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Izvorni znanstveni članak

Analysis of Structure Surveying Method by 3D Laser Scanners

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ABSTRACT. Terrestrial laser scanning (TLS) in carrying out projects in the construction industry is increasingly applied. This paper is considering the issue of accuracy that can be achieved by pulse TLS, evaluation of the measurement results and the applicability of this technology for the structure survey. Analyzing the measurement methods allows the identification of systematic errors of the instrument, which is serious obstacle for high-accuracy of TLS. In this article a standardization measurement procedure and the relationship between the projected tolerance and TLS calibration are given. At the same time the results of individual calibration of pulsed Leica scanners are presented, in which the systematic errors of measurement results are determined by the given model. Evaluation of survey results confirmed the high applicability of TLS for the structures survey.

Keywords: terrestrial laser scanners, structures survey, scanner calibration, survey results evaluation.

1. Introduction

Terrestrial laser scanning provides a new approach to gathering information about the structures and allows the registration of thousands of different information per second. There are both: spatial as well as other types of information – the attributes of objects which are the subject of the scanning. The scanning process is almost completely automated, and the 3D information regarding the position of the scanned points are characterized by high precision. This allows considerable savings in terms of the amount of field work and the speed of the project

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realization. There is a significant advantage over conventional technologies which are limited by low spatial resolution because they are based on collecting 3D information of the characteristic object points. Superior characteristics lead to the growing application of laser scanning in the implementation of various projects, particularly in the field of structures survey.

Terrestrial laser scanners are still produced in limited series and their accuracy varies from instrument to instrument, even though they have been produced in the same series. Manufacturers declare the accuracy characteristics of these instruments, but research shows that data often do not correspond to reality. However, the question of accuracy of laser scanners is essential for their optimal use and the right answers can be obtained in the process of testing the accuracy and the individual calibration (Nedeljkovic 2010). The first tests that describe the accuracy of the laser systems were carried out about 2000 and since then articles considering this issue are constantly being published.

The focus of the research is analysis of structures survey method by terrestrial laser scanning and to this end is necessary to examine objectively and evaluate the accuracy of the results before and after completion of measurements (Nedeljkovic 2010).

In the analysis of measurement method the identification and description of random and systematic measurement errors are made. In the group of assigned errors random errors are those that predominantly affect the measurement results of laser scanners with direct georeferencing and are included in the formula evaluating of the accuracy of the scanned point (Nedeljkovic 2010).

The research of systematic errors and the definition of functional models are also focused in this article. The corrections described by functional models need to be entered in the uncorrected results of measurements in the process of instrument calibration. Calibration is performed using an independent procedure, comparing the scanned results with true values of the control points. Mathematical model (Mikhail 1976) was developed to meet the specific needs of the required task (Reshetyuk 2009, Nedeljkovic 2010).

Laser scanners Leica HDS 3000 and Leica Scan Station 2 are calibrated in the laboratory in a predetermined test area which also define reliable geodetic coordinate system. Scan Station 2 was also calibrated in field conditions during the scanning of the Belgrade University College of Professional Studies for Civil Engineering and Geodesy (VGGS) building.

The subject of the paper research is also evaluation of measurement results by laser scanners. In order to estimate the results obtained by scanning, more than one view of uncorrected and corrected measurement results are used. The obtained results enabled the evaluation of the applicability of laser scanning technology in the structure survey.

2. Review of Experiences and Problem Description

2.1. Structure Survey Experiences by TLS

In early use of TLS (Schulz and Ingensand 2004a, Lichti and Gordon 2004) the authors were focused on description of characteristic use such as scans of cultural heritage and infrastructure scanning. The focus was on describing the scanning process, scan registration and 3D structure modeling. Information on the achieved precision were often described by qualitative indicators. Influence parameters and errors caused by them have not been comprehensively examined in this period which was necessary for quantitative expression of achieved precision.

The errors of direct georeferencing were studied in the survey project of the temple under the protection of UNESCO in Thailand (Lichti and Gordon 2004). The accuracy of the scanned points on the object was lower than declared precision for the type of scanner, which the authors assigned to the uncertainty of length measurement and poor identification of the laser beam center within the laser spot print.

The importance of evaluation of scanner performance is pointed out in the scope of the calibration scheme for the determination of instrumental errors (Tsakiri et al. 2006) and the other procedures in cases with millimeter tolerances, or below. The authors pointed out that they managed to detect reflective signals movement of 0.5 mm in monitoring the object deformation using Cyrax 2500. Such high precision is rarely declared in later papers.

It is interesting to explore the possibility of urban modeling and reconstruction using a vehicle equipped with TLS (Boström et al. 2006), which can provide data collection from a large area in a relatively short time and without using artificial signals. Of course, the precision achieved was lower than the one that fixed TLS provides.

The characteristic use of TLS is also shown during the project of reconstruction of the water tower in Hamburg (Kersten et al. 2009). The network of control points determined by TC technology was used for the purposes of controlling the quality of results of TLS scanning.

