TERRESTRIAL LASER SCANNING IN ENGINEERING SURVEY: ANALYSIS AND APPLICATION EXAMPLES

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ABSTRACT

Terrestrial laser scanning broadens its application areas in civil engineering, and claims even more attention in engineering survey. The paper shows the results of a laboratory test of a laser scanner. The laboratory test involved complex 3D accuracy analysis, reflectivity investigation of different colors and materials used at construction sites and observation of reflection angles. Instead of focusing on a particular laser scanner, the accuracy analysis put the emphasis on the evaluation procedure that enables the calibration and validation of different laser scanners.

The paper also discusses the application of laser scanning through examples of load test measurements of bridges. The authors have been involved in 4 bridge load test measurements; the modeling and evaluation techniques, the emerging challenges and results will be presented. Besides presenting the measurement techniques and results of the load test measurements, analyzing the effect of temperature on steel bridge is also presented in the paper.

ANALYSIS EXAMPLES

3D Accuracy

In order to apply terrestrial laser scanning in engineering survey complex analysis under laboratory circumstances required. The Department of Photogrammetry and Geoinformatics already validated the ranging accuracy (±5 mm) of the particular scanner Riegl LMS Z420i in 2006. The new laboratory measurement scenario in 2009 applied the same scanner in order to avoid differences caused by different manufacturer and to ensure the homogeneity of measurements.

The first laboratory investigation focused on expanding the ranging accuracy result to a more complex three dimensional accuracy value. The investigation was done in a laboratory where 9 points were measured with the laser scanner and with a Leica TRCM 1203 total station as well. The measurements from the total station were used to verify the results measured with the scanner and to validate the developed method.

The RMSE values of the distances in every point combination were calculated, the result is a 9 by 9 matrix with the following main statistical values:

$$\min(\mu_d) = 2{,}9mm,$$
$$\mathrm{mean}(\mu_d) = 8{,}3mm,$$
$$\max(\mu_d) = 13{,}2mm.$$

These results clearly show that under the particular circumstances of the test in the laboratory the overall precision of the measurements were better than the accuracy claimed by the manufacturer (Berenyi et al 2009).

Effects of Different Colors and Materials

In this particular examination the focus was put on the effect of different materials and colors from the reflected laser beam’s point of view. The reflectivity analysis would support future measurement campaigns by analyzing the laser beam’s reflectance capability from different materials used in civil engineering practice, such as concrete, brick, steel and different wooden surfaces.

Besides the effect of different materials, investigation of the effect of different colors for the reflected laser beam was carried out. In both cases the post-processing was done by self-developed software to minimize the possibility of human errors (e.g. selection errors) and to ensure the applicability in the future laboratory measurements.

The particular materials and the related reflectivity values can be seen in Table 1. Note that the best material from the reflectivity (and thus from the laser scanning) point of view is brick, and worst is steel.

Table 1. Reflectivity values of different materials

Material	N^{o} of points (per dm^{2})		Reflectivity	
		Min.	Max.	Mean
steel	3621	0,133	0,195	0,147
concrete (painted)	3626	0,141	0,227	0,186
concrete	3598	0,172	0,227	0,198
natural wood	3597	0,168	0,250	0,204
natural wood bark	3590	0,184	0,254	0,216
sawn wood	3596	0,199	0,254	0,226
raw wood	3597	0,203	0,231	0,232
varnished wood	3652	0,203	0,270	0,246
brick	3597	0,227	0,281	0,251

The effect of different colors was tested by scanning a board painted to matte white, grey and black. The results were calculated with the same software that was used in the previous investigation, Table 2 shows the results.

Table 2. Reflectivity values of different colors

Color	N^{o} of points (per dm^{2})		Reflectivity	
		Min.	Max.	Mean
white	3640	0,207	0,258	0,232
gray	3640	0,156	0,211	0,181
black	3619	0,035	0,129	0,085

It can be clearly seen that energy of the points reflected from the black area is significantly less. This could be very useful information regarding measurement planning, mainly in measurement scenarios where the color of the object could negatively affect the measurement accuracy and point density.

