Application of Terrestrial Laser Scanning to Determine Deformations – Practical Aspects

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Abstract. When using laser scanning for deformation analysis of a given object, there are no pre-signalled points or identical points to compare between two epochs, so we can judge for whether an object deforms only by modelling the surface of the object. There are a number of challenges in this regard presented in the paper. The first challenge is that for the deformation analysis the configuration of the measurement parameters is no longer set by the surveyor-engineer by the number and position of the observed points, but from the laser scanner. Only the location of the scanner and the scanning density could be controlled. The second challenge is to expand the error model, as the surface modelling is included in the deformation process. This unifies both the metrological and the model errors that arise from the insufficient knowledge of the object and the simplification of its surface. All these challenges are oriented to the created 3D surface model. In addition, the metrological aspects of the use of laser scanners should be considered, especially for applications where the determination of the deformation requires high accuracy. A number of conclusions and recommendations are formulated. The influence of the factors influencing the accuracy of ground laser scanning in the deformation study is summarised, and the influence of the external orientation and georefering of the point cloud on the accuracy of the digital model is established. Preliminary assessment of the accuracy of the TLS results are given. Justification of the reliability of the determined deformations through TLS is presented. Technological scheme and recommendations for determination of deformations with TLS is shown.

1. Introduction
Terrestrial laser scanning (TLS) is increasingly used in geodetic practice for deformation applications. The 3D position of the surface points is measured in a very short time and of good quality. After measurement, the point cloud is further processed for use in other applications. Since the error at the individual point affects the final product, a good description of the quality of the points is needed. Manufacturers provide basic technical specifications, which are often obtained in laboratory conditions. In practice, the quality of the individual point is influenced by 4 main factors. Three of them are described in [1] and [2], namely instrumental errors, atmospheric influences and properties of the material of the object. In practice, the end-user has a limited influence on these three factors. It is difficult to change parameters such as the rotation of the mirror or the material of the object in order to obtain better measurement conditions. The last factor is the scan geometry, for which the user plays a crucial role, since the position of the scanner relative to the object is selected by the scanner.

All factors considered influence the measurement of a separate point by adding noise or changing the intensity and shape of the emitted signal. The accuracy of the distance measured depends on the
quality of the received signal. The accuracy of the measurement of the individual point is a combination of all these errors on the premise that they are uncorrelated:

\[
m_{\text{изм}} = \sqrt{m_{\text{instr}}^2 + m_{\text{atm}}^2 + m_{\text{material}}^2 + m_{\text{geometry}}^2}
\]

This article offers an analysis of the accuracy of the displacements obtained as a result of TLS, taking into account the influence of the external orientation (georeferencing) of the scan. Measurement planning is crucial for field preparation and cost planning. It is now possible to fully unleash the potential of the TLS in terms of achievable accuracy by determining the optimal position of the scanner.

2. Preliminary assessment of the accuracy of the TLS results

The TLS results are an array of points with known spatial coordinates in the scanner's coordinate system, which are subsequently transformed into a desired global system. The total mean square error in determining the 3D coordinates of the points in the digital model can be represented by the formula:

\[
m^2 = \sqrt{m_{\text{fix}}^2 + m_{\text{target}}^2 + m_{\text{orientation}}^2 + m_{\text{measure}}^2},
\]

where \(m_{\text{fix}}\) is the mean square error of the coordinates of the fixed points. The size of the target depends on the accuracy \(m_{\text{target}}\) of determining the coordinates of the special marks on which the external orientation is performed. \(m_{\text{orientation}}\) is the mean square error of the scanner's external orientation, \(m_{\text{measure}}\) is the mean square error of the measurement of the individual point, which reflects the influence of the external environment and the metrological properties of the instrument and the surface of the object.

One of the important stages in TLS technology is the external orientation of the station. The final accuracy of the digital model depends on the accuracy of execution at this stage. The external orientation can be performed with measurements to points with known coordinates in two ways (Figure 1):

- directly (instrumental), when the scanner is placed on a point with known coordinates;
- indirectly (free station).

\[\text{Figure 1. External orientation and registration with targets}\]

Formula (2) corresponds to the cases when the external orientation elements of the scanner are determined indirectly by a free station. In direct orientation there will be no error in determining the centers of special marks \((m_{\text{target}}^2)\).
In the external orientation of the station, coordinates of reference points are used, which in TLS are called special marks. The coordinates of the reference points must be known in both coordinate systems (CS): in the coordinate system of the scanner SXYZ and the external coordinate system of the object OXYZ (Figure 2).

