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MONITORING TECHNICAL CONDITIONS OF ENGINEERING STRUCTURES USING THE TERRESTRIAL LASER SCANNING TECHNOLOGY

Janina Zaczek-Peplinska, Mariusz Pasik, Artur Adamek, Anna Adamek, Maria Kołakowska, Sławomir Łapiński

Warsaw University of Technology
Faculty of Geodesy and Cartography
Warsaw, Poland

Abstract

The laser scanning technology offers quite new possibilities in the field of the existing monitoring of engineering structures. The basic advantage of the laser scanning technology is huge amount of measuring observations and practically complete geometric and spectral information about the measured structures, which may be required within the short time. In the context of detection of threatens related to deformations and displacements of building structures, the surface - quasi-continuous distribution of measuring points is one of the most important factors. which ensure the possibility to perform correct evaluation of safety conditions of investigated structures. The proposed technological solution offers a series of new possibilities and the resulting methodology of determination of deformations and displacements of various structures, will considerably increase the scope of possible works and analyses. This will also create the new segment of data, which will result in delivery of additional information concerning conditions of the structure to experts from various fields, such as, among others, civil engineering, construction or geotechnique, who monitor the given structure.

Keywords: monitoring, terrestrial laser scanning, displacement

1. Advantages and limitations of terrestrial laser scanning with respect to its utilisation for evaluation of technical conditions of engineering structures

Building investments performed within the urban space, in particular in city centres, require geodetic monitoring to be performed with respect to their impacts on the environment. The basis for evaluation of technical conditions of monitored structures, are mainly the values of vertical displacements (precise levelling) and horizontal displacements (precise angular-and-linear measurements), performed by means of conventional methods.

These methods are based on observations of measuring targets, mounted in characteristic points of investigated objects. Often the historical and monumental values of an object do not allow for placing the measuring targets and values of displacements, observed by means of conventional methods in discrete points do not present the complete information concerning deformations of investigated structures. Therefore, the frequency of utilisation of modern methods for imaging deformations of structures is increasing; such methods include laser scanning, which allows for considerable increase of the density of measuring points, without the necessity of signalling them (Reshetyuk, 2009).

The paper will discuss the advantages and limitations of terrestrial laser scanning with respect to utilisation of this technique for determination of displacements. Until now, TLS has been introduced for deformation monitoring of different applications in the field of engineering geodesy. (Tsakiri et al., 2006) Terrestrial laser scanning proved its potential in deformation test measurements. The laser scanned point cloud hold information about the whole visible part of the structure and enable measuring the displacement and deformations during the post-processing, without previously marked, dedicated points (Lovas et al., 2008).

Besides the lack of the necessity of signalling, the advantage of scanning is the high resolution of points of measurements; as a result, the quasi-continuous image of surface of scanned structures is obtained in the form of 3-dimensional clouds of points. The resolution of recorded scans - with the same angular resolution - depends on the value of the incidence angle and the distance from the object. The high resolution allows, among others, for achieving the millimetre accuracy of determination of components of displacements. Due to the possibility of overlaying clouds of points, recorded within specific time intervals, laser scanning is characterised by the simplicity of obtaining displacements of analysed structures, in the direction perpendicular to the scanned surface, as well as deformations in the form of hypsometric maps.

Terrestrial laser scanning is based on a remote data acquisition and allows the registration of a set of points, each of which has x, y, z coordinates and additional information such as serial number and intensity of the reflection (Vosselman, 2010). Examples of the applications of TLS include: as-built surveys of buildings and facilities (industry, architecture, etc.) for the purpose of documentation of their existing condition; documentation of historical monuments (churches, castles, places, etc.) for the purpose of virtual reality (VR) modeling, detailed condition and damage assessment, as well as restoration at any given time in the future in case of damage or destruction, deformation monitoring of engineering constructions and excavations, surveys of tunnels and rail tracks for the purposes of inspection, damage identifications, etc., volume calculations, stability monitoring and geotechnical and geological mapping in mining, rock face surveys forensic investigations; documentation of excavations in archeology (Reshetyuk, 2009). Deformation monitoring in a Geodetic sense is conducted by surveying a region of interest at different points of time and by identifying geometric changes based on the captured data in between the respective epochs (Möser et al., 2000).

