions.

The next section explains the optimized tunnel measurements and the processing of the data, as performed during the ‘Liefkenshoek Rail Link Project’. Section 3 goes into more detail on the comparison of the different measurement instruments, after which the results of that comparison are presented in section 4. Finally, in section 5 a conclusion is formulated.

2. TUNNEL MEASUREMENTS

2.1 Measurement procedure

The monitoring of the ovalisation of the newly built tunnels implies that the deviations from ovalisation are measured at different points in time and that they are mutually compared for each tunnel section. Only a limited number of tunnel sections have to be monitored. In each 6 km long tunnel, fourteen sections are indicated to be monitored. Each of these sections is measured with laser scanning immediately after placement (‘critical measurement’), once a week during the first month after placement (‘control measurement 1-4’) and two and three months after placement (‘control measurement 5 and 6’).
Especially the critical measurements have to be performed within a strict time frame and with limited space in the head of the TBM (Figure 1). Because no vibrations or movement of the TBM may occur during the laser scan measurements, the drilling works have to be stopped for each critical measurement. This downtime of the TBM has to be reduced to the minimum.

Because the whole tunnel section cannot be measured from one single scanning position during a critical measurement, due to the obstruction caused by the TBM, three scanning positions are needed to cover the whole section's surface.

Figure 1: Scanning position in the head of the TBM

For the control measurements, only one scanning position in the middle of the tunnel section is needed to cover a maximal area of the tunnel section. Also, during control measurements, the scanning time has to be minimized as the scanning position blocks the work traffic from and to the TBM.

From each scanning position, all points within the field of view of the laser scanner (360° horizontal – 310° vertical) are scanned (Figure 2). Each scan results in a data set with a point density of approximately 1.5 mm or higher for a critical measurement and approximately 4 mm or higher for a control measurement. The point density differs between those two types of measurements to optimize the data collection and processing workflow.

Simultaneously with the ovalisation measurements, eight of these cross-sections in each tunnel tube are also monitored with strain gauge measurements. Each of these monitored rings is equipped with several strain gauges across the whole ring perimeter. Some of these gauges are already installed during precasting of the concrete segments; the other gauges are fixed to the inner surface of each ring segment during the placement of the tunnel ring. In total, eighteen wired strain gauges are installed for each monitored tunnel ring. Strain data is then measured from immediately after placement of the tunnel ring until final delivery of the project, foreseen in 2013. The results of these strain gauge measurements show good resemblance with the ovalisation measurements with laser scanning. Both techniques and their close combination demonstrate the role of separate features of each measurement section in the stress, strain and deformation phase (Schotte *et al.*, 2011).

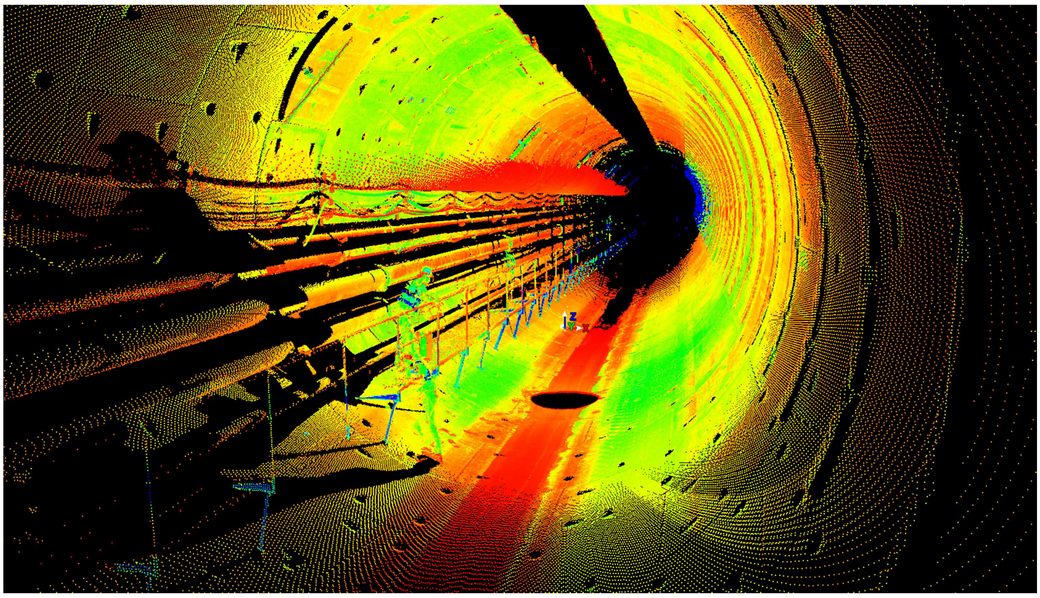
Figure 2: Example of control measurement - Unprocessed point cloud

