TLS data georeferencing - error sources and effects

Jelena PANDŽIĆ, Marko PEJIĆ, Branko BOŽIĆ, Verica ERIĆ

University of Belgrade, Faculty of Civil Engineering
Belgrade, Serbia
E-mail: jpandzic@grf.bg.ac.rs, mpejic@grf.bg.ac.rs, bozic@grf.bg.ac.rs, veric@grf.bg.ac.rs

Abstract

Depending on the requirements of a certain engineering task, point coordinates obtained through terrestrial laser scanning (TLS) can be either in a scanner coordinate system (CS) or in the coordinate system of a geodetic control network. When point coordinates in some external CS are needed point cloud georeferencing must be done, i.e. point coordinates have to be transformed from the scanner CS into the desired CS.

Different procedures can be followed during the transformation process of point coordinates from one CS to the other and consequently it can be distinguished between several types of georeferencing. The principal classification is into direct and indirect georeferencing and the main difference between the two is that direct georeferencing can (and usually does) give point coordinates in the CS of a geodetic control network instantly in the field, while indirect georeferencing inevitably needs some work to be done in the office in order to obtain these coordinates. Indirect georeferencing is necessarily done in some software and it distinguishes between the process itself being completed in either one or two steps. On the other hand, direct georeferencing does not involve transformation into some intermediate CS which is the case with the two-step indirect georeferencing. Direct georeferencing essentially mimics the procedure of orienting a total station with respect to a geodetic control network which can be achieved either through backsighting (the "station-orientation" procedure) or resection.

This paper briefly presents different georeferencing procedures and related main error sources that cause errors in transformed point coordinates. Additionally, the covariance model for direct georeferencing following the "station-orientation" procedure is verified through statistical analysis of the data collected in the experiment performed in the field. True point position errors calculated as differences between point coordinates obtained from the least squares adjustment of the geodetic control network and those from direct georeferencing of the TLS data are compared with theoretical errors, i.e. model-derived standard deviations of point positions. It is shown that these two sets of errors or, more precisely, the variance of the true errors and the pooled model-derived variance of the control point positions do not feature a significant difference at the confidence level of 99%. This makes us optimistic in terms of possibility of using the reported model for predicting true errors of point positions by model-derived standard deviations obtained as a result of direct georeferencing of TLS data following the "station-orientation" procedure.

Key words: terrestrial laser scanning (TLS), georeferencing, error model

1 INTRODUCTION

Every laser scanning process results in a point cloud, i.e. a great number of points by which terrain or an object of interest is discretized. Having in mind that a terrestrial laser scanner operates in a similar manner as a total station in a sense that it determines point coordinates by measuring angles and distances, and thanks to numerous similarities in construction of these instruments (e.g. a possibility of instrument centring, orienting, height measuring, etc.), terrestrial laser scanning (TLS) has been increasingly utilized in everyday engineering practice. Stability monitoring and maintenance of various engineering structures using the technology of TLS has been an object of interest for a number of authors (e.g. Park, H.S. et al. 2007; Pesci, A. et al. 2013), but only few of them have dealt with the issue of planning these tasks so far (e.g. Soudarissanane, S. et al. 2011; Wujanz, D. 2016).

Although raw data can be efficiently used for some scene investigations, transformation of point coordinates into a desired coordinate system (CS) is often needed due to certain project requirements. CS transformation distinguishes between registration and georeferencing. And while scan georeferencing means transforming scan data from an arbitrary CS (e.g. the CS of a particular scan) into an external CS (usually the CS of a geodetic control network), scan registration involves transforming multiple scans acquired from several station points into some optional common CS, not necessarily the external one. And since the topic of this paper is TLS data georeferencing rather than registration, it is important to define the process of georeferencing in more detail. A method of point cloud (scan) georeferencing is determined on the basis of predefined experiment methodology (Pejić, M. et al. 2013), i.e. predetermined approach to solving a particular engineering task. Although some authors prefer another way of classifying georeferencing methods, it is distinguished here between direct and indirect georeferencing. The main difference between them is reflected in the fact that the first one can (and usually does) give point coordinates in the CS of a geodetic control network already during fieldwork, while indirect georeferencing requires additional post-processing of scan data in the office in order to get these coordinates.