One example of the application of TLS in Serbia is scanning and modeling the facade of the Town Hall in Novi Sad (Pajic et al. 2009).

Based on presented papers it is obvious that the terrestrial laser scanning is used extensively to collect spatial information in solving problems related to structure survey. This information provides a detailed description of the spatial geometry of scanned object with high-speed data collection. Most often the accuracy of this information is such that they meet specified tolerance. However, there is a lack of general evaluation of the applicability of this structures survey technology that connects the projected tolerance and used observation method.

2.2. Experience in TLS Calibration

In recent years, numerous research papers appeared and they present testing accuracy results and various calibration models of laser scanners. The most of the authors use a test field of control points, i.e. signals, in laboratory conditions to determine the accuracy of 3D laser systems, test measurement results r, φ, θ and individual calibration.

Testing the accuracy and calibration of laser scanner Cyrax 2500 are performed by comparing measured and true values (Santala and Joala 2003). A paper on testing the laser scanner Imager 5003, Zoller + Froehlich (Schulz and Ingensand 2004b), in laboratory and field conditions is published. Based on these results it was concluded that high accuracy operations require investigation of instrumental – the systematic instrument errors. Also, an analysis of accuracy and exploring the use of Leica HDS 3000 for tunnel deformation measurements (Lindenbergh et al. 2005) is performed. All this pointed to the possibility to combine scans from different periods and different scanning positions, during deformation monitoring. It is stated that the maximum systematic error is 2 mm, and standard deviation below 6 mm.

The paper on the modeling and calibration of AM-CW (amplitude-modulated-continuous-wave) scanning system, Faro 880, which belongs to the group of panoramic scanners by its characteristics is published (Lichti 2007). The tests were conducted under laboratory conditions using test field of signal points. The mechanism of correlation between model parameters and elements of the instrument calibration is thoroughly researched.

Comparative test analysis of terrestrial laser scanners of new generation has given useful information on the accuracy of these instruments (Kersten et al. 2008). The test under field conditions and determination of 3D accuracy is described. The influence of the size of the laser spot and the value of incident angle on the accuracy of measurement results is researched.

2.3. Problem Description

This paper discusses the following aspects:

- The accuracy of spatial information obtained by terrestrial laser scanning and
- The applicability of technology for structures survey.

Based on detailed analysis of the structures survey method by TLS the standardization of measurement procedure as a prerequisite for ensuring the quality of the project is made (Nedeljkovic 2010).

Random errors which predominantly affect the accuracy of the position of the scanned point are identified and they are: errors of measurement results r, φ and θ; measurement method errors coming from the way of positioning the center of the scanner and orientation; scanner position errors in the vertical plane; scanner adjustments errors. Errors can also occur during the registration of multiple scans. The overall accuracy of georeferenced point in a point cloud is described by covariance matrix $\mathbf{C}_{\mathrm{X_e}}$, 3x3, in which the main diagonal variances are σ_X^2, σ_Y^2 i σ_Z^2 (Lichti and Gordon 2004, Reshetyuk 2009).

This research is aimed to determine the instrument systematic errors that are caused by incorrect position of the instrument axes, the discrepancy of optical-mechanical and electronic center of the instrument, errors in time measuring and the impact of temperature on the measuring electronics components causing errors in measured distance. A large number of measurements per second which are realized by instrument without using a prism make serious obstacles to achieve adequate accuracy of the measured distances. Information about systematic errors and understanding their impact on the measurement results allow correction of these errors and the approximation of ideal structure of the instrument (Schulz 2007), using an appropriate mathematical model. Assigned instrumental systematic errors that affect the accuracy of the measurement results are entered in the calibration model of the laser scanner.

Introducing corrections for the influence of systematic errors increases accuracy of measurement results. However, this procedure has a purpose only when it achieves a significant increase in accuracy of measurement results. The accuracy of correction is limited due to incomplete understanding of the influencing variables effects and their inaccurate determination; due to the limited accuracy of the correction the standard deviation of the corrected measurement results is increased.

Model for assessment of systematic errors of measured distance Δr, horizontal angle $\Delta\varphi$ and vertical angle $\Delta\theta$, is greatly correspondent to total station model. However, the construction of laser scanners do not enable elimination of these errors by measuring in two positions of the instrument or multiple measurements (as with a total station), because the position of the scanned point can not be reproduced with a laser beam in the second position of the instrument nor any point can be measured twice by laser scanner. Therefore, the systematic errors of the measurement results must be made irrelevant by entering the correction, in order to increase the accuracy of the scanned measurement results.

Another important aspect of the paper is the evaluation of possible applications of TLS technology to structures survey. The basis for this evaluation are the previous research, performed measurements and analysis of the results. TLS technology applicability evaluation is done by analyzing the results of the scaned both test field and the facade of the building of VGGS, Belgrade, as well as the results of calibration of Leica Scan Station 2 in the laboratory and field conditions (Nedeljkovic 2010).