2.2 Processing of the scan data

A lot of spurious points have to be filtered out, especially in measurements immediately after placement due to the obstacles from the TBM. The filtering of the point cloud is performed manually to ensure the highest filtering quality. Although this manual method is very time consuming, it is applied for processing all measurement data in this project. Currently, research and implementation tests are being performed on an automatic filtering algorithm for tunnel point clouds. The preliminary results of this research are very promising. During processing of the data, the excess points of adjacent tunnel sections, points of scanned obstructions such as a pathway, a ventilation shaft, pipes … are deleted. Also the holes for the connecting bolts between segments and adjacent sections are deleted during the filtering. This filtering means a considerable reduction of the number of points in the data set. Depending on the fact whether it is a critical or a control measurement, respectively around 70% and 80% of the points are discarded (Figure 3).

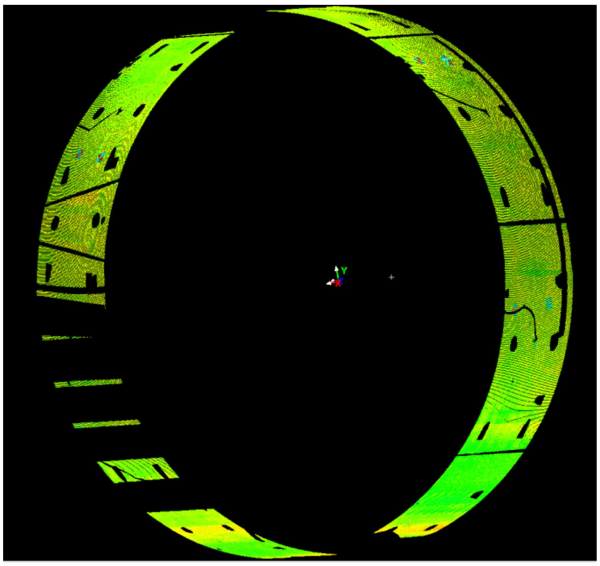

Figure 3: Example of filtered point cloud (control measurement)

The filtered point cloud is used for the computation of a best-fit cylinder with a free diameter and orientation. This cylinder with variable diameter is automatically fitted by the processing software, based on all remaining points after filtering the point cloud. Perpendicular to the axis of this cylinder, a cross-section is defined to intersect with the triangulated surface of the point cloud at the exact location of the 'Master Reference Target'. This 'Master Reference Target' is one of the reference marks on the concrete surface, specifically selected as the indicator for the exact location for the cross-section for all measurements of that tunnel section. The cross-section is defined by a polyline, which is further processed in CAD software.

The CAD program is used to further evaluate the cross-section derived from the fitting process. Every 0.1 grad, the length of a ray from the cylinder's center to the cross-section is determined. To eliminate high frequency noise and to improve the readability of the cross-section, the resulting length is then smoothened by averaging its length using the original length and the adjacent ray lengths over an area of maximum 1 grad. Thus, an average of eleven values over an angle of 1 grad (X-0.5 to X+0.5) is determined. In the areas where certain parts of the tunnel surface are not scanned, it is possible that the average radius value is calculated with less than eleven adjacent values, because not all adjacent values are available.

2.3 Monitoring conclusions

For each measurement, the averaged radius values for 0.1 grad rotations are compared with the theoretical inner radius of 3.6500 m, according to the design of the tunnel. For later control measurements, these values are also compared with the radius values from the measurement immediately after placement and the radius values from the previous control measurement and thus deviations from ovalisation are calculated. Significant changes from ovalisation are observed during the first week after placement of the tunnel section. After the first week after ring erection, no more statistical significant changes are observed, taking into account the 2σ significance level (ca. 0.8 mm) based on the experimental standard deviation of the used laser scan instrument.

3. COMPARISON OF DIFFERENT SCANNING INSTRUMENTS

3.1 Importance of testing alternatives

The project requirements mainly determine the selection of the measurement equipment. Depending of the field conditions, the required final products and the requested accuracy, the number of qualified measuring instruments is limited. Specifically for the ovalisation measurement in the 'Liefkenshoek Rail Link Project', there was the requested use of laser scanning, a standard deviation of less than 0.5 mm, the restricted time frame to perform the measurements on site and the very limited space in the head of the TBM for the critical measurements.

The choice of one specific type of scanning instrument does not only depend on the project's requirements but also on the availability of instruments, technical developments and possibilities at the beginning of the project. Because of the fast and high-level developments in scanning technology, a constant comparison and testing of different types of instruments is advisable to choose the most suited instrument. New developments in scanning instruments may deliver a faster measurement time, a more accurate result in a comparable time frame or other significant improvements. These new improvements may influence the decision to change the measuring equipment during the project. Tests with alternative and new equipment are valuable, not only for the project's purposes, but also for developing and improving research knowledge on the issue.