![Diagram of coordinate systems](image)

**Figure 2.** Transformation of the measurements from the coordinate system of the scanner SXYZ into the global coordinate system OXYZ

In this method, the process of external orientation or georeferencing is performed in two stages. In the first stage, the transformation parameters $X_0$, $Y_0$, $Z_0$, $\omega$, $\phi$, $\chi$ are determined, and then the coordinates from the scanner in the outer CS are calculated. Both stages are realized according to the known formulas for transformation. The accuracy of the external orientation depends on the errors in determining the transformation parameters.

The mean square error of georeferencing depends on the number and geometry of the location of the special marks and their distance to the scanner. The influence of the error in determining the parameters of transformation on the total error in the coordinates of a point determined by TLS is determined by the law of propagation of errors. For the mean square error to determine the X coordinates of a point on the object is:

$$m_X^2 = m_{X_0}^2 + \left[ \left( \frac{\partial a_1}{\partial \omega} \right)^2 m_{\omega}^2 + \left( \frac{\partial a_1}{\partial \phi} \right)^2 m_{\phi}^2 + \left( \frac{\partial a_1}{\partial \chi} \right)^2 m_{\chi}^2 \right] X^2 +$$

$$+ \left[ \left( \frac{\partial a_2}{\partial \omega} \right)^2 m_{\omega}^2 + \left( \frac{\partial a_2}{\partial \phi} \right)^2 m_{\phi}^2 + \left( \frac{\partial a_2}{\partial \chi} \right)^2 m_{\chi}^2 \right] Y^2 +$$

$$+ \left[ \left( \frac{\partial a_3}{\partial \omega} \right)^2 m_{\omega}^2 + \left( \frac{\partial a_3}{\partial \phi} \right)^2 m_{\phi}^2 + \left( \frac{\partial a_3}{\partial \chi} \right)^2 m_{\chi}^2 \right] Z^2,$$

where $\left( \frac{\partial a_1}{\partial \omega} \right)$, $\left( \frac{\partial a_1}{\partial \phi} \right)$, $\left( \frac{\partial a_1}{\partial \chi} \right)$ etc. are the partial derivatives with respect to the indicated cosines of the elements of external orientation $\omega$, $\phi$, $\chi$.

In a similar way, the formulas for the mean square error $m_Y$ and $m_Z$ in determining the transformed coordinates $Y$ and $Z$ can be obtained. Since the angular elements of the external orientation are small, we can assume that
cosω≈cosφ≈1 \hspace{1cm} (4)
sinω≈ω \hspace{1cm} (5)
sinφ≈φ. \hspace{1cm} (6)

After some transformations, the formulas for determining the errors of the coordinates of the digital model depending on the accuracy of the transformation parameters take the form:

\[
\begin{align*}
    m_X^2 &= m_{X_0}^2 + m_{\omega}^2 \cdot Y^2 + m_{\phi}^2 \cdot Z^2 \\
    m_Y^2 &= m_{Y_0}^2 + m_{\omega}^2 \cdot X^2 + m_{\chi}^2 \cdot Z^2 \\
    m_Z^2 &= m_{Z_0}^2 + m_{\phi}^2 \cdot X^2 + m_{\chi}^2 \cdot Y^2
\end{align*}
\] \hspace{1cm} (7)

As a result of the analysis, the following conclusions can be made:

The direct method of external orientation of the scanner is preferable as it provides higher accuracy and less cost. The disadvantage is the complexity of compensating for the angle of inclination of the scanner with the large weight of the devices.

In practice, there are cases of measurements of objects when large angles of inclination of the scanner are deliberately set to reduce "white spots" near the scanner. In this case, direct georeferencing cannot be applied.

In order to establish the final accuracy of the TLS method, it is necessary to take into account the factors influencing the accuracy of the single angle and distance measurement. The total error in the coordinates of the points of the object related to the instrumental accuracy of the TLS and the atmosphere are set on the basis of the metrological attestation of the instrument, and the errors as a result of the properties of the object are described in [2]. To the detailed analysis of the accuracy of the external orientation made in [3] the modeling error to determine the center of the special mark should be added. Manufacturers give in the documentation an error for brand detection with an accuracy 10 times higher than the accuracy of single point measurement.