Effect of Incident Angle

The effect of scanning under critical angle of reflection has been analyzed in order to support planning laser scanning projects in difficultly accessible areas. By laser scanning the Megyeri Bridge (see later) the problem of incident angles were experienced and identified, thus during the laboratory investigation this factor has been tested as well. In order to simulate the different angles a steel plate was rotated in front of the instrument. The exact rotation angles were determined by two reflectors (special point markers) on the surface of the plate.

The results showed that under ~10° (170°) the point cloud becomes scattered and the determination of reflector coordinates becomes unstable. This result correlates with other investigations in this topic (Kersten et al, 2009).

APPLICATION SCENARIOS

Bridge Load Test Measurements

The capability of the laser scanning technology in engineering survey applications was proved by bridge load test measurements.

This kind of engineering survey application is very complex and needs a lot of time and manpower. Usually the bridge is loaded with trucks according to the predefined load plan. The load test starts with the 0th, unloaded case that would provide the reference level to the other load cases. In each load case the vertical displacements are measured with high precision leveling, the stresses are measured with strain gauges and the three dimensional movements (if needed, e.g. measuring pylon tilt) are measured with total stations. From these measurements the high precision leveling is the most time consuming, thus each load case lasts until the leveling teams are done that is usually around 20-25 minutes. Obviously this depends on the length of the particular bridge.

High precision is needed in this kind of engineering survey application and although laser scanning can provide results with limited accuracy its potential was confirmed during several load tests. The authors participated in 4 bridge load test measurements in the past few years that are briefly discussed as follows.

Pentele Bridge

The Pentele Bridge is a basket handle type tied arch bridge with a span of 307.8 m and height of 48 m. The first static load test was performed on 28th of June, 2007, started at 9 p.m. and lasted 9 hours. According to the time requirement of the high precision leveling, the bridge was loaded for 20-30 minutes in each load case.

Since only one scanner was available, the proper selection of the scanning position was critical; the most characteristic points of the bridge should be captured. Considering the available measurement time windows and the measurement range of the scanner, the station was selected at the left river bank (Fig. 1).

Figure 1. Laser scanning the Pentele Bridge.

The load cases lasted for only a short period of time and cannot be repeated, thus in order to capture the entire structure the scanning resolution was reduced. Therefore the displacements of particular points of two structural parts (the northern arch and the bottom part of the girder) close to the scanner have been obtained. Applying only a single station during laser scanning caused sizeable shadowed areas in the data set. These problems could be bypassed by multi-station scanning; the paper presents such example (see “Megyeri Bridge”).

The structural displacements derived from the laser scanned data sets are in strong correlation with those obtained from the traditional techniques. The computed maximum vertical displacement is ~35cm in both methods in the fourth load case (Fig. 2).

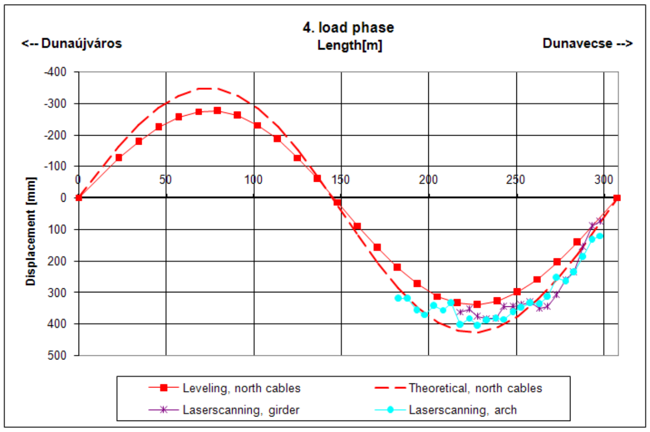

Figure 2. Displacements of the girder and arch derived by different techniques in the fourth load case.