Highly accurate spatial data obtained in a great quantity through TLS provide a possibility to build quality models of various structures and, consequently, monitor and maintain them in an efficient manner. However, the scanning process and its results are inseparable of errors that inevitably occur on that occasion. Since positional uncertainties of scanned points propagate through data processing from a raw point cloud into a final 3D as-is model or structural monitoring results (Soudarissanane, S. 2016), in order to adequately solve an engineering task it is essential to acquire quality data and, if necessary, georeference them in a proper manner. To do so, error sources and their influence on final scanning deliverables have to be carefully considered.

Investigation of error sources in TLS became an object of interest for many authors about 15 years ago when TLS took its part in the everyday of an engineer. Since then a number of papers have been published on that topic (e.g. Schulz, T. et al. 2004; Polo, M.-E. et al. 2012), but very few authors have worked on deriving georeferencing error models. Lichti and Gordon were the first ones to derive an error model of direct georeferencing following the “station-orientation” procedure (Lichti, D.D. et al. 2004). They published another paper with Tipdecho in 2005 (Lichti, D.D. et al. 2005) and in the same year Scaioni expanded their model (Scaioni, M. 2005). Reshetyuk mainly cited the previous authors (Reshetyuk, Y. 2009). Years after that Fan and his colleagues dealt with errors of indirect georeferencing and managed to prove that statistics obtained from TLS data processing software provided by scanner manufacturers are incompetent measures of the actual registration and georeferencing errors in TLS data and offered a suitable replacement (Fan, L. et al. 2015).

Nevertheless, none of the aforementioned models was verified using independent data acquired in the field. (Fan, L. et al. 2015) considered only simulated data, while (Lichti, D.D. et al. 2004) compared model-derived errors of point positions for point clouds acquired in cultural heritage environment with figures advertised in a scanner datasheet issued by a manufacturer. (Scaioni, M. 2005) gave a comparison between model-derived errors of point positions for real and simulated data. In this paper different georeferencing procedures and related main error sources that cause errors in transformed point coordinates are presented. Additionally, the covariance model for direct georeferencing following the "station-orientation" procedure is verified through statistical analysis of the data collected in the experiment performed in the field. The values of the uncertainty measures, obtained both from the theoretical model and in the field test, which are in the order of magnitude of a few millimetres, make us optimistic in terms of a possibility of using direct georeferencing of a point cloud even for more demanding surveying tasks during construction process, quality monitoring and risk management of buildings or infrastructure.

2 GEOREFERENCING OF TLS DATA

As already said in Section 1, georeferencing is the process of transforming scan data from an arbitrary coordinate system into an external one which can be mathematically represented as:

$$\mathbf{X_e} = \mathbf{X_0} + s \cdot \mathbf{R_{se}} \cdot \mathbf{x_s} \,. \tag{1}$$

If we assume that Eq. (1) describes transformation of scan data from a scanner CS into the CS of a geodetic control network, then here $\mathbf{X_e}$ stands for the vector of point coordinates in the CS of the geodetic control network, $\mathbf{x_s}$ is the vector of coordinates of the same point in the scanner CS, $\mathbf{X_0}$ is the translation vector between the two coordinate systems, $\mathbf{R_{se}}$ stands for the rotation matrix between them, while s denotes the scale factor.

Direct georeferencing, as a process commonly resulting in obtaining point coordinates in the coordinate system of a geodetic control network instantly in the field, in fact mimics the procedure of orienting a total station with respect to a geodetic control network. This can be achieved either through backsighting (the "station-orientation" procedure) or resection. At the same time, indirect georeferencing can be completed in either one or two steps, with the first step in the two-step method being essentially the process of scan registration. Anyway, all georeferencing procedures are inseparable of making certain errors. In the following subsections direct georeferencing through the "station-orientation" procedure and the one-step indirect georeferencing with the accompanying error sources are discussed in more detail.

