Approach for comparing design and as built models based on data acquisition using a 3D terrestrial laser scanner, a case study.

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Abstract

Substantial research effort has been devoted to the use of terrestrial 3D laser scanning as 3D modeling technique of the built environment. However, there has been relatively little study of the opportunity to use this data acquisition technique for the comparison between design and as-built geometry of large structures. Nevertheless, accurate knowledge about as-built geometry is useful in research concerning the improvement of construction or assembly methods and calculation techniques for structural design.

In this paper a case study is used to explore the possibilities of laser scanning for gathering information about the as-built geometry of large structures for comparison with the design geometry. This is done by following the whole trajectory, from the planning phase over the generation of 2D drawings based on the point clouds to the interpretation of the resulting deviations.

As a result of some shortcomings during the planning phase the outcome for this particular case study is not conclusive, however based on the analysis of the deviations noticed between as-built and design and the difficulties encountered during the data processing, the reader is provided with some points of interest to be taken into account when considering the use of laser scanning as data acquisition technique to investigate geometry and/or assembly variations of the different elements of a construction.

Introduction

3D models of the built environment can be obtained using different instruments and techniques such as total stations, GPS, photogrammetric applications and more recently terrestrial 3D laser scanning. (Grussenmeyer, Landes, Voegtle & Ringle, 2008) The latter is a fast method for acquiring 3D information and results in a high density point cloud with accuracies of a few millimeters. In most cases several scans have to be combined to produce an accurate 3D model. This model can then be used to produce 2D drawings.

Up until now, most scanning applications are situated in the field of architecture, renovation, preservation of cultural heritage, archaeology, spatial planning, modeling of industrial installations and even the film industry.

Knowledge of deviations between the as-built geometry and the design model is useful in the search for improved calculation, construction and assembly methods of large structures. Therefore, in this paper, the possibility to use laser scanning as a data acquisition technique to model the as-built situation is explored.

This is done by means of a case study for which every step, starting from the survey planning up to the comparison of the as-built and design geometry is carried out and commented.

The outcomes of the case study lead to some recommendations for future projects.

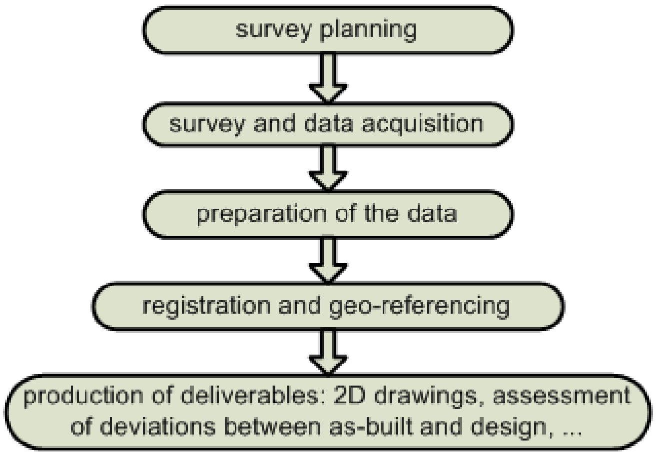

Fig. 1: Workflow

Case study: Bridge element at Lummen (Belgium)

The Lummen (Belgium) motorway interchange connects the European motorways E313 and E314. To address safety and traffic congestion issues, all conflict situations will be resolved by reshaping the interchange. An innovative concept, in which new bridge elements are prefabricated alongside the existing infrastructure, makes it possible to move the elements into their final location in merely one week-end, hence reducing the hinder for the daily traffic. The company responsible for the realization is Jan De Nul NV.

Fig. 2: Motorway interchange - Lummen (old situation: confliction traffic flows) - source: www.klaverbladlummen.be, 2008

Fig. 3: Construction site near E313 – Lummen - source: Jan De Nul NV, 2008

Fig. 4: Design visualisation

Fig. 5: Design visualisation: case study element

source: www.klaverbladlummen.be, 2008

Survey planning

When comparing as-built and design situations, exact knowledge of the tolerance values is needed in order to be able to determine the required level of detail of the end result and thus also the required measurement accuracy.