In this paper we will focus at deformation monitoring of engineering constructions. Terrestrial laser scanning is limited by the difficulty in determination of displacements in the plane of the investigated structure. This difficulty will be further discussed in next sections of this paper.

2. Experimental works concerning utilisation of terrestrial laser scanning

The test site was located within the neighbourhood of the Skanska Atrium South investment, implemented close to the UNO Roundabout (Rondo ONZ) in Warsaw. Investigations of the impacts of deep foundation of this investment included determination of components of displacements of three buildings: Ciepła 3, Pereca 1A and Prosta 12/14 (Fig. 1).

Fig. 1. Controlled structures of the "Rondo ONZ" polygon (Zaczek-Peplinska et al., 2013a)

In the period between December 2011and June 2012 4 sessions of precise, angular-and-linear measurements, to about 50 controlled points, signalled by targets of the reflective film, were performed in co-operation with Skanska S.A. (Zaczek-Peplinska et al., 2013a). Measurements were performed on: December 27,2011 (cycle 1), March 19-22, 2012 (cycle 2), April 24-25, 2012 (cycle 3) and May 22-24, 2012 (cycle 4).Leica TCRP 1201+ and TCRP1202 total stations were used for measurements. Figure 2 presents the distribution of points on the northern walls of the investigated structures, which directly neighbour the excavation; that is why they are interesting from the perspective of observed values of displacements.

Together with conventional measurements, the measuring experiment concerning the utilisation of laser scanning was performed in order to specify its usefulness and accuracy of determination of displacements, which obtained by this technique. Laser scanning was performed in the measuring cycles 2 and 4. The Z+F Imager 5010 scanner was applied for recording the scans.It was assumed that the basis for evaluation of accuracy will be determination of positions of measuring targets from scanning and their comparison with positions specified by means of conventional surveying methods.

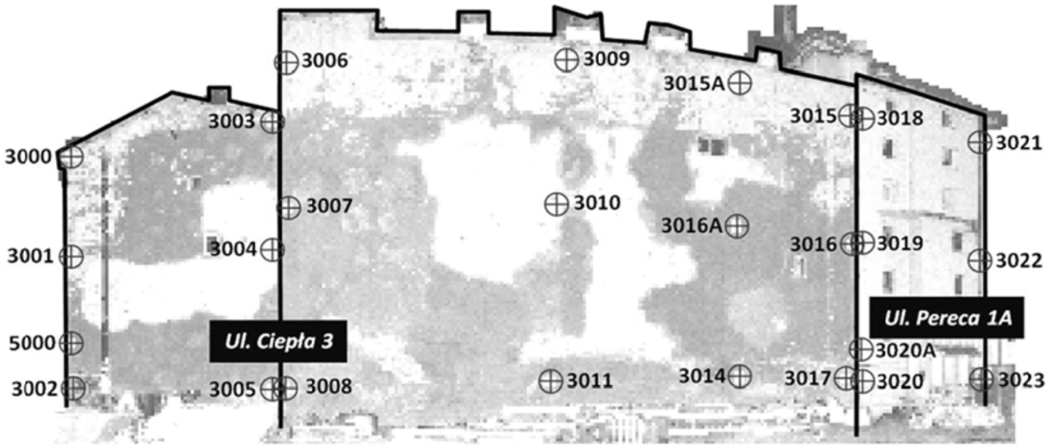

Fig. 2. Distribution of control points on the northern walls of Ciepła 3 and Pereca 1A buildings