2.1 ERROR MODEL OF DIRECT GEOREFERENCING FOLLOWING THE "STATION-ORIENTATION" PROCEDURE

The "station-orientation" procedure of direct georeferencing is completely analogous to the polar method of surveying which means that a scanner is centred over some geodetic control network point and oriented towards another point of the same network. Having that in mind, it can be said that the application of this method in geodetic engineering is limited by the fact that the instrument height measurement error, centring error, levelling error and azimuth error significantly contribute to the total error budget of georeferenced point cloud data. Besides these method-specific errors, the scanner random errors (angle and range measurement errors) affect the process of direct georeferencing as well.

In TLS the scale factor is often considered to be equal to 1, except in some special scanner performance investigations. Additionally, if the scanner is precisely levelled using a built-in dual-axis compensator, Eq. (1) can be rewritten as:

$$\mathbf{X_e} = \mathbf{X_0} + \mathbf{R_{se}}(\kappa) \cdot \mathbf{x_s}\,, \tag{2}$$

where (κ) indicates that the scanner CS is rotated only about its z-axis, i.e. the rotation matrix between the scanner CS and the CS of the geodetic control network depends solely on the azimuth from the scanner station point to the backsight target.

According to (Lichti, D.D. et al. 2004), (Scaioni, M. 2005) and (Reshetyuk, Y. 2009), the covariance matrix of point coordinates in the CS of the geodetic control network obtained following the "station-orientation" procedure of direct georeferencing then has the form:

$$\mathbf{C}_{\mathbf{X_e}} = \mathbf{C_0} + \left[\mathbf{R_{se}}(\kappa) \cdot \mathbf{J} \cdot \left(\mathbf{C_{int}} + \mathbf{C_{set}}\right) \cdot \mathbf{J}^{\mathrm{T}} \cdot \left[\mathbf{R_{se}}(\kappa)\right]^{\mathrm{T}}\right] + \frac{\partial \mathbf{X_e}}{\partial \kappa} \cdot \left(\frac{\partial \mathbf{X_e}}{\partial \kappa}\right)^{\mathrm{T}} \cdot \sigma_\kappa^2\,. \tag{3}$$

Here $\mathbf{C_0}$ stands for the covariance matrix related to the CS translation error (the uncertainty of determining the scanner position), while $\mathbf{J}$ comprises partial derivatives of point coordinates in the scanner CS with respect to the range and angle measurements towards that point. The covariance matrix $\mathbf{C_{int}}$ actually sums up two covariance matrices – the covariance matrix of observations and the covariance matrix that reflects the uncertainty of the observation results caused by the laser beamwidth at the object surface. $\mathbf{C_{set}}$ denotes the covariance matrix containing the uncertainties of the observation results caused by the scanner setup (initialization) process, whereas σ_κ^2 models the contribution of the azimuth error to the total error budget of direct georeferencing through the "station-orientation" procedure.

The error model given in Eq. (3) can hardly be verified since the point, whose coordinates in the CS of the geodetic control network can be obtained for example using a total station, in most cases cannot be unambiguously identified within the point cloud. Using a target instead of an arbitrary point from the point cloud enables verification of the model, but this requires tailoring the model for that particular situation. Eq. (3) then becomes:

$$\mathbf{C}'_{\mathbf{X_e}} = \mathbf{C_0} + \left[\mathbf{R_{se}}(\kappa) \cdot \left(\mathbf{J} \cdot \mathbf{C_{lev}} \cdot \mathbf{J}^{\mathrm{T}} + \mathbf{C_T}\right) \cdot \left[\mathbf{R_{se}}(\kappa)\right]^{\mathrm{T}}\right] + \frac{\partial \mathbf{X_e}}{\partial \kappa} \cdot \left(\frac{\partial \mathbf{X_e}}{\partial \kappa}\right)^{\mathrm{T}} \cdot \sigma_\kappa^2\,. \tag{4}$$

$\mathbf{C_{lev}}$ stands here for the covariance matrix reflecting the uncertainties of the angle observations due to the scanner levelling error, while $\mathbf{C_T}$ comprises the uncertainties of the target centre position by the scanner CS axes.