For the case when the vertical axis of the scanner is vertical, the following conclusions about the accuracy of the external orientation could be made:

- The accuracy in determining the elements of the station's external orientation increases in proportion to the number of marks used. Practical research [4] has shown that it is optimal to use 8 special marks located in the circumference of the scanner.
- The more the angle Θ between the scanned marks differs from 100°, the more inaccurately the elements of transformation X0, Y0, Z0, ω, φ, χ are determined.
- The error in determining Zo depends only on the accuracy of the measured distance and the number of marks used.

As the distance of the special marks from the scanner increases, the accuracy in determining the angular elements of the scanner's orientation increases, but the accuracy of the measured distance decreases, therefore the mean square error per unit of weight increases. Therefore, for the final conclusions to optimize the geometry available for each scanner model, it is necessary to conduct experimental measurements.
For a priori assessment of the accuracy in the determination of the elements in a non-standard scheme of available brands, it is necessary to use programs for modeling the process of external orientation of the scanner.

When assessing the accuracy of the external orientation of the scanner as a free station, it is necessary to take into account the accuracy of determining the coordinates of special marks in the external system. If the coordinates of the points are obtained with the help of a total station, the centering and orientation errors reach 2 mm. The direct method gives better accuracy of the angular elements of orientation, and the analytical - of the lengths. It should be noted that nowadays only some scanner models have devices for leveling and centering the instrument.

3. Justification of the reliability of the determined deformations through TLS

The accuracy with which the displacements of objects are determined by geodetic methods largely depends on the accuracy with which the measurements are performed. Therefore, the accuracy of the measurements must be justified in advance so that these measurements can then be planned and performed correctly. This accuracy should be determined on the basis of the accuracy ($m_{\Delta d}$) with which the corresponding displacement ($\Delta d$) must be obtained. In this way it will be possible to take into account the peculiarities of the different objects, as well as the size of the displacements, which are different even for objects of the same type.

The relationship between $m_{\Delta d}$ and $\Delta d$ will be determined based on the confidence interval that covers the true value of the minimum displacement, ie.

$$P\{\Delta d^{(i-1,i)} - t. m_{\Delta d} \leq \Delta d \leq \Delta d^{(i-1,i)} + t. m_{\Delta d}\} = p$$

where,

$\Delta d^{(i-1,i)}$ is determined by measuring the value of the displacement between two adjacent cycles;

$\Delta d$ is the true value of the displacement;

$m_{\Delta d}$ – the mean square error by which the corresponding displacement must be determined;

$p$ – confidence level;

$t$ – normalization coefficient, which depends on the accepted confidence probability $p$ ($t = 3$ at $p = 99.7\%$ and $t = 2$ at $p = 95.5\%$).

In order to find the required ratio between $m_{\Delta d}$ and $\Delta d$, only the lower limit is used, namely:

$$\Delta d^{(i-1,i)} - t. m_{\Delta d} \leq \Delta d$$

Inequality (8) will only make sense if

$$\Delta d^{(i-1,i)} \geq t. m_{\Delta d}$$

or

$$m_{\Delta d} \leq \frac{\Delta d^{(i-1,i)}}{t}$$

If the established ratio between $m_{\Delta d}$ and $\Delta d$ is observed at $p = 0.955$ and $t = 2$, then with a probability of $95\%$ it can be stated that the value obtained on the basis of the respective measurements for $\Delta d$ is actually a displacement and not a result of measurement errors. The error $m_{\Delta d}$, which determines the
corresponding displacement, is the result of the influence of the errors at the starting points, the errors of the measured values and the scanning geometry.

\[ m^2_{\Delta d} = m^2_{\text{measure}} + m^2_{\text{fix}} + m^2_{\text{geometry}} \]  \( (12) \)

When using the same starting points and configuration of measurements in all cycles, errors in the output data and geometry will be destroyed at the difference, i.e. upon receipt of the displacement \( \Delta d \).