The degree of detail that can be recognized in the end product depends on the resolution of the point cloud. A decision table for the selection of the appropriate point density is given in "3D Laser Scanning for Heritage. Advice and guidance to users on laser scanning in archaeology and architecture." (English Heritage, 2007)

In general it is not useful to use a resolution higher than the measurement accuracy which is dependent on a lot of parameters and can be divided into four categories: instrumental, object-related, environmental and methodological errors. (Lerma García, Van Genechten, Heine & Santana Quintero, 2008)

Before starting the scan process, due attention has to be paid to the selection of the different scan positions and the selection of the target types and their positions.

On construction sites it is often not possible to choose ideal scan and /or target positions so compromises have to be made due to safety regulations, obstacles and visibility of the targets and the objects, ongoing construction processes and time frames.

Comment on the case study

Due to the strict time frame and the availability of the scanning equipment, not enough attention could be paid to the survey planning.

survey and data acquisition

In the case study at hand ten scan positions and seventeen targets were used to assure full coverage of both the inside and outside of the bridge element.


Fig. 6: Flat target (Trimble 3DS target)

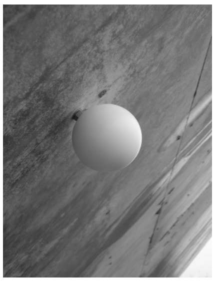
Fig. 7: spherical target (Trimble)


Fig. 8: Attachment of spherical target to upper side bridge element

For the data acquisition two Trimble GX Advanced 3D (Fig. 9) scanners were used.

The scanner is operated by the Trimble® PointScapeTM Software, installed on a Panasonic Toughbook CF-19 (Fig. 10).

Fig. 9: Trimble GX Advanced

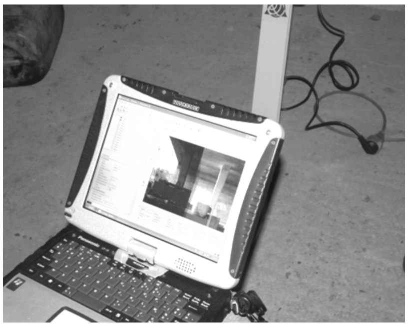

Fig. 10: Control of laser scanner with Trimble® PointScapeTM Software

Preparation of the data

Before processing the data a completeness check has to be performed and data voids have to be detected and, if necessary, completed by additional scans. This was especially important in this case study because after assembly most parts of the bridge element are no longer accessible for scanning.

During the scanning process a lot of unneeded points are registered. Trimble® RealWorks Survey™ advanced version 6.2 was used to clean up the data.

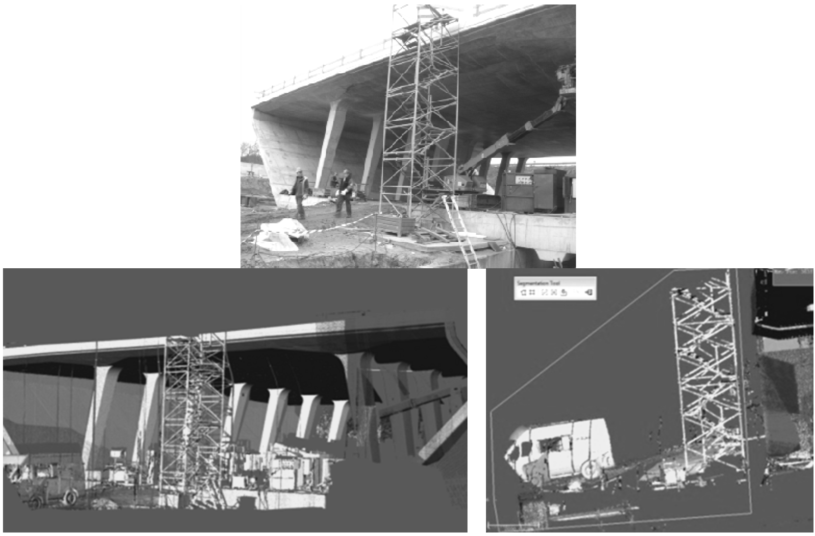

Fig. 11: Removal of obstruction with Segmentation Tool in Trimble® RealWorks Survey™ advanced version 6.2

Comment on the case study

A lot of obstructions were still present at the time of the survey. Due to the narrow time frame it was not possible to wait for all the obstructions to be removed. As a consequence some data voids caused by the removal of unwanted objects could not be avoided.