The error model given in Eq. (4) enables standard deviations of point coordinates obtained following the "station-orientation" procedure of direct georeferencing to be calculated. Since a target is used instead of a point from the point cloud, its coordinates in the CS of the geodetic control network can be obtained through precise measurements, e.g. using a total station. These coordinates can be considered true in comparison with those obtained in the process of georeferencing. In this way model-derived errors can be compared to corresponding true errors enabling the error model to be verified through some statistical tests using data acquired in the field. The discussed error concept does not take into account effects of an object reflectivity, environmental perturbation and a laser beam incidence angle on scanning results since these errors can be reduced to insignificance if the appropriate procedure is followed.

For more details on the presented error model of direct georeferencing following the "station-orientation" procedure including a thorough derivation of corresponding formulae please see (Pandžić, J. et al. 2017).

2.2 ERROR MODEL OF THE ONE-STEP INDIRECT GEOREFERENCING

Indirect georeferencing of scan data through the one-step method means transforming them directly from the scanner coordinate system into the coordinate system of the geodetic control network. Unlike this procedure, the two-step indirect georeferencing involves the existence of some auxiliary CS as an intermediate step in the transformation process.

Indirect georeferencing is affected by the scanner random errors (angle and range measurement errors), as well as the errors of parameters of transformation between coordinate systems. In the case of the one-step indirect georeferencing only one set of transformation parameters and corresponding errors exists. Hence, the covariance matrix of point coordinates in the CS of the geodetic control network reads:

$$\mathbf{C}_{\mathbf{X_e}} = \mathbf{J}_{\mathbf{trans}} \cdot \mathbf{C}_{\mathbf{trans}} \cdot \mathbf{J}_{\mathbf{trans}}^{\mathrm{T}} + s^2 \cdot \mathbf{R}_{\mathbf{se}} \cdot \left(\mathbf{J} \cdot \mathbf{C}_{\mathbf{int}} \cdot \mathbf{J}^{\mathrm{T}}\right) \cdot \mathbf{R}_{\mathbf{se}}^{\mathrm{T}}. \tag{5}$$

$\mathbf{C}_{\mathbf{trans}}$ denotes the covariance matrix of the transformation parameters between the scanner CS and the CS of the geodetic control network, whereas $\mathbf{J}_{\mathbf{trans}}$ comprises partial derivatives of point coordinates in the CS of the geodetic control network with respect to the aforementioned transformation parameters.

Similarly as the corresponding error model for the "station-orientation" procedure of direct georeferencing, the error model for the one-step indirect georeferencing can be tailored in order to allow for its verification using targets. Accordingly, Eq. (5) has to be rewritten as:

$$\mathbf{C}_{\mathbf{X_e}} = \mathbf{J}_{\mathbf{trans}} \cdot \mathbf{C}_{\mathbf{trans}} \cdot \mathbf{J}_{\mathbf{trans}}^{\mathrm{T}} + s^2 \cdot \mathbf{R}_{\mathbf{se}} \cdot \mathbf{C}_{\mathbf{T}} \cdot \mathbf{R}_{\mathbf{se}}^{\mathrm{T}}. \tag{6}$$

3 EXPERIMENT SETUP AND RESULTS

In order to acquire data necessary for verification of the error model of direct georeferencing through the "station-orientation" procedure field measurements had to be done. Leica ScanStation P20 terrestrial laser scanner and planar B&W (black&white) targets were used alongside Leica Nova MS50 MultiStation for collecting the data. A geodetic control network consisting of 11 points was the test field (Fig. 1). The sample of 90 measurements was at our disposal and it could be divided into two groups based on the average horizontal distance between the station and the backsight target point (37 m and 73 m).