A critical component within the process chain of deformation monitoring is the transformation of subsequently captured point clouds into a reference respectively superior coordinate system (Wujanz et al, 2013). In order to transform the cloud of points from the local system of the scanner to the external reference system in the field, positions (XYZ) of the scanner and signalling targets were determined; they were recorded on scans and measured using the conventional, angular-and-linear, precise methods of surveys. The maximum errors of their positions were obtained from independent, free, horizontal and vertical adjustments; they were equal to: 1.3 mm - for the horizontal position and 1.4 mm - for the vertical position. Basing on these reference points transformation of scans to one system was performed using the ASCAN Astragis software package. Then, co-ordinates of control points, obtained from scanning, were determined. Those co-ordinates were compared with co-ordinates of control points obtained from independent, horizontal and vertical adjustments, based on precise, angular-and-linear measurements. For those operations the following, maximum errors of positions were obtained for control points: 2.0 mm for the horizontal positions and 1.3 mm for the vertical positions.

3. The issue of identification of positions of control points placed on scanned structures

In the scanning, control points are an ideal accessory for ensuring good accuracy and, at the same time, checking the scan. The accurate determination of the position of control points and their multiple determination from various scanning positions allow reaching the maximum accuracy in the evaluation of the whole project. The accuracy of the position of control points may be verified by classic geodetic methods (Štroner et al., 2011).

Due to the fact that the experiment concerning the utilisation of laser scanning was accompanying conventional angular-and-linear measurements, control points of the reflective film were used; they are not dedicated to the phase measuring systems, which are used in the Z+F Imager 5010 scanner. The reflective film used for distance measurements caused some difficulties in precise identification of control points on scanned images, both in the plane of the scanned walls of buildings, as well as in the perpendicular direction. This may be visible in Fig.3, as the blurred cloud of points.

Fig. 3. The blurred cloud of points, presenting control points of the reflective film

It should be added that - in the plane of scanned structures - the accuracy of identification of positions of specified control points and details of the structure also depends on the scanning resolution. The low resolution decreases the accuracy of determination of displacements of details, which are not signalled, in the plane of the scanned structures.

When the professional measuring targets, dedicated by the scanner manufacturer, which are applied in laser scanning, the difficulty concerning identification of control points may be reduced or eliminated. Contrasting fields of such targets allows for precise determination of their central points, with the use of recorded intensity of reflection of the scanner beam (which is called the fourth coordinate) (Fig.4). Additionally, such targets have two axes and they are produced with the high precision. The manufacturer specifies the accuracy of placing the central point as 0.2mm.

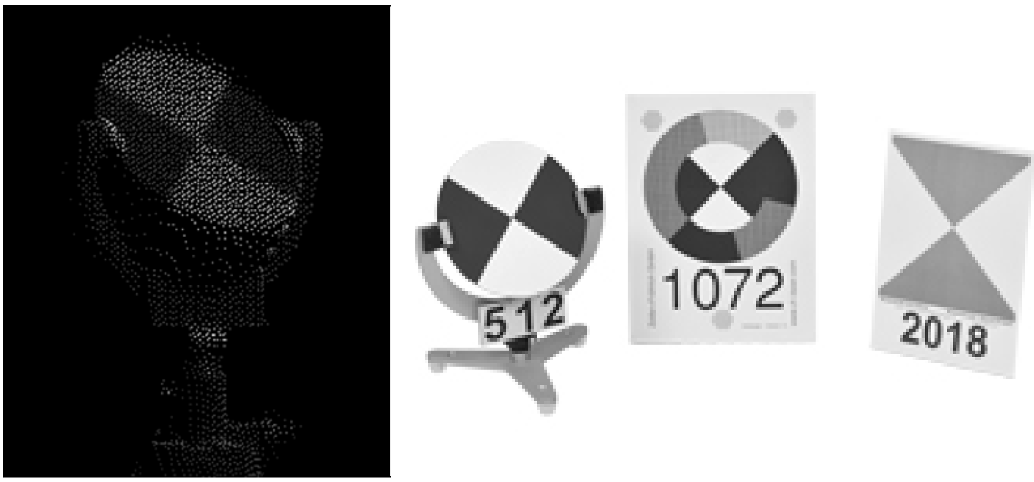

Fig. 4. Professional signalling targets for laser scanning and examples of their images (left) with the use of the intensity of reflection of the scanner beam (Zoller-Frohlich 2013).