3. Calibration of Terrestrial Laser Scanner

3.1. Standardization of Structures Survey Procedures by TLS

Considering the specific characteristics of the scanning subjects, as well as the different requirements of accuracy – project tolerance, a standardized solution varies from case to case. Therefore the diagram (Fig. 1) includes a minimum content of a standardized scanning plan.

In accordance with the official standards in civil engineering and surveying practice in Serbia, for a survey of metal constructions designed tolerance is s_p = 3 mm, for concrete structures s_p = 1 cm and for built facilities s_p = 3 cm.

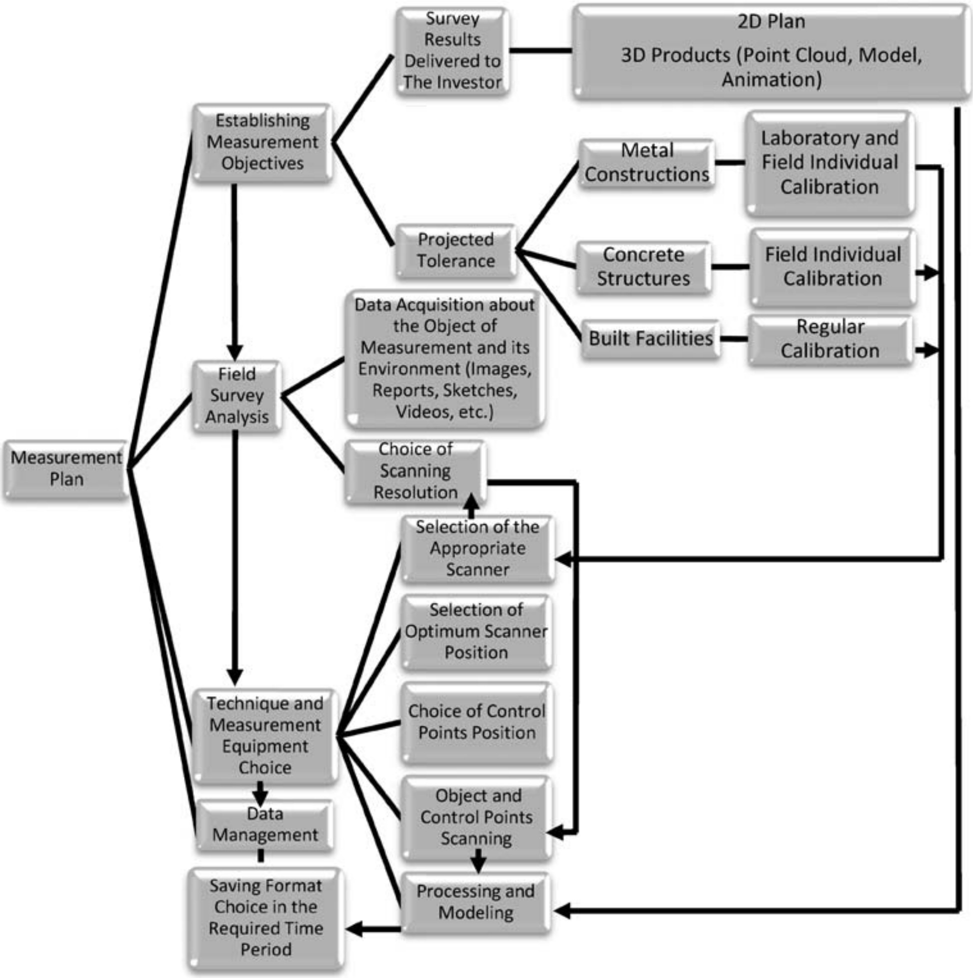

Fig. 1. *Flow Chart of the Measurement Plan.*

3.2. Selection of Laser Scanner Calibration Method

System calibration is performed using appropriate mathematical model, in this case the Least Squares Method is applied. Calibration of pulse scanner Leica Scan Station 2 is performed in the laboratory and field conditions and calibration of Leica HDS 3000 only in laboratory conditions. It is believed that the laboratory conditions are stable and allow a reliable determination of one part of scanning errors budget, especially for the instrumental errors. On the other hand the results of field measurements are exposed to constant change of measurement conditions and undetected effects which enable objective accuracy of these results to be obtained.

3.3. Mathematical Model

In this paper a calibration model of laser scanner that is based on formulas (Mikhail 1976) with modifications (Reshetyuk 2009, Nedeljkovic 2010) is proposed. It is a unified approach to Least Squares Adjustment with nonlinear functions. This model is applied in the same equations with conditions where measured values and the unknown parameters are involved.

The equation that connects adjusted measuring results and adjusted coordinates on one side and the measured results and transformation parameters on the other side has following form:

$$f_j^{(i)}(\hat{\boldsymbol{L}}_j^{(i)}, \hat{\boldsymbol{X}}_j^{(i)}) = \Delta \boldsymbol{X}^{(i)} + \mathbf{R}(k^{(i)}, \varphi^{(i)}, \omega^{(i)}) \boldsymbol{X}^{(i)}_{scan\ j} - \boldsymbol{X}^e_j = 0; \qquad i = 1, 2, \ldots, p; \qquad j = 1, 2, \ldots, m \tag{1}$$

where p is total number of scanner positions, and m is total number of signals that form the calibration field (Reshetyuk 2009).