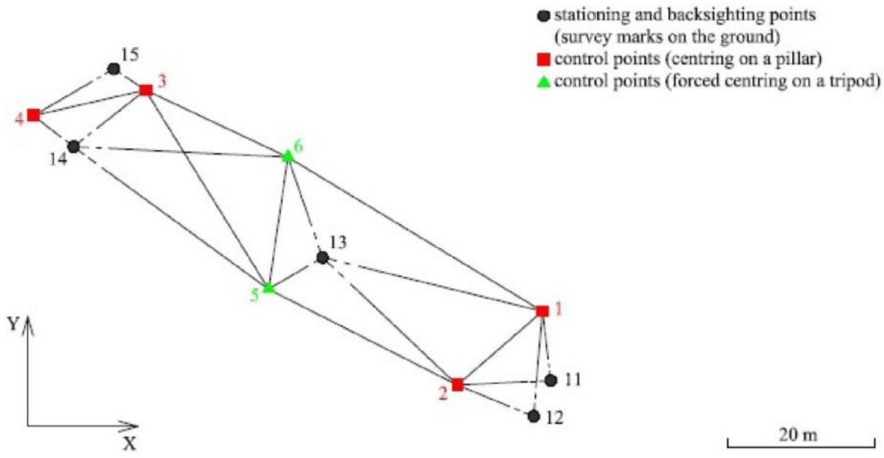

Fig. 1 Geodetic control network

The conducted experiment resulted in two sets of uncertainties of control point coordinates – true errors and model-derived standard deviations. The true errors were calculated by subtracting the control point coordinates estimated within the network adjustment from the corresponding coordinates acquired in the scanning process, while the model-derived standard deviations were determined based on Eq. (4).

Following the observed differences between these two sets of uncertainties, we conducted a couple of statistical tests to investigate the significance of these differences. In order to do so, for each of the two groups (the separation distance of 37 m and 73 m) pooled model-derived variances of the control point coordinates were calculated as a simple average of the whole group of the model-derived variances. Additionally, variances of the true errors were determined for both groups. Table 1 shows the aforementioned variances.

Table 1 Pooled model-derived variances and variances of true errors

Group	Number of setups within the group	σ^2_{avXY} [mm]^2	σ^2_{avZ} [mm]^2	s^2_{avXY} [mm]^2	s^2_{avZ} [mm]^2
37 m	42	9.95	5.41	5.95	6.11
73 m	48	6.37	5.43	3.51	4.91

The hypotheses for statistical testing of the equality of the pooled model-derived variance and the corresponding variance of the true errors read:

$$\begin{aligned} H_0 &: \quad \sigma^2_{avC} = s^2_C \\ H_a &: \quad \sigma^2_{avC} \neq s^2_C \end{aligned}, \qquad (7)$$

where C stands for either XY or Z since the analysis was done separately for XY-plane and Z dimension.
By comparing the values of the test statistic to the corresponding quantiles of χ^2 distribution it can be said that the observed difference between the pooled model-derived variance and the variance of the true errors both for XY-plane and Z dimension can be considered statistically insignificant at the confidence level of 99%. This is valid for the group of the setups where the average horizontal distance between the station and the backsight target point was 37 m, as well as for the group where this distance was about 73 m. In this way the reported error model of point positions obtained through the "station-orientation" procedure of direct georeferencing was verified using the real data collected in the field.

Please see (Pandžić, J. et al. 2017) for a more detailed report on this experiment.

4 CONCLUSION

Building and infrastructure surveying could greatly benefit from terrestrial laser scanning since this method can provide us with a great quantity of highly accurate geometric and radiometric data. However, various error sources typical of an employed method of data acquisition and processing have to be carefully considered.

Georeferencing, whether direct or indirect, is the process of transforming scan data from an arbitrary CS (e.g. the CS of a particular scan) into an external CS (usually the CS of a geodetic control network). It is inseparable of errors occurring on that occasion. The scanner random errors (angle and range measurement errors) affect georeferenced data accuracy no matter which georeferencing method is employed. Yet, some method-specific errors propagate through georeferencing as well. These are, for example, the scanner centring and levelling error when the “station-orientation” procedure of direct georeferencing is considered and the errors of parameters of transformation between the scanner coordinate system and the coordinate system of a geodetic control network in the case of the one-step indirect georeferencing.