It should be emphasized that if we use original targets the accuracy of the determination of control points' position is practically doubled against the value declared by the manufacturer (the standard deviation being half its value) (Štroner et al., 2011).

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4. Comparison of the values of displacements on control points, obtained by conventional methods and by terrestrial laser scanning

Figure 5 presents the values of horizontal displacements obtained with the use of conventional methods and laser scanning for the most representative, northern wall of the Ciepła 3 and Pereca 1A buildings in cycles 2 and 4 (Zaczek-Peplinska et al., 2013b). Displacements for both techniques were referred to the cycle 1 - which was the initial one. Figures present the values of horizontal displacements of control points at three levels. Continuous lines present the trends of changes observed with conventional methods and dotted lines present corresponding trends of determined with the use of scanning. Lines parallel to the walls of the buildings are placed within intervals of 2mm, what allows for evaluation of the values of displacements, as well as the discrepancies of trends for both techniques of measurements.

As both trends prove, the high compliance of horizontal displacements obtained by both methods was obtained, although difficulties concerning identification of control points occurred. The maximum discrepancy of trends for the highest level equals to 8 mm, both for the direction parallel and perpendicular to the wall; the average value equals to approx. 4mm. Discrepancies for lower level do not exceed the value of 4mm, and their average values - 2 mm. This should be considered as the satisfactory result and the high compliance of the applied techniques of measurements. It should be stressed that those discrepancies slightly exceed the level of accuracy of determination of control points, being the basis for the analysis; this proves the high compliance of results of conventional measurements and laser scanning. This is also proved by the maximum errors of adaptation, equal to 2-3 mm, obtained for tie points (the scanner positions and signalling targets), in the process of transformation of scans to one system.

The slightly higher discrepancy of trends for both techniques, observed at the highest level, may be justified by the big incidence angle of the scanning beam, which reaches 40 degrees.

Discrepancies of vertical positions of control points, determined by means of precise angular-and-linear measurements and with the use of laser scanning achieved the maximum value of the order of 1cm, and the average value equalled to approx. 4 mm. It is the accuracy which far exceeds the accuracy of precise levelling. Therefore the evaluation of vertical displacements of engineering structures is still mainly based on values of displacements obtained by this method. It should be remembered that slightly worse accuracy of vertical components of displacements is also the resultant values of the scanning resolution and impacts of the vertical refraction.

At present, experimental works concerning utilisation of precise levelling for improvement of the accuracy of vertical displacements obtained by means of laser scanning have been performed at the Chair of Engineering Geodesy and Topographic Measurements of the Warsaw University of Technology.