Equations (1) are nonlinear and require its linearization around the approximate value of $\mathbf{R}^{\mathbf{0}}$ and $\mathbf{X}^{\mathbf{0}}_{scan}$:

$$\mathbf{X}^e = \Delta\mathbf{X} + \mathbf{R}\mathbf{X}_{scan}. \tag{2}$$

Considering the small values of rotation angles, the matrix $\mathbf{R}$ can be written in the following form (Kruck 1983):

$$\mathbf{R} = \mathbf{R}^{\mathbf{0}}(\mathbf{I} + \delta\mathbf{R}). \tag{3}$$

After substituting (3) into (2) and linearization it is obtained:

$$\mathbf{X}^e + \boldsymbol{v}_x = \Delta\mathbf{X}^{\mathbf{0}} + \delta\Delta\mathbf{X} + \mathbf{R}^{\mathbf{0}}(\mathbf{I} + \delta\mathbf{R})(\mathbf{X}^{\mathbf{0}}_{scan} + \delta\mathbf{X}_{scan} - \Delta\mathbf{X}_{scan}). \tag{4}$$

The final estimate value of vector $\hat{\mathbf{L}}$ must be equal to observed values $\mathbf{L}$ plus residuals V obtained by Least Squares and all this must be the same as approximate values $\mathbf{L}^0$ plus the corrections $\Delta\mathbf{L}$:

$$\hat{\mathbf{L}} = \mathbf{L} + \mathbf{V} = \mathbf{L}^0 + \Delta\mathbf{L}. \tag{5}$$

After derivation the equation (4), excluding the members of the second order and taking into account the equation (5) it is obtained (Nedeljkovic 2010):

$$\begin{aligned} &\mathbf{R^0 I}\delta\mathbf{X}_{scan} + \delta\Delta\mathbf{X} + \mathbf{R^0}\delta\mathbf{R}\mathbf{X}^{\mathbf{0}}_{scan} - \mathbf{R^0 I}\Delta\mathbf{X}_{scan} = \\ &= [\mathbf{X}^e - (\Delta\mathbf{X}^{\mathbf{0}} + \mathbf{R^0 I}\mathbf{X}^{\mathbf{0}}_{scan}) + (\mathbf{L^0} + \Delta\mathbf{L} - \mathbf{L})]. \end{aligned} \tag{6}$$

After rearranging equation (6) it can be written as:

$$\mathbf{B} \cdot \mathbf{V} = \mathbf{R^0 I}\delta\mathbf{X}_{scan} \tag{7}$$

$$\mathbf{A} \cdot \delta\mathbf{X} = \delta\Delta\mathbf{X} + \mathbf{R^0}\delta\mathbf{R}\mathbf{X}^{\mathbf{0}}_{scan} - \mathbf{R^0 I}\Delta\mathbf{X}_{scan} \tag{8}$$

$$\mathbf{W} = [\mathbf{X}^{e} - (\Delta\mathbf{X}^{0} + \mathbf{R}^{0}\mathbf{I}\mathbf{X}^{0}_{scan}) + (\mathbf{L}^{0} + \Delta\mathbf{L} - \mathbf{L})]. \tag{9}$$

From equations (7), (8) and (9) and taking into account the equation (4), mixed adjuistment model in an explicit form can be formed, ie.:

$$\mathbf{B}_{rxn}\mathbf{V}_{nx1} + \mathbf{A}_{rxu}\delta\mathbf{X}_{ux1} = \mathbf{W}_{rx1}, \quad r = 3pm; \quad n = 3pm; \quad u = 6p + u_{cp} \tag{10}$$

where u_{cp} is the number of scanner calibration parameters and 3 of them are Δr, $\Delta\varphi$ and $\Delta\theta$.

In equation (1) observed values are the distance r, the horizontal angle φ and the vertical angle θ. Unknown parameters are the translation vector $\Delta\mathbf{X}$, rotation matrix $\mathbf{R}$, the unknown corrections of the approximate values of scanner observations δr, $\delta\varphi$ and $\delta\theta$, and the systematic errors of scanner observations Δr, $\Delta\varphi$ and $\Delta\theta$.

All variables of the model are treated in the same way, i.e. linearization and iteration is done in relation to both groups of variables, the observation results and the unknown parameters. Practically, in the proposed model all variables are considered as the observations.

Solving the problem of calibration of laser scanner by using the above mentioned mathematical model is realized through several iterations and after each iteration the calculated residuals and corrections are added to the approximate values of observation results and unknown parameters. These values are considered as approximate (L^0, X^0) for each subsequent iteration (Nedeljkovic 2010).