Using the data collected in the field the error model of direct georeferencing through the “station-orientation” procedure reported within this paper was verified. The observed differences between the pooled model-derived variances and the variances of the true errors of the control point positions were shown to be statistically insignificant at the confidence level of 99%. This makes us optimistic in terms of the possibility of using the reported model for predicting true errors of point positions by model-derived standard deviations obtained as a result of direct georeferencing of TLS data following the “station-orientation” procedure. However, the lack of ISO standards in declaring specific uncertainty measures of a terrestrial laser scanner as a geodetic instrument (ISO 17123-9 is currently under development) that enter the error model as a priori values introduces a potential problem in the practical adoption of the reported model for planning TLS measurement data errors.

ACKNOWLEDGMENTS

This paper was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through Contract No. TR 36009.

REFERENCES

Fan, L. – Smethurst, J.A. – Atkinson, P.M. – Powrie, W. 2015. Error in target-based georeferencing and registration in terrestrial laser scanning. In *Computers and Geosciences*. Vol. 83, pp. 54-64.

Lichti, D.D. – Gordon, S.J. 2004. Error propagation in directly georeferenced terrestrial laser scanner point clouds for cultural heritage recording. In *Proceedings of FIG Working Week, 22-27 May 2004, Athens, Greece*. 16 pp.

Lichti, D.D. – Gordon, S.J. – Tipdecho, T. 2005. Error models and propagation in directly georeferenced terrestrial laser scanner networks. In *Journal of Surveying Engineering*. Vol. 131, No. 4, pp. 135-142.

Pandžić, J. – Pejić, M. – Božić, B. – Erić, V. 2017. Error model of direct georeferencing procedure of terrestrial laser scanning. In *Automation in Construction*. Vol. 78, pp. 13-23.

Park, H.S. – Lee, H.M. – Adeli, H. – Lee, I. 2007. A new approach for health monitoring of structures: terrestrial laser scanning. In *Computer-Aided Civil and Infrastructure Engineering*. Vol. 22, No. 1, pp. 19-30.

Pejić, M. – Božić, B. – Abolmasov, B. – Gospavić, Z. 2013. Design and optimization of laser scanning for tunnels geometry inspection. In *Tunnelling and Underground Space Technology*. Vol. 37, pp. 199-206.

Pesci, A. – Teza, G. – Bonali, E. – Casula, G. – Boschi, E. 2013. A laser scanning-based method for fast estimation of seismic-induced building deformations. In *ISPRS Journal of Photogrammetry and Remote Sensing*. Vol. 79, pp. 185-198.

Polo, M.-E. – Felicisimo, A.M. – Villanueva, A.G – Martinez-del-Pozo, J.-A. 2012. Estimating the uncertainty of terrestrial laser scanner measurements. In *IEEE Transactions on Geoscience and Remote Sensing*. Vol. 50, No. 11, pp. 4804-4808.

Reshetyuk, Y. 2009. *Self-calibration and Direct Georeferencing in Terrestrial Laser Scanning*. PhD Thesis. Royal Institute of Technology (KTH).

Scaioni, M. 2005. Direct georeferencing of TLS in surveying of complex sites. In *XXXVI-5/W17 of The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 8 pp.

Schulz, T. – Ingensand, H. 2004. Terrestrial laser scanning – investigations and applications for high precision scanning. In *Proceedings of FIG Working Week, 22-27 May 2004, Athens, Greece*. 15 pp.

Soudarissanane, S. – Lindenbergh, R. 2011. Optimizing terrestrial laser scanning measurement set-up. In *XXXVIII-5/W12 of The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. pp. 127-132.

Soudarissanane, S. 2016. *The Geometry of Terrestrial Laser Scanning – Identification of Errors, Modeling and Mitigation of Scanning Geometry*. PhD Thesis. Delft University of Technology, Faculty of Civil Engineering and Geosciences.

Wujanz, D. 2016. *Terrestrial Laser Scanning for Geodetic Deformation Monitoring*. PhD Thesis. Technical University of Berlin, Faculty VI – Planning, Building, Environment.