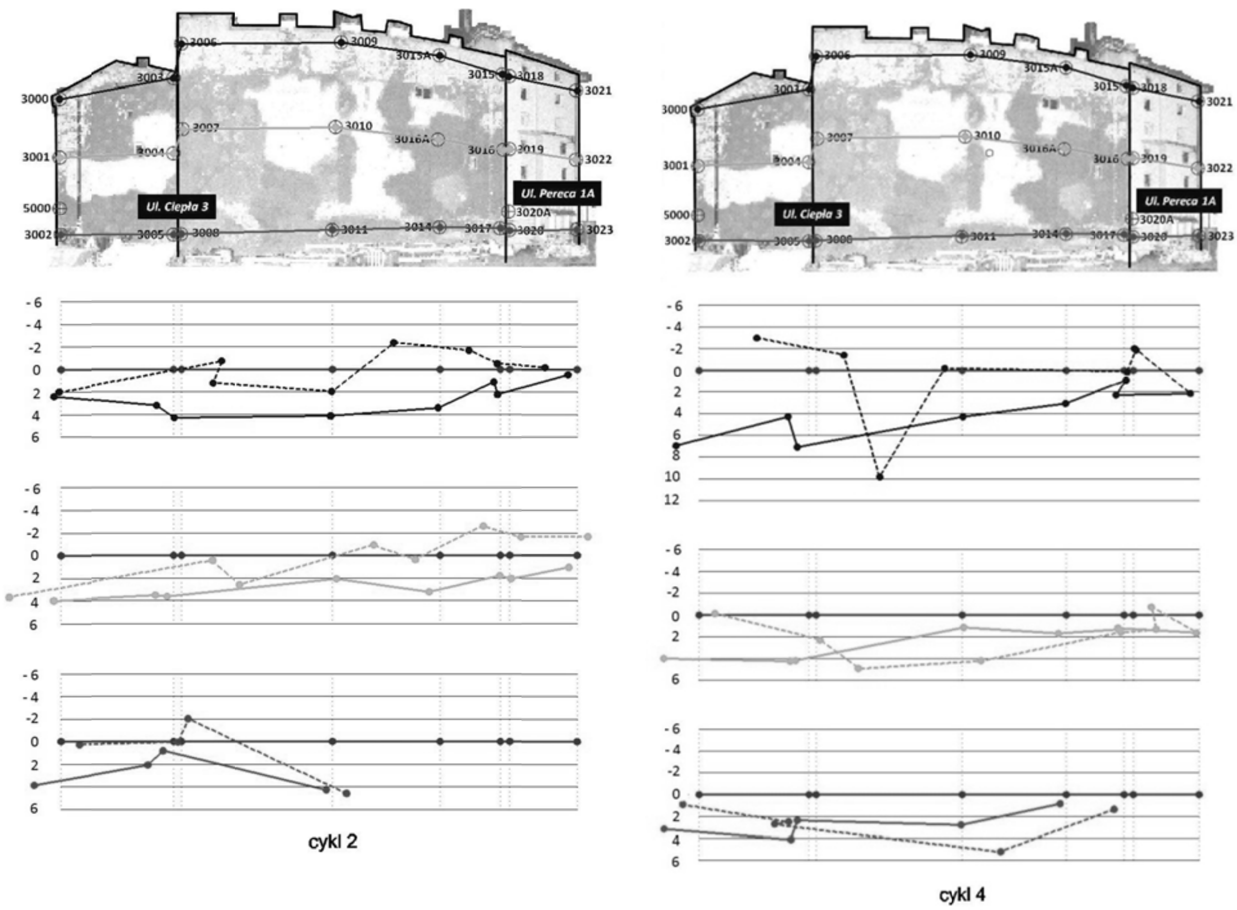

Fig. 5. Comparison of vertical displacements of controlled points on the northern walls of Ciepła 3 and Pereca 1A buildings obtained by conventional methods (straight Line) and by laser scanning (dotted line) in cycles 2 and 4 (Zaczek-Peplinska et al., 2013b)

5. Utilisation of hypsometric maps for analysis of scanned surfaces

The existing accuracy analyses of displacements obtained by means of scanning were discrete due to the nature of conventional methods, which are the bases of their evaluation. Since the clouds of points allow for obtaining "quasi-continuous" image of scanned surfaces, it allows for comparing scans from various measuring cycles and for obtaining hypsometric maps of displacements in the direction perpendicular to scanned surfaces or maps of deformations of measured structures. Therefore hypsometric maps allow for continuous presentation of results, and for signalling changes which are invisible for discrete conventional methods (Fig. 6); undoubtedly it is the advantage of the discussed method. Figure 6 presents values of deformations between cycles 2 and 4, when laser scanning was performed.