Registration and geo-referencing

In the case study Trimble® RealWorks Survey™ advanced version 6.2 is used to visualize, register and manipulate the data.

In the registration module the different point clouds are joined together based on corresponding targets. In this case a minimum of three common targets was selected for each registration. The resulting residual errors are all less than 2.5 mm.

No geo-referencing is performed because the position of the bridge element is of no relevance to the geometrical properties which are the subject of this study.

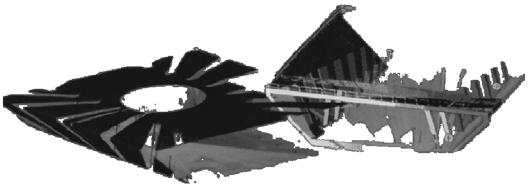

Fig. 12: Two point clouds before registration

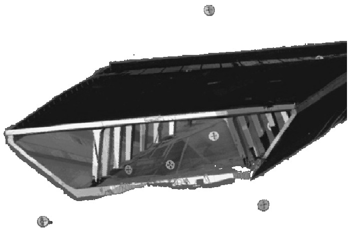

Fig. 13: All point clouds joined together

Trimble® RealWorks Survey™ advanced version 6.2

Production of deliverables

In order to compare the design with the as-built geometry, 2D drawings are generated from the point clouds.

During the case study several geometry features are examined: the column dimensions, the implantation (placement) of columns, the dimensions of the side panels and the level of the bottom plate.

In this paper the most relevant results will be mentioned and only the column dimensions will be explained more in depth to provide the reader with an understanding of the methodology used.

Evaluation of the column dimensions

To evaluate the column dimensions, horizontal cross sections are generated from the scan data and compared to the corresponding cross sections of the design. This is done by using four slightly different methods.
Method 1:

- Creation of horizontal reference plane for later comparison with the design model.
- Creation of triangulated meshes from a selection of the entirely merged point cloud.
- Smoothing of the mesh surface.
- Using the Cutting Plane tool to cut the mesh with a horizontal plane every 10 cm. The result of this cut is a polyline.
- Export to dxf file for further comparison in AutoCad®.

Method 2: Same as method 1, except that the meshes are created from a selection of the minimum amount of point clouds needed to assure full coverage (no data voids) of the column. The reason for not using the fully merged point cloud is to diminish the scan noise.
Method 3: Same as method 1, except that the Cutting Plane tool is used directly on the entirely merged point cloud. The result of this cut is a sectioned point cloud. Every point has the same Z-value. Then, the 2D-EasyLine™ tool is used to create polylines from the point cloud's slice.
Method 4: A combination of method 2 and 3 which means that the Cutting Plane tool is applied on the assembly of as little as possible point clouds after which polylines are created using the 2D-EasyLine™ tool.
Comparison of the results for all four methods is done by calculation of the area of each cross section and comparing it with the areas of the corresponding sections of the design drawings.
The acceptable deviations between as-built and design are given as a function the dimensions of the columns cross section (Jan De Nul NV, 2009).
Tab. 2 shows the results for column 6. The same calculations are done for columns 1, 7, 10, 11 and 16. All deviations are between 0.30% and 1.98%, which is well beneath the tolerance thresholds.
The results of method 1 are the most stable, so this seems to be the best method.

Tab. 1: Relation between dimension and tolerance value (source: Jan De Nul NV, 2009)

dimension	maximum deviation
< 150 mm	± 10 mm
= 400 mm	± 15 mm
≥ 2500 mm	± 30 mm

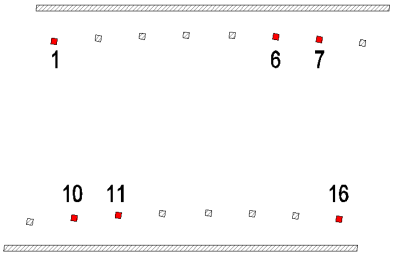

Fig. 14: Location of the columns that were assessed

Tab. 2: Column 6: calculation of the area of cross sections at different levels (using 4 methods), comparison with design values and evaluation of the established deviations