3.2 Scanning instruments

For the measurement of civil technical constructions, such as tunnels, the focus lies on the two general types of laser scanners based on time measurements: phase-based and pulse-based (time-of-flight) laser scanners. The measurement principle of pulse-based laser scanners (such as Leica ScanStation C10, Leica ScanStation2 and Trimble GX) is based on emitting pulses of a laser beam towards an object and recording the reflection of that laser beam on the object. By accurately measuring the time delay between emitting of the laser beam and capturing the reflection, the distance between laser scanner and the object can be calculated. By combining this measured distance with the registered horizontal and vertical angles of the measured point, the 3D coordinates of that point are calculated (Pfeifer & Briese, 2007). The scanning speed of this type of terrestrial laser scanner can be up to 50 000 points per second and they have a scan distance of 200 till 700 meter or more (Leica Geosystems, 2009a). Phase-based laser scanners (e.g. Leica HDS6100) have a shorter measurement range (up to 120 meter) but a much higher scanning speed (500 000 points per second for Leica HDS6100) (Leica

Geosystems, 2009b) (Figure 4). Their measurement principle is based on emitting a continuous laser beam and calculating the phase difference between the emitted and reflected laser beam. From this phase difference, the time delay can be calculated and so the distance between scanner and object (Pfeifer & Briese, 2007). Next to these types of laser scanners, also the latest developments of robotic total stations with special scanning functionalities are investigated.

Key Leica HDS6100 Performance Specifications			
Instrument type	Compact, phase-based, dual-axis sensing, ultra-high speed laser scanner, with survey-grade accuracy and full field-of-view		
User interface	Onboard touch panel, or external notebook or Tablet PC, or PDA		
Data storage	Integrated hard drive		
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 µrads/125 µrads (7.9 mgon/7.9 mgon) one sigma	
Spot size	3 mm at exit (based on Gaussian definition) + 0.22 mrad divergence; 8 mm @25 m; 14 mm @50 m;		
Modeled surface precision/noise**	1 mm at 25 m; 2 mm at 50 m, for 90% albedo; one sigma 2 mm at 25 m; 4 mm at 50 m, for 18% albedo; one sigma		
Target acquisition***	2 mm std. deviation		
Dual-axis sensor	Selectable on/off; Resolution 3.6"		
Laser scanning system	Range	79 m ambiguity interval	
		79 m @90%; 50 m @18% albedo	
	Scan Rate	Up to 508,000 points/sec, maximum instantaneous rate	
	Scan density	@10 m	@50 m
	"Preview"	50.6 x 50.6 mm	250 x 250 mm
	Middle (4x)	12.6 x 12.6 mm	62 x 62 mm
	High (8x)	6.3 x 6.3 mm	31.4 x 31.4 mm
	Super High (16x)	3.1 x 3.1 mm	15.8 x 15.8 mm
	Ultra High (32x)	1.6 x 1.6 mm	7.9 x 7.9 mm
Laser Class	3R (IEC 60825-1)		
Lighting	Fully operational between bright sunlight and complete darkness		
Power supply	24 V DC; integrated Li-ion battery (2.5 hrs) and/or optional external DC power supply (4 hrs) or AC supply		
Power consumption	65 W max.		
Temperature	Operation: -10° C to +45° C; Storage: -20° C to +50° C		

Figure 4: Specifications phase-based laser scanner Leica HDS6100 (http://www.leica-geosystems.com)

Based on earlier experiments ('Diabolo Project'), an accuracy assessment of the results with a phase-based laser scanner Leica HDS6100, a pulse-based Leica ScanStation2 and a Trimble robotic total station S6 (2" DR300+) with scanning function was possible (Nuttens *et al.*, 2010). These results will be complemented with the comparison results of the new research on new measurement instruments. Both sets of test measurements are based on the same experimental set-up so that a completion of and comparison with the earlier results are possible and justified.

Recently, a series of tunnel measurements have been carried out with the pulse-based Leica C10 laser scanner and the Trimble VX robotic total station. Based on the earlier test set-up, a single tunnel section is measured four times within a one hour time frame with the pulse-based Leica C10. In this short time frame, it can be assumed that no significant deformation of the tunnel section has appeared. Based on these measurement series, an experimental standard deviation for the laser scanner is calculated and compared with the previously determined standard deviation of the Leica HDS6100 laser scanner and other measurement instruments. Due to the time restrictions on site, it was not possible to perform the same measurement series with the Trimble VX total station. The tunnel section is therefore measured only one time, but the derived cross-section after the processing of the scan data can be compared with the results of the Leica C10 to compare the Trimble VX with the other results. Due to the lower scanning speed, the point density of the point cloud from the Trimble VX is much lower than the point density of the point set from the Leica C10.The performed accuracy assessment can be the main basis for a comparison of the different scanner types, not only for tunnel deformation measurements but also for other civil engineering applications with similar requirements and field conditions.