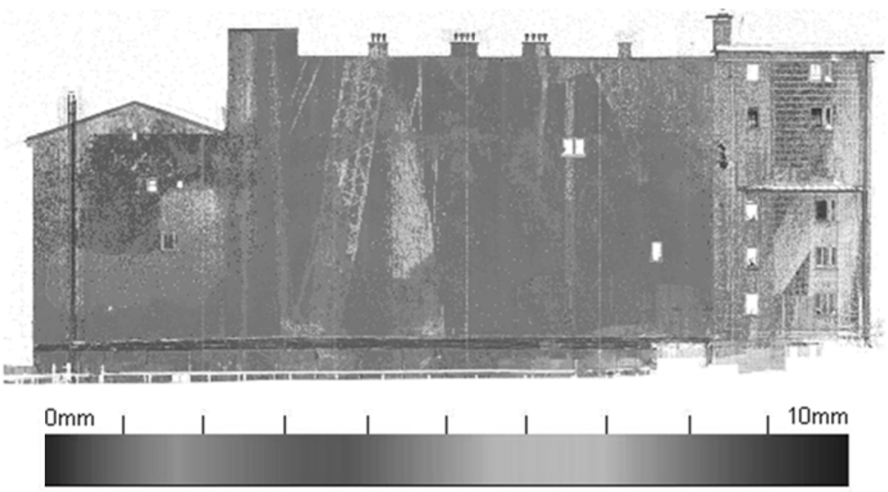

Fig. 6. A hypsometric map of deformations of the northern walls of Ciepła 3 and Pereca 1A buildings in the direction perpendicular to the scanned surface (Zaczek-Peplinska et al., 2013b)

It is also possible to create hypsometric maps, which present the geometry of scanned structures with respect to the horizontal plane; besides the values of displacements or deformations, it is also the valuable information concerning the safety and technical conditions of structures.

It may be also added that the laser scanning technique allows for creation of sections and for inventory of cracks, as well as determination of the size of cracks on surfaces of scanned structures. It also may be used in many other possible fields of applications.

6. Final conclusions

The results of research, presented above, proved the usefulness of the terrestrial laser scanning technique for determination of displacements and deformations of engineering structures. Those results allow for drawing the following conclusions:

1. Insufficient resolution of scanning is the limitation of the ability to achieve the high precision of components of displacements, in particular in the plane of a scanned structure.
2. In order to achieve the high precision of determination of displacements in the plane of the scanned structure, signalling in the form of targets dedicated to the given scanner type (phase or pulse) should be applied.
3. Terrestrial laser scanning allows for determination of the horizontal displacement (in particular in the perpendicular direction to surfaces being scanned) with the accuracy which is similar to the accuracy of conventional methods.
4. Laser scanning allows for fast identification of areas of potential threats for the safety of the structure.The advantage of images obtained from scanning is the information continuity, therefore they may amend, or even compete, with conventional methods (in the field of determination of deformations of large areas).
6. Scanning not only allows for determination of displacements of an investigated structure, but also for recording variations within its neighbourhood.

7. Laser scanning delivers many additional information which can be used by experts from many sectors.
8. The presented experiment confirms the possibility to monitor technical conditions of engineering structures with the use of terrestrial laser scanning.

Integration of measurements, the inclusion of numerical modeling to evaluate the behavior of the object and the assessment of technical condition qualitatively different data, allow to assess objects more comprehensively, and thus more fully, and gives the picture, which is more clear and transparent. (Adamek et al., 2012).

At present the laser scanning technique has been one of techniques of survey measurements, which grows very fast; its applications also grow. The above experiments allow for consideration of this technique from the perspective of severe accuracy requirements, which are formulated in engineering measurements, such as measurements of displacements. It may be stated that - when specified requirements are met - terrestrial laser scanning meets such requirements, at least with respect to the horizontal components of displacements, in many types of works. We should hope that the current experiments will allow, in the near future, for formulation of similar conclusions with respect to the vertical component of displacements.

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Authors:

PhD Janina Zaczek-Peplinska [1)], j.zaczek@gik.pw.edu.pl
Msc Mariusz Pasik [1)], m.pasik@gik.pw.edu.pl
Msc Artur Adamek [1)], a.adamek@gik.pw.edu.pl
Msc Anna Adamek [1)], adamek.ania@gmail.com
Msc Maria Kołakowska [1)], m.kolakowska@gik.pw.edu.pl
Msc Sławomir Łapiński [1)], s.lapinski@gik.pw.edu.pl
[1)] Warsaw University of Technology, Faculty of Geodesy and Cartography,
Pl. Politechniki 1, 00-661 Warsaw, Poland