	height above horizontal reference plane					
	4000 mm			**5900 mm**		
Design	area (mm^2)		% deviation between design (=100%) and as-built	area (mm^2)		% deviation between design (=100%) and as-built
	606689			**749364**		
	tolerance interval (±15 mm/side)			tolerance interval (±15 mm/side)		
	min. area (mm^2)	583660		min. area (mm^2)	723723	
	max. area (mm^2)	630400		max. area (mm^2)	775668	
As-built:	area (mm^2)			area (mm^2)		
method 1	616861	OK	+1.68	758281	OK	+1.19
method 2	618975	OK	+2.03	765882	OK	+2.20
method 3	619615	OK	+2.13	756526	OK	+0.96
method 4	624595	OK	+2.95	769799	OK	+2.73

Comment on the case study

Because no characteristic features such as edges or intersecting lines were marked before scanning it is difficult to determine the exact beginning and ending of the columns which makes it not easy to determine the exact reference plane or the exactly matching cross sections.

Registration errors tend to augment as the distance to the targets increases, so more target should have been attached to the elements (in this case the columns) under investigation.

Verification of the angle between the column axis and the horizontal plane

The axis of symmetry of the as-built column is determined by connecting the center points of the lowest and highest column sections obtained in method 1. For column 6 the design angle is 76.143°, while the as-built angle is 76.359°, or a deviation of 0.216°. Connecting the centre points of different column cross sections leads to slightly different deviations.

Comment on the case study

Because no characteristic features such as edges or intersecting lines were marked before scanning it is difficult to determine the exact direction of the column axis. Also, there is no known tolerance on the angle, so conclusions regarding the angle deviations cannot be made.

Volume calculation of the side panels

The volume was calculated in two ways.

Method 1: Using the Volume Calculation tool which is based on a grid method. To calculate the volume of the side panels, meshes of both the inside and the outside are created. The bottom and upper border planes are created by selecting three points.

Method 2: Using the cutting plane tool several vertical sections are created. To obtain the volume, the area of a section is multiplied by the design length of the side panel (38.60 meters). This is done for five different sections for each side panel.

The results for the panel on the right are shown in Tab. 3.

The as-built volumes are slightly smaller than the design volume. The volumes calculated from the vertical sections are not stable due to the scan noise. Their mean value however is the same as the volume calculated by

RealWorks which leads to the conclusion that this method (method 1) is preferable to method 2.

On the other hand further investigation of the vertical sections calculated in method 2, shows that for the panel width, the mean of the deviation between as-built and design is -16 mm. This deviation exceeds the tolerance of ±15 mm. This observation however does not automatically lead to the conclusion that construction errors were made, because the deviation is the result of construction parameters together with standard deviations of the scanning process (Tsakiri, Lichti & Pfeifer, 2006; Boehler, Bordas Vicent & Marbs, 2003). In the same way a deviation not exceeding the tolerance, doesn't automatically mean that no construction errors were made.

Tab. 3: Volume comparison for the side panel on the right

DESIGN		area	design length	**volume**	% deviation from design (=100%)
3D-model		4.40 m^2	38.6 m	**169.86 m^3**	
AS-BUILT (method 1)	Volume calculation in RealWorks			**164.53 m^3**	-3.1%
AS-BUILT (method 2)	distance from start				
	0.0m	4.28 m^2	38.6 m	165.17 m^3	-2.8%
	10.0m	4.14 m^2	38.6 m	159.78 m^3	-5.9%
	20.0m	4.27 m^2	38.6 m	164.74 m^3	-3.0%
	30.0m	4.28 m^2	38.6 m	165.31 m^3	-2.7%
	37.0m	4.35 m^2	38.6 m	167.95 m^3	-1.1%
	mean:	4.26 m^2	38.6 m	**164.59 m^3**	-3.1%

Based on the observation that the distances between the scanner and the bridge element were (almost) always less than 50 meters, the number of shots was 4 for each point and the grid resolution was variable, Tab. 4 suggests a standard deviation on the distance measurements of 1.4 mm. The overall thickness of the point cloud is 2.5 times this standard deviation. Considering that the thickness of the panel is the result of two distance measurements and that during registration additional errors were introduced, in this case it is probably safe to say that construction errors do not exceed the tolerance values.