A practical approach to justify the accuracy of TLS measurements can be performed by presenting the expected displacements at a point in the form of a construction tolerance, as differences between the measurements in (i) and (j) cycles, i.e.

\[ \Delta d = d_i - d_j \]  \( (13) \)

where it comes from

\[ m^2_{\Delta d} = m^2_{d_i} + m^2_{d_j} \]  \( (14) \)
\[ m_{\Delta d} = m_d \sqrt{2} \]  \( (15) \)
\[ m_{\Delta d} \leq \frac{\Delta d}{\sqrt{2} t} \]  \( (16) \)

where \((md)\) is the mean square error of the individual measurement.

From (15) and (16) it follows

\[ m_d \leq \frac{\Delta d}{\sqrt{2} t} \]  \( (17) \)

where \(t\) is a normalizing coefficient that depends on the accepted confidence probability \(p\) (\(t = 3\) at \(p = 99.7\%\) and \(t = 2\) at \(p = 94.5\%\)).

In the specialized literature, several different approaches have been developed to determine the accuracy with which geodetic measurements should be performed when studying deformations [5], [6]. One approach is to use the criterion of minimum deformation \(Q_{\text{min}}\), which can be registered with a value greater than the mean square error of the measurements. Another common approach uses the critical deformation \(Q_{\text{max}}\) for the investigated facility - the maximum allowable value at which the facility can be operated. In the third approach, the accuracy of the measurements is determined on the basis of the magnitude and speed of the deformation process for a certain period of time \(Q_{j, k}\). This approach gives the most precise justification of the accuracy and is widely used in modern practice, and in this case it is necessary to have the results of measurements already performed or forecast data from similar types of equipment.

Applied to justify the accuracy of measurements when determining displacements in the process of operation, for the mean square errors in the position of the point \(m_p\) in each cycle of measurement with TLS the dependence is obtained:

\[ m_p \leq \frac{\Delta d(i-1,i)}{t\sqrt{2}} \]  \( (18) \)

where \(\Delta d(i-1, i)\) is the value of the relative displacement between two measurement cycles.
Table 1. Displacements and accuracy of measurements

| t=2 | p=0.955 | Δd (i-1,i), mm | md, mm | t=3 | p=0.997 | Δd (i-1,i), mm | md, mm |
|-----|---------|----------------|--------|-----|---------|----------------|--------|
| 15  | 5       | 15             | 4      |
| 20  | 7       | 20             | 5      |
| 25  | 9       | 25             | 6      |
| 30  | 11      | 30             | 7      |
| 35  | 12      | 35             | 8      |

By formula (18) the opposite problem can be solved - at a given accuracy of measurements (md) to determine the minimum displacement ΔQmin with a confidence probability of 95%. If it varies with values of Δd(i-1,i) in the interval 10 mm ÷ 35 mm, it can be seen that the values of m_md vary from 5 mm to 12 mm (Table 1). The above formulas are valid when the starting geodetic points are stable and do not change their position in time between two consecutive cycles. If there is a displacement greater than the allowable and the starting points are unstable, the corresponding corrections and coefficients should be entered in the formulas for calculating the mean square error of the minimum displacements, for each subsequent cycle. Therefore, it is reasonable to draw the following general conclusion:

In case the points of the investigated facility are determined by TLS with accuracy in the interval 5 mm ÷ 12 mm, it could be stated that the reliably determined minimum displacements in these points are in the range (10 ÷ 35) mm.

4. Technological scheme and recommendations for determination of deformations with TLS

Stages of operations in terrestrial laser scanning to determine deformations are shown below:

Figure 3. Technological scheme

4.1. Preparation
The condition of the existing ground points is first checked. Is it necessary to make new points to perform the scan? Station locations are selected by looking for the best scanning geometry: reflection angles less
than 60° and the closest possible distance to the subject. If the object cannot be scanned by only one station, several locations are selected, but the subsequent processing and determination of displacements is done separately for each station, without merging the cloud of points. The goal is to eliminate the registration error. We are looking for the best possible configuration for the placement of marks for external orientation analogous to conventional geodetic measurements.

4.2. Carrying out the measurements

Placing the scanner on the selected point on a tripod or pole with forced centering;

Placement around the scanner of special marks, which are points of the working geodetic basis. The type of special marks depends on the model of scanner used;

Determining the coordinates of the centers of special marks by geodetic methods or scanning. If a scanning station is used, the given points are signaled by reflective prisms. The assessment of accuracy is made both on the reverse angular - longitudinal resection and free station;

Measurement mode selection - scan frequency / speed and density defined by number of points per second and distance between points or offset angle. Measurement noise with a laser rangefinder (SNR) by the square of the measurement time is improved. A 9 sec measurement has 3 times better SNR than a 1 s measurement. The choice of measurement frequency affects the accuracy of the measured distance.