After appropriate transformations a system of equations (Mikhail 1976), (Reshetyuk 2009), (Nedeljkovic 2010) is obtained:

$$\overline{\mathbf{B}}_{r'xn'}\overline{\mathbf{V}}_{n'x1} + \overline{\mathbf{A}}_{r'xu}\mathbf{X}_{ux1} = \overline{\mathbf{W}}_{r'x1}, \quad r' = n' = r + 6p + u_{\text{cp}} \tag{11}$$

$$\overline{\mathbf{N}}\mathbf{X} = \overline{\mathbf{U}} \tag{12}$$

Mixed model adjustment, equations (11) and (12), enable calculation of: residuals of observation r, φ and θ for each scanned point, the unknown parameters of translation ΔX and rotation $\mathbf{R}$ for each scanner position and scanner calibration parameters Δr, $\Delta\varphi$ and $\Delta\theta$.

All coordinates of test field signals were considered as known values, which allows obtaining reliable information about the accuracy of the scan results that are used to calculate the weight coefficients by comparing of vectors $\mathbf{X}_{TS}$ and $\mathbf{RX}_{\text{scan}}$.

The importance of monitoring the values of Least Square residuals V_{l_i} and their limitation should be pointed out. The following criterion (Berberana 1995) is applied:

$$|v_i| \geq 3\sigma_{l_i} \tag{13}$$

The residuals of observation results which are larger than preset criteria (13) are considered to contain gross errors. Such selection is somewhat simplified and more objective assessment using the G-test to confirm the presence of gross errors is applied.

3.4. Test Field Realization

3.4.1. Laboratory Test Field Realization

Test field for the metrological control of laser scanners was carried out in the laboratory for survey measurements at the VGGS in early July 2008 (Nedeljkovic 2010). Room size is 18.07 x 5.50 x 4.00 m (Fig. 2).

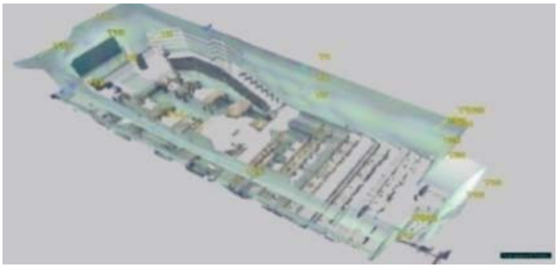

Fig. 2. *Test Field.*

The test field is formed by 27 black and white square signals (Fig. 3-a), 10 x 10 cm. Signals are well distributed in the vertical plane, and also on all wall surfaces of the Laboratory, which is important for accuracy assessment of horizontal and vertical angles observations. There are five pillars with equipment for survey instrument centering in the Laboratory.

Observations of pillars and signals using Leica TCRP1201+, with features $\sigma_a = 1''$, $\sigma_d = (1 + 1\ \text{ppm})$ and professional prism Leica GPR121 are made. The pillars are used for centering of instrument and signals and in the first phase 3D coordinates of the pillars centers are determined. The determination of these coordinates is done in software tool Network Adjustment, Licensed to Leica Geosystems AG. The standard deviation of these values is in the range of $0.1\ \text{mm} < \boldsymbol{S}_{x,y,z} < 0.46\ \text{mm}$. Then, 3D coordinates of signals with the standard deviation of $0.12\ \text{mm} < \boldsymbol{S}_{x,y,z} < 1.00\ \text{mm}$ were determined by direction observations from the pillars (Nedeljkovic 2010).

In this way a reliable coordinate system is established and considering the declared scanner precision, the coordinates of the test field signals can be considered as true values. This coordinate system will hereinafter be referred as geodetic reliable coordinate system.

In late November 2009, 30 circular signals, 10 cm in diameter (Fig. 3-b) were added to the test field.

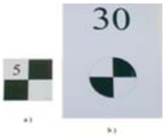

Fig. 3. *Test Field Signals.*

In early December 2009 the observations were carried out to determine coordinates of circular signals and control stability of square once. Observations were performed by the same instrument and the same method as observations in July 2008. Processing of the measurement results was also made in the software Network Adjustment, Licensed to Leica Geosystems AG.

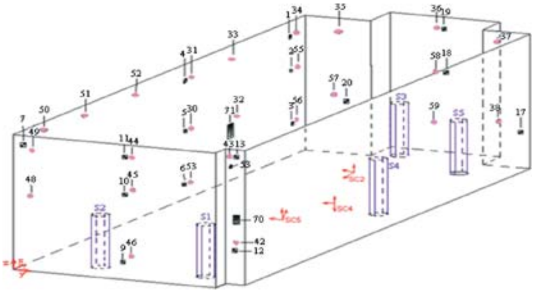

Fig. 4. *Laboratory of Geodetic Measurements – Draft Position of Scan Station 2 and the Scanned Signals.*

Standard deviation of pillars centers in the interval of 0.2 mm < $\boldsymbol{S}_{x,y,z}$ < 0.4 mm and signals coordinates in the range 0.2 mm < $\boldsymbol{S}_{x,y,z}$ < 0.7 mm are obtained (Nedeljkovic 2010).