For the side panel on the left the deviations are well below the tolerance values (Tab. 5).

Tab. 4: Standard deviations of the scan process (source: Trimble, 2007)

range		50 m			100 m			150 m		
N° of shots		1	4	9	1	4	9	1	4	9
Grid resolution (point spacing)	4 mm	(2.8)	(1.4)	0.9	(5.0)	(2.5)	(1.7)	(7.2)	(3.6)	(2.4)
	8 mm	(2.8)	1.4	0.9	(5.0)	(2.5)	1.7	(7.2)	(3.6)	(2.4)
	12 mm	2.8	1.4	0.9	(5.0)	2.5	1.7	(7.2)	(3.6)	2.4
	25 mm	2.8	1.4	0.9	5.0	2.5	1.7	7.2	3.6	2.4

Tab. 5: Volume comparison for the side panel on the left

DESIGN		area	design length	volume	% deviation from design (=100%)
3D-model		4.40 m^2	38.6 m	**169.86 m^3**	
AS-BUILT (method 2)	distance from start				
	0.0m	4.36 m^2	38.6 m	168.13 m^3	-1.0%
	10.0m	4.36 m^2	38.6 m	168.18 m^3	-1.0%
	20.0m	4.35 m^2	38.6 m	168.01 m^3	-1.1%
	30.0m	4.37 m^2	38.6 m	168.60 m^3	-0.7%
	37.0m	4.40 m^2	38.6 m	169.66 m^3	-0.1%
	mean:	4.37 m^2	38.6 m	**168.52 m^3**	-0.8%

Column implantation

Verification of the column implantation is done by creating horizontal cutting planes of the meshes of all columns and the two side panels. Three cutting planes are selected for further examination: 0.10 m, 3.55 m and 6.20 above the floor level.

The column implantation is checked against cuts of the design model on the same levels.

The angles between the best fitting line through the front of the column and a line perpendicular to the nearest side panel are measured and compared to the design model. The results of this comparison differ from column to column, but as the tolerances are not known in this stage of the research it is not meaningful to include the results in this paper.

Conclusions and discussion

Deviations between as-built and design are inevitable. When using laser scanning as data acquisition method to generate the as-built model, the deviations are the result of errors in construction together with uncertainties induced by the scanning procedure and the processing of the scan data. The question to be answered is whether these deviations are acceptable in terms of, for instance, stability or esthetical issues. Hence the tolerance values are part of the constraints of the construction process.

Several methods can be used to determine the order of magnitude of the deviations and although for the case study the given geometrical constraints seem to be met, this cannot be stated with absolute certainty because of a number of shortcomings in the planning of the scan survey of which the impact on the resulting deviations is uncertain.

This leads to some conclusions for future projects.

For every topographic survey the planning of the field campaign is an essential part that, to a large degree, contributes to the quality of the end result and to the efficiency of the whole data acquisition and post processing process. When using 3D laser scanning this is even more the case, especially when geometry issues are the main topic of the research.

It is very important to determine the goals and objectives of the project and to have an insight in the requirements concerning the deliverables (2D, 3D, volume calculations,…), the level of detail and the desired accuracy. This knowledge is needed to determine the correct scanning parameters such as resolution, distance, target configuration etc. and to be able to interpret the established deviations.

When examining the geometry of construction parts it is imperative to attach targets to the part itself instead of in the surroundings, because the accuracy of the registration diminishes as the distance to the targets increases.

To facilitate the comparison between as-built and design characteristic, points or edges can be marked. These characteristic elements can later be used to establish axis of symmetry of element parts, determine, adjust or synchronize the orientation of the as-built and design models, tie the design model to the as-built model etc.

During the scanning one can be confronted with obstructions (scaffoldings, cables, construction waste, machinery, etc.) and time restrictions. Timely knowledge concerning such limitations is useful information for a better planning of possible laser scanner setup positions and target locations.

If possible two types of scans should be considered in this kind of projects. The first scan should be used to determine construction flaws and should take place before assembly. A second after assembly can provide information concerning the correctness of - and deformations due to the assembly. Follow up scans can be performed to determine deformations under service load and deformations in time.

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