Figure 2 shows the displacement values obtained from different methods: high-precision leveling (north cables), theoretical (computed/simulated) values and those of derived from laser scanning for both the girder and the arch. Note that the vertical displacement of the deck is measured directly at the cables, whilst the laser scanner captured the edge of the girder; however these structural elements are solidly coupled to each other. The reason of the oscillation on the curves derived from laser scanned data is the reduced point density; in the resulted data set it is difficult to fit regular edges and planes on the point cloud. After all, the trend of the curves and the displacement values validate the laser scanning measurements (Lovas et al 2008b).

Megyeri Bridge

By the load test of the biggest cable-stayed bridge in Hungary two scanners were used in order to maximize the point density and the overall coverage. This was needed not only because the bridge is relatively long (591 m), but also because the scanning positions were close to the bridge and the effect of small incident angles is always to be avoided (see chapter “Effect of incident angle”). The first scanner was deployed on Pest side, south from the bridge; the second scanner was deployed on the Szentendrei Island north from the bridge. Each load case lasted for about 20 minutes, thus the scanning resolution was determined according this time frame and was set to 0.03° for each scanner, resulting 6 million points (!) per load case.

During the post processing geometric elements were fitted to the point cloud and the results were determined by using these elements. This was needed in every laser scanned load case, because the raw measurement data contains only 3D points. After the fitting procedure the displacement can be measured between any points, no predefined points are needed. The results of laser scanning and leveling have been compared and proved laser scanning’s capability. As it can be clearly seen on Fig. 3 the results on the side where the scanning has begun are more correlated showing that the bridge wasn't 'standing still' during the load case, small displacements occurred even during the scanning (Berenyi and Lovas 2009).

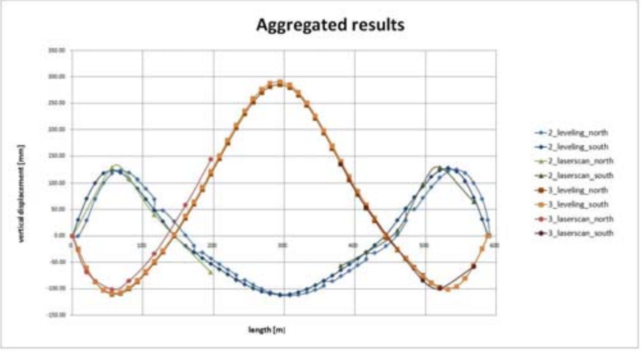

Figure 3. Aggregated results (high precision leveling and laser scanning) of Megyeri Bridge.

In addition to the vertical displacement of the deck, a lot of other results can be evaluated from a laser scanned point cloud that are not measured by traditional geodetic techniques. In this particular case the movements of the cables were analyzed. The point density of the scanned load cases allowed the modeling of the cables (Fig. 4), thus the different states could be compared to each other.

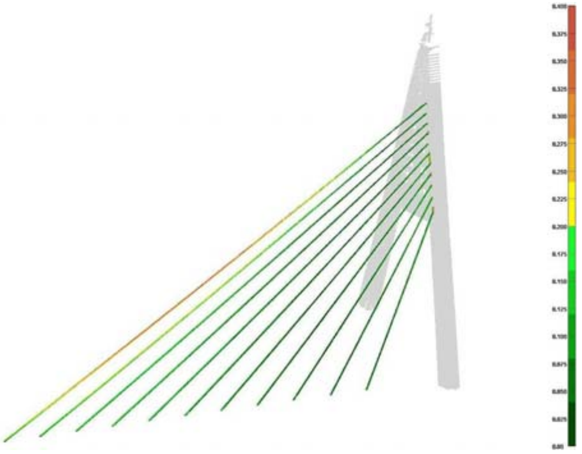

Figure 4. Cable displacements [m] in load case 3, Megyeri Bridge.