3.4.2. Outdoor Test Field Realization

Calibration test field for accuracy testing of Scan Station 2 in outdoor conditions consists of 29 signals on the school building facade, which overlooks Radoja Domanovica Street. Signals are black and white, circular, 10 cm in diameter.

The signals are arranged on the windows of all four levels of the building (Fig. 5), so that they cover space courtyard facade of the school as far as possible. Such a geometric arrangement of points of the test field is a precondition for successful calibration (Nedeljkovic 2010).

Fig. 5. *Circular Signal.*

Signals coordinates true values are determined by measuring using TCRP1201+. Distances between the instrument and signals are measured without prism, σ_d = (2 + 2 ppm). At a distance of about 30 m from the building, and nearly parallel with the direction of the facade, two TC positions are determined at the distance of about 25 m. Observation of signals are carried out from these positions. Distances, horizontal and vertical angles are measured. Processing of signals coordinates is carried out by using software Network Adjustment, Licensed to Leica Geosystems AG.

3D signals coordinates are determined with a standard deviation of 0.5 mm < $\boldsymbol{S}_{x,y,z}$ < 1.5 mm. According to declared accuracy of position and distance measured by Scan Station 2, test field coordinates can be considered as true values. Established coordinate system is used as a reliable 3D basis for field laser scanner calibration.

3.5. Terrestrial Laser Scanner Calibration

3.5.1. Leica HDS 3000 Calibration

The calibration of laser scanner HDS 3000 was carried out in July 2008, based on an orthogonal scan containing 27 scanned signals (Fig. 2). The spatial position and orientation of the scanner is determined by scanning of the three pillars and using semi spherical signals. The scanner center position is determined with a standard deviation $\boldsymbol{S}_{x,y,z}$ of about 1.5 mm.

Test field is scanned by resolution of 2 cm to distance of 7.5 m and then signals are scanned with a resolution of 5 mm. The observations for some of these signals contained gross errors, due to unfavorable values of the incidence angles in relation to the scanned surface and other causes such as additional reflection.

Results with gross errors are eliminated before the start of data processing. Analysis of these errors is made by estimation of total error η, where η is calculated as a function of TC coordinates and scanner observations. Removal of gross errors is objectified using G Test where the results for 9 signals are rejected and 18 signals are used for further processing.

The Excel application is formed for data processing according to the model (Nedeljkovic 2010). Calculating the calibration parameters is performed in 3 iterations according to the adopted criteria to complete the iteration process. The values of residuals and corrections are limited by these criteria which should be less than 10^{-7}.

Table 1. *Calibration Parameters and Accuracy Assessment.*

Systematic errors	Δr **[mm]**	$\Delta\varphi$ **[″]**	$\Delta\theta$ **[″]**
$\sum_1^3\Delta r, \sum_1^3\Delta\varphi, \sum_1^3\Delta\theta$	2.107	10.″45	–5.″80
$\sigma_{\Delta r}, \sigma_{\Delta\varphi}, \sigma_{\Delta\theta}$	0.23	1.″82	0.″77

Based on the analysis of the systematic errors Δr, $\Delta\varphi$ and $\Delta\theta$ it is concluded that the distance systematic error (Δr = 2.11 mm) is significant and measurement results should be corrected by Δr with respect to accuracy requirements. The same conclusion can be applied both to systematic errors of measured horizontal

($\Delta\varphi$ =10.″45) and vertical ($\Delta\theta$ = –5.″80) angle. Accuracy evaluation for systematic errors indicates good precision of their determination (Nedeljkovic 2010).

By using the covariance matrix $\mathbf{Q}_{xx}$ (Mikhail 1976) the correlation between adjusted system parameters is calculated. The values are shown in Table 2. The value of correlation $\rho_{k-\Delta\varphi}$ = 0.92 is very high. Other parameters of the system are characterized by low correlation.

Table 2. *The Correlation Coefficients.*

$\rho_{k-\Delta\varphi} = 0.92$	$\rho_{\omega-\Delta\theta} = 0.20$	$\rho_{\varphi-\Delta\theta} = -0.37$	$\rho_{\varphi-\omega} = -0.41$

3.5.2. Calibration of Leica Scan Station 2

3.5.2.1. Calibration in Laboratory Conditions

Test field scanning (Fig. 2) was performed in December 2009 at three positions of scanner and all three scans were orthogonal. Coordinates and orientation of all three positions were determined by observing the semispherical signals centering at 4 pillows. Scanning was performed at different heights of scanner.

The first scanning is performed with a resolution of 2 cm at the distance of 7.5 m and each signal is scanned at a resolution of 2 mm. After elimination of gross errors using G test and identification of residuals on the basis of criteria (13), calibration of Scan Station 2 is carried out using 37 points. Calibration results are shown in Table 3, (Nedeljkovic 2010).