It is advisable to scan a small section of the construction at the maximum distance from the scanner or with the maximum angle of reflection before the complete survey of the object, in order to determine the optimal scanning frequency.

Scanning of the marks in a special mode with maximum resolution in order to determine the coordinates of their centers with maximum accuracy for the scanner.

Object scanning. If the scanner has a digital camera, taking a digital photo showing the shooting range, if not - 360° view picture.

4.3. Registration

Transforming of the measurements into a selected coordinate system, in which the comparison between the clouds will be performed to determine the displacements / deformations that have occurred. This stage is skipped, when a total scanning station is used and the external orientation is performed on site.

4.4. Modelling

For cloud modeling, one can choose between two main methods - an irregular surface model and an approximation of a plane or a second-degree surface [7]. The choice on the one hand depends on the available processing software, and on the other hand - on the shape and roughness of the studied object. The irregular pattern is suitable for rough surfaces [8] and high cloud density, but has a significant disadvantage for overhanging parts. This requires choosing the best fitting plane to create the triangles. CloudCompare software provides two options for creating an irregular surface model - in the XY plane and in the best fitting plane. In Trimble Real Works, it is also possible to select a second-degree reference surface (cylinder, sphere) that best describes the object. In Autodesk Civil3D, the only option is to rotate the point cloud around the X or Y axis.

The orientation of the triangles relative to the real surface of the object determines the direction of the measured distance to another cloud of points. For this reason, it is recommended that the net of triangles to be created as far as possible perpendicular to the direction of the maximum expected displacement. In the case of dam walls, this is most often a direction perpendicular to the axis of the crown of the wall.

4.5. Point cloud comparison

To make a comparison between two point clouds, it is necessary to specify one cloud to be the reference. Regardless of which of the known methods for comparing point clouds is chosen, it is necessary for the reference point cloud to be wider and denser. This provides higher accuracy of the obtained results. The
direct comparison of two clouds results in absolute distances, while the Cloud-to-Model comparison between a cloud and a model (irregular or approximated surface) gives distances with the corresponding sign. Depending on the selected options, the distances could be calculated separately for the three axes X, Y and Z and in space.

4.6. Visualization

The visualization could be done through a map of the relocations or profiles of characteristic places of the object. In the case of dam walls, these are horizontal and vertical sections over a certain distance or through places where reverse plumbs or other non-geodetic sensors for monitoring deformations are located. An analysis is made of which displacements are acceptable or statistically significant to visualize.

5. Conclusions

The extraction of information about structural deformations from laser scanning data makes it possible to improve the accuracy of the single measurement, as the surrounding points are also taken into account, i.e. a group of points is considered as an element of a surface. In the simplest case, this surface can be a plane. It is also possible to simplify the task by means of 2D analysis by presenting the surface with profile lines.

Ground-based laser scanning makes it possible to capture the subject as a whole. Its great advantage is that it is not necessary to know in advance where deformations are expected to occur. Deformations will be reported where they occur.

The article presents a spatial technology, independent of the specialized software of TLS tools, which can be implemented with various existing software products.

From the analyzes of the capabilities of TLS and experimental studies, the following conclusions can be defined:

- Displacements larger than 15 mm can be reliably determined using different TLS models.
- Using different scanner models may produce different results, even when scanning the same subject under the same conditions.
- Periodic measurements require the use of the same instruments and technological scheme of measurements to ensure the best representation of the results.
- Selecting the optimal location for the scanner can improve scanning geometry and reduce the impact of errors.
- Choosing a lower scan density reduces scanning time, optimizes costs and simplifies processing, but must comply with the requirements so as not to lose surface representativeness. In cases where TLS measurements will be used to detect small collapses and deformations on the surface of the construction, the full potential of the point cloud must be worked on.

If the equipment used for measurement provides accuracy of the order of (5 ÷ 15) mm in the position of the points, it can be considered that with the help of this equipment displacements of (10 ÷ 40) mm can be registered depending on the used instrument and scan geometry. There is a necessary reason to believe that laser scanners and scanning stations have the appropriate technical parameters to achieve such results.

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9
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