The fitted geometric elements were analyzed with numerical and graphical methods as well; results showed that displacements more than 4 decimeters occurred in the second load case (Fig. 5) (Lovas et al 2008a).

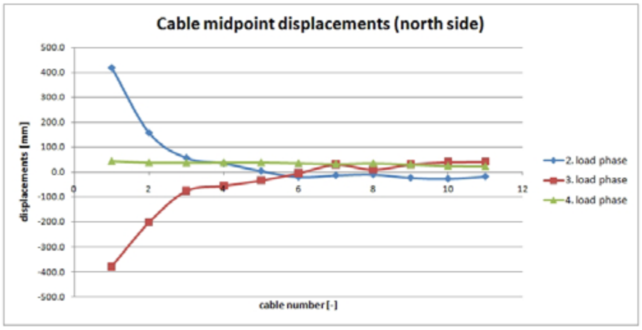

Figure 5. Cable displacements [m] in load case 3, Megyeri Bridge.

Szabadság Bridge

After the positive experiences from Pentele Bridge and Megyeri Bridge the authors were able to execute measurements during the load test of Szabadság Bridge. This steel truss bridge is relatively small with its total length of 333.6 m and its longest span of 170.75 m. The renovation of the bridge finished in fall 2009, and the load test was scheduled to 17th of December 2008.

Because the ambient temperature was close to the minimum value (0 °C) of the operation limit, and because of the hard weather circumstances (rain, later snow) the scanner was deployed under the trunk-lid of a car (Fig. 6). The lid defended the scanner from the rain and the car’s heating system ensured a bit higher temperature for the scanner.

Figure 6. Scanning position, Szabadság Bridge.

By this particular load test the expected vertical displacements were only around 10 cm, thus this was a good opportunity to prove that the technology can be reasonably applied even at smaller displacements.

The post-processing took more time, because the laser beam reflects from raindrops and these points had to be filtered out. The time frame of scanning was also defined by the time consumption of high-precision leveling, thus the angular resolution was set to 0.03°. With this value a single scan lasted 14.5 minutes and captured 1.5 million points.

Another challenge was the geometry element fitting during the post processing. Because of the shaded deck (from the scanning position it was not visible) other elements have to be found that moved together with the deck; finally the north sidewalk of the bridge was chosen. The post-processing method included cross-section generation, analysis and geometric element fitting as well. These procedures proved the technology's potential again, the results are shown on Fig. 7.

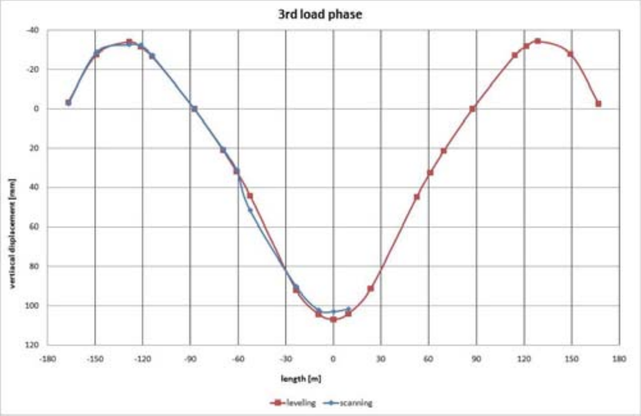

Figure 7. Results from leveling and laser scanning, Szabadság Bridge, 3rd load case.

Besides the regular measurements, the positions of the trucks in different load cases were analyzed. This is very important in order to check whether the load is exactly located according to the plan. The results showed that the maximum difference was about 0,5 m (Fig. 8). The effect of this kind of displacement needs further analysis.

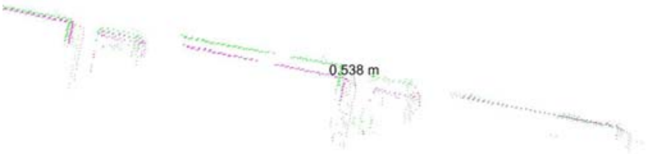

Figure 8. Truck position in different load cases, Szabadság Bridge.