Table 3. *Parameters of Calibration and Accuracy Assessment.*

Systematic errors	**Δr [mm]**	**$\Delta\varphi$ [″]**	**$\Delta\theta$ [″]**
$\sum_1^3\Delta r, \sum_1^3\Delta\varphi, \sum_1^3\Delta\theta$	-2.192	-5.935	11.193
$\sigma_{\Delta r}, \sigma_{\Delta\varphi}, \sigma_{\Delta\theta}$	0.53	1.25	0.20

Systematic errors Δr, $\Delta\varphi$ and $\Delta\theta$ are determined by three iterations and their values significantly affect the accuracy of measuring results by Scan Station 2. The values of standard deviations (Table 3) point out good accuracy of system parameters determination.

The value of the correlation coefficient between the adjusted system parameters (Table 4) is very high for k and $\Delta\varphi$ and it is $\rho_{k-\Delta\varphi}$ = 0.95. Other parameters of the system have low correlation.

Table 4. *The Correlation Coefficients.*

$\rho_{k-\Delta\varphi} = 0.95$	$\rho_{\Delta Y-\Delta r} = -0.43$	$\rho_{\Delta X-\Delta Y} = 0.12$	$\rho_{\Delta Z-\Delta\theta} = 0.21$

3.5.2.2. Calibration in Field Conditions

Field calibration of Scan Station 2 is performed by scanning the courtyard facade of VGGS building, Belgrade, size is 64.982 m x 15.364 m.

Twenty nine test field signals are scanned at one scanner position with a resolution of 1 cm at the distance of 30 m for the building and then fine-scan signals at resolution of 5 mm to 30 m followed. Using G test gross errors are identified at 11 points in total. They are eliminated from further processing.

Calibration parameters are calculated by three iterations (Table 5) (Nedeljkovic 2010).

Table 5. *Calibration Parameters.*

Systematic errors	Δr **[mm]**	$\Delta\varphi$ **['']**	$\Delta\theta$ **['']**
$\sum_1^3 \Delta r, \sum_1^3 \Delta\varphi, \sum_1^3 \Delta\theta$	–0.945	–0.96	8.69
$\sigma_{\Delta r}, \sigma_{\Delta\varphi}, \sigma_{\Delta\theta}$	1.28	1.68	0.60

Values of systematic errors Δr, $\Delta\varphi$ and $\Delta\theta$ are less than those specified in the laboratory (Table 3). It was expected that the values of listed parameters are higher than in laboratory conditions. However, the scanner was calibrated by the manufacturer just before scanning the facade. Naturally, calibration leads to a decrease of the parameters value.

Systematic errors are tested (Table 5) using the t-test to determine whether Δr, $\Delta\varphi$ and $\Delta\theta$ are significant in statistical terms. It is found out that the values of Δr and $\Delta\varphi$ are insignificant while the value of $\Delta\theta$ is significant (Nedeljkovic 2010).

Accuracy assessment of system parameters (Table 5) indicates that their setting is done with a larger standard deviation compared to laboratory conditions, as it is expected due to the fact that the field measurements are always followed by lower accuracy. This is especially true for $\sigma_{\Delta r}$, but the parameters still show good determination accuracy.

Analysis of correlation between adjusted system parameters (Table 6) shows a very high correlation between k and $\Delta\varphi$, which is expected because both values are determined as the horizontal angle. Significantly high correlation between ΔX and Δr is a consequence of the orientation of the scanner coordinate system.

Table 6. *The Correlation Coefficients.*

$\rho_{k-\Delta\varphi} = 0.95$	$\rho_{\Delta X-\Delta r} = 0.84$	$\rho_{\varphi-\Delta\theta} = -0.21$	$\rho_{\omega-\Delta\theta} = -0.38$

4. Evaluation of TLS Survey Results

4.1. Measurements and Results Analysis

Scanning the facade VGGS and Geodetic Metrology Laboratory scans are obtained which are georeferenced and they can be used for modeling in accordance with the requirements of the project. Based on these results, regardless of the small sample size, the proposed method can be carried out for scanning of other buildings of arbitrary shape, size and position. This conclusion applies to both the exterior and the interior of the building, as well as the underground corridors and rooms. The results of scanning are point clouds which in the smallest details describe the structure surface. It is evident advantage over conventional survey methods (Nedeljkovic 2010).

Accuracy is another aspect to be taken into account in assessment of the technology applicability. To this end, the following analyses are made (Nedeljkovic 2010):

1. 3D deviation for 18 signalized points on the facade, obtained as the difference between scanned (uncorrected and unadjusted) coordinates and true values is total accuracy of the scanned points. Deviations are in the range of $2.14 \text{ mm} \leq \eta_{xyz} \leq 4.13 \text{ mm}$ for particular points, and the representative value for the entire series is $\eta_{xyz} = 2.95$ mm. The value of total error is an indication that the coordinates of signalized points are accurately determined.
2. The total error of scanned points can be reduced by introducing the correction for systematic errors in measurement results, as indicated on the facade by vectors view (Fig. 6).