3.3 Results

The earlier accuracy assessment of the phase-based laser scanners Leica HDS6100, the pulse-based laser scanner Leica ScanStation2 and the robotic total station Trimble S6 (2” DR300+) yielded different achievable experimental standard deviations. The experimental standard deviation with the Leica HDS6100 is 0.4 mm; with the pulse-based Leica ScanStation2 it is 1.6 mm and the standard deviation of the robotic total station Trimble S6 is 0.8 mm. These results indicate that the phase-based laser scanner (Leica HDSD6100) delivers the most accurate results. This result is not surprising, as the working principle of a phase-based laser scanner is known to be more suited for accurately measuring short distances than a pulse-based laser scanner. Nevertheless, the performed test measurements confirm the general given in these specific tunnel measurements. Moreover, the total equipment of this scanner is proven to be suitable for the use in the difficult field conditions and the limited set-up space in the head of the TBM.

In addition, the new test measurements with the pulse-based Leica C10 result in an experimental standard deviation of 0.4 mm in the specific tunnel measurement conditions with maximum measurement distances of 6 meter. This is of the same accuracy level of the tested phase-based laser scanner. Nevertheless, the smaller field-of-view (360° x 270°), the significant slower scanning speed (Leica Geosystems, 2011) of this type of laser scanner and the more extensive user interaction needed for the operation of the instrument are still an important issue for the use of this type of laser scanner in these tunnel measurement projects.

Because for the new series of test measurements, the same tunnel section has been measured with both measurement instruments, the cross-section derived from the measurement of the tunnel section with the Trimble VX spatial station is compared with the cross-section derived from the measurements with the laser scanner Leica C10. The cross-sections from all four measurements with the Leica C10 are averaged into one result. The radius values, averaged over a 1 grad interval as described in the processing workflow, are compared and show an average algebraic difference of -1.6 mm (cross-section Leica C10 – Cross-section Trimble VX). The average absolute difference between both cross-sections is 1.7 mm. This difference is relatively large, considering the standard deviation of the laser scanner Leica C10. A possible partial explanation for this difference is the lower scanning resolution of the measurement with the Trimble VX. Also in this case, the slow scanning speed and the resulting lower resolution for the same measurement time are important issues with the use of this instrument for tunnel measurements.

4. CONCLUSIONS

In the most recent Belgian railway tunneling project (‘Liefkenshoek Railway Connection’, Antwerp, Belgium), two side-by-side tunnels with a length of approximately six kilometers are being monitored with terrestrial laser scanning. This research focuses on the comparison of different scanning instruments for tunnel deformation measurements and on the achievable experimental standard deviation of the instruments in tunnel measurement conditions.

The earlier accuracy assessment of the phase-based laser scanners Leica HDS6100, the pulse-based laser scanner Leica ScanStation2 and the robotic total station Trimble S6 (2” DR300+) indicates an experimental standard deviation with the Leica HDS6100 of 0.4 mm; with the pulse-based Leica ScanStation2 it is 1.6 mm and the standard deviation of the robotic total station Trimble S6 is 0.8 mm. This accuracy assessment, together with other parameters such as scanning speed, user interface and possible color information allow for comparison of the different scanner types not only for tunnel deformation measurements but also for other civil engineering applications with similar requirements and field conditions.

In addition, the new test measurements with the pulse-based Leica C10 result in an experimental standard deviation of 0.4 mm in the specific tunnel measurement conditions with maximum measurement distances of 6 meter. This is of the same accuracy level of the tested phase-based laser scanner. Nevertheless, the smaller field-of-view, the significant slower scanning speed of the laser scanner Leica C10 and the more extensive user interaction needed for the operation of the instrument are still important issues for the use of this type of laser scanner in these tunnel measurement projects. The cross-section derived from the measurement of the tunnel section with the Trimble VX spatial station is compared with the cross-section derived from the measurement with the laser scanner Leica C10 and this comparison shows average difference of -1.6 mm (absolute difference is 1.7 mm). The lower scanning speed is also an important issue with the use of this instrument for tunnel measurements.

Combining all these factors, of which the achievable accuracy is the most important one, the phase-based laser scanner Leica HDS6100 still seems to be the most suited type of instrument for these tunnel measurements.

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BIOGRAPHICAL NOTES

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