Szebényi Bridge

Laser scanning the load test of the Szebényi Bridge resulted interesting experiments. The measurement was done in January 2010 at low temperature (-4-5 °C degrees). The applied Leica C10 scanner enabled scanning in this extreme temperature range. This motorway viaduct spans above a valley that enabled to set up the scanner close to the bridge ensuring ideal scanning angles and even scanning from a station under the bridge (Fig. 9).

Figure 9. Scanning station at Szebényi Bridge.

The displacement results correlated properly with the outcome of the leveling. The free setup of the scanning stations made the technology capable of:

- cross section analysis of the bridge and
- analysis of pillar tilt in each load case.

Scanning the main girder from underneath the bridge enables investigating the asymmetric displacements, i.e. the differences of the left and right side of the bridge. This scanning station underneath and that one exactly in the middle of the particular span provided good visibility to the pillar heads, therefore enabled the analysis of their horizontal movements (i.e. tilt distances). Obviously these kinds of measurements can also be executed by conventional geodetic measurement but would require previously dedicated points, more manpower, and finally more time.

Effect of Ambient Temperature, Erzsébet Bridge

In addition to bridge load test measurements the technology was tested in different civil engineering applications as well. One of these is the investigation of the effect of ambient temperature on steel bridges. The authors have chosen Erzsébet Bridge (Fig. 10), a cable bridge with a span of 290 m, thus reacts relatively fast for small changes in the ambient temperature, and has the specialty, that both of its pylons are standing on the Danube bank, not in the river.

Figure 10. Erzsébet Bridge from the first scanning station.

The first (reference, 0th) measurement was done in November 2008. Measurements were taken from both sides of the bridge (Pest and Buda) in 7°C ambient temperature. On both sides of the bridge local reference ground networks were set up, in order to support the future measurements. The measurements were done around midnight in order to minimize the effect of traffic on the bridge. This is essential because several public transport lines cross the bridge. The scanning positions were deployed about 200 meters far from the bridge to minimize the effect of incident angles. The second measurement was done in August 2009, in 22 °C ambient temperature.

Figure 11. Modeling the main cable and the deck.

The post process included the analysis of the vertical displacement of the main cable and the deck: the fitted polylines on these elements are shown on Figure 11. Considering the first as reference the differences were investigated; the results showed maximum difference (i.e. the vertical displacement of the main cable) of 12.8 cm in the middle of the main cable. The displacement values were determined from deck's point clouds as well. The exact values were calculated indirectly, because from the scanning position only a small part of the deck was visible, however other structure elements (e.g. pavement, handrail) that move together with the deck were easy to be identified and analyzed.

CONCLUSION

Laser scanning can support several civil engineering applications. Prior to specific measurements the capabilities, performance and limitations of the technology have to be investigated.

The authors carried out laboratory measurements in order to assess the overall 3D accuracy of the laser scanner. The investigations confirmed the manufacturer’s accuracy claim. In civil engineering applications not only accuracy values but specific circumstances are also to be considered. The laboratory investigations included the analysis of the reflection angle of the laser beam; as a result, a critical angle has been derived. Besides, reflectivity performances from different materials and colors have been also evaluated that can reasonably support future civil engineering projects.

The authors participated in several bridge load test measurement campaigns by surveying the displacements and deformations by terrestrial laser scanner. Comparing the results to the traditional high precision geodetic measurements has proved the remarkable potential of laser scanning. Besides measuring the vertical displacements of the bridge deck, laser scanning enables measurements in any points that should not be defined prior to the measurement. Moreover, in many cases laser scanning was able to provide data about specific structural elements that are not surveyed by other methods (e.g. cables).

As further application related to bridges, the effect of ambient temperature on sizeable steel structures has been also investigated by laser scanning.

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