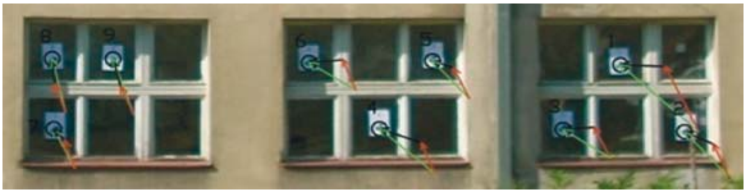

Fig. 6. *VGGS Part of the Facade, Signals Display with Vector Errors.*

The vector indicates total and systematic errors, as well as the remaining error. Remaining error includes random errors of scanner measurement results (r, φ and θ) transformation errors due to atmospheric conditions and other undetected errors.

Figures 6 and 7 Legend:

→ total error, → systematic error → remaining error

The coordinate system zox (Fig. 7) approximately presents some of signalized points, where a circle indicates true point position. The corresponding scanned point is moved from true position for the value of total error, indicated in green. The intensity and direction of the systematic error vector, indicated in red, is the same for each point of the test field shown in Fig. 7, the intensity differences are ostensible and are caused due to graphical design display on the plane zox.

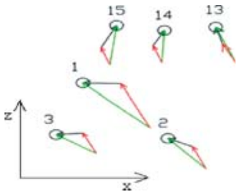

Fig. 7. *Vectors of Measurement Errors.*

Based on the vector display it is certain that vector of systematic error significantly reduces the total TLS measurement errors. In this case remaining error has values in the range of 0.88 mm ≤ σ_{ost} ≤ 3.81 mm.

3. After adjustment of scanned measurement results, 3D coordinates of the test field points are calculated. These values are compared with true values and it is concluded that these two sets of coordinates are identical.
4. Four characteristic points numbered 1, 2, 3 and 4, which are not marked with artificial signals, are identified on the facade and are scanned at a resolution of 1 cm. These points are identified in point cloud and their coordinates are measured by Cyclone software. Comparing the scanned coordinates and the coordinates measured by TC, some differences are expressed by vector intensity and they are shown in (Table 7):

Table 7. *Scanned and TC Coordinates Differences.*

Point 1: 14.2 mm	Point 2: 6.4 mm	Point 3: 16.8 mm	Point 4: 12.6 mm

The intensity of the position vector for each of the 4 points proved that projected precision for built facilities is achieved by TLS survey. This precision can be increased by selecting more appropriate resolution and applying corrections of systematic errors, which depends on the project goals.

5. Conclusion

Based on the research and the analysis, the following can be concluded:

- Standardization of the scanning procedures is possible and it is presented by the measurement plan of scanning. Based on the projected tolerance, the application of TLS individual calibration or regular calibration by the manufacturer is defined.
- Individual calibration of pulsed laser scanners HDS 3000 and Scan Station 2 is carried out in accordance with the proposed mathematical model in the labora-

tory. Correcting scanned results for the values of systematic errors can significantly contribute to increasing the accuracy of these results for pulsed scanners.

- The results of field calibration, which is carried out simultaneously with scanning the facade of VGGS, are statistically significant for systematic errors of distance and horizontal angle.
- TLS survey results evaluation of VGGS building indicates that the projected tolerance is achieved using uncorrected results and regular scanner calibration is required.
- Individual TLS calibration is required for survey of concrete and steel structures, for the tolerances designed for 1 cm and 3 mm. For the highest standards of accuracy it is necessary to perform TLS individual calibration in laboratory and field conditions. In cases where the total measurement error after correction of systematic errors is bigger than projected tolerance measurement results should be updated with systematic errors of transformation. These errors are determined simultaneously with systematic errors of measurement results by the proposed model.
- Evaluation of TLS survey results of VGGS building presents high applicability of this technology for structure survey.

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Analiza metode izmjere građevinskih objekata 3D laserskim skenerima

SAŽETAK. Pri realizaciji projekata u građevinarstvu sve češće se primjenjuje terestričko lasersko skeniranje (TLS). U radu se opisuje točnost koja se može postići impulsnim TLS-om, evaluacija rezultata mjerenja i primjena ove tehnologije za izmjeru građevinskih objekata. Analiza metode mjerenja omogućava identifikaciju sustavnih pogrešaka instrumenta, koje su ozbiljna smetnja za postizanje visoke točnosti TLS-om. U radu je dan standardni postupak mjerenja te veza između projektirane tolerancije i kalibracije TLS-a. Istovremeno su prikazani rezultati individualne kalibracije impulsnih skenera tvrtke Leica, pri kojoj su sustavne pogreške rezultata mjerenja određene integralno prema prikazanom modelu. Evaluacija rezultata mjerenja potvrđuje visoku primjenljivost TLS-a za izmjeru građevinskih objekata.

Ključne riječi: terestrički laserski skeneri, izmjera građevinskih objekata, kalibracija skenera, evaluacija rezultata mjerenja.

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