Getting a Correct Geometrical Information from TLS Data for Building Constructions Control Surveying

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Key words: Control Survey, Ideal Model, Deviation, Point Cloud, CAD Model, Solid Model.

SUMMARY

In this study, the results of research of different approaches for determining the structures deviations from the CAD model based on the results of terrestrial laser scanning (TLS) are presented. The presented researches carried out by the example of determining the deviations for the two types of structures: office building and the underground section of the metro tunnel. The theoretical bases of control survey accuracy calculation by TLS were given and preliminary accuracy calculation was made. The obtained values were used to analyze the different approaches to define the deviations from the actual CAD model. Next, were considered two cases for determination the deviations from the project. In the first case, when CAD model for the building it is known and is necessary to determine the building deviations from this design model. Three different comparison approaches were investigated: CAD vs. TIN; CAD vs. point cloud; CAD vs. solid model. In the second case, a specific requirement on one parameter of structure was fixed. In this case, it is advisable to compare the structure model not with the results of the scanning, and perform pre-transformation of scanning results in order to determine directly the desired parameter. By the results of research were developed short practical advice on the implementation of the structures control survey by method of TLS.

SUMMARY

В представленной работе приведены результаты исследования различных подходов к определению отклонений сооружений от CAD моделей по результатам наземного лазерного сканирования. Представленные исследования выполнены на примере определения отклонений для двух типов сооружений: офисного здания и участка тоннеля метро. Приведены теоретические основы расчета точности исполнительной съемки методом наземного лазерного сканирования и выполнен предварительный расчет точности. Полученные значения были использованы для анализа различных вариантов определения отклонений CAD модели от реальной. Далее рассмотрены два варианта определения отклонений от проекта. В первом случае, для здания известна CAD модель и необходимо определить отклонения здания от этой проектной модели. Были исследованы три различных варианта сравнения: CAD/TIN; CAD/облако точек; CAD/твердотельная модель. Во втором случае, установлено конкретное требование на один параметр сооружения. В таком случае целесообразно сравнивать не модель сооружения по результатам сканирования, а выполнять предварительное преобразование результатов сканирования, для того чтобы определить непосредственно искомый параметр. В результате исследования получены практические рекомендации

по выполнению исполнительной съемки сооружений по материалам наземного лазерного сканирования.

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1. INTRODUCTION

Control surveys are an important part of geodetic works in construction. The main task of the control survey is to obtain actual deviations of structure from the project. Today, the most common methods of performing such surveys are total station and photogrammetric surveying. However, in recent years to carry out control surveys widely applied method of terrestrial laser scanning (TLS). A special feature of this method is the presentation of the survey results in several versions: point cloud, solid model, TIN-model and geometric model from geometric primitives or CAD model. Each of these models allows to extract different types of data. Which of these models are used to compare with the project? At first glance, it is obvious to use point cloud after preliminary processing (cleaning, filtering etc.), because the cloud corresponds to the actual position of the structure. However, discreteness of point cloud often makes it impossible to fix the position of individual structure elements. The solid model allow to determine the position of all the elements, but its accuracy depends on the mathematical modeling algorithm. The same can be said about the geometric model, which is more approximate, but geometrically rigorous, that is, in theory, the most appropriate to the project. In this paper, on the example of the TLS data processing the accuracy analysis of the deviations determination was held. The deviations were obtained like a difference between measurements and real structure position using different types of models. Here and after under real position we will understand coordinates from CAD model. As the object of study were chosen two structures, which contains a large number of geometric elements. The elements of this structures can be described by rigorous mathematical models. The methodic of quality evaluation of different models has been developed. The comparison of point clouds, the solid model and TIN model have been performed. These types of data were then compared with the CAD model. As a result were obtained the deviations, which can be analyzed to determine an optimal model for the control survey.

2. THE OBJECT OF RESEARCH AND EQUIPMENT

First of all we present the objects of our research and equipment which was used for measurements. For the first case was chosen the building of insurance company Deutscher Herold in city Bonn, Germany (Fig. 1). The geometry of this building is quiet simple and therefore well fits for analysis. The approximate scanning distance was in range 50-60 m. TLS was made from three scan station. For scan station coordination on the building facade were fixed and determined six marks. The spatial coordinates of marks were determined by total station with spatial accuracy RMS 1.5 mm. For scanning was used Leica ScanStation P40. Technical specifications of this scanner are well-known. Since for us the most important is scanning accuracy, in the follow we will use the next technical characteristics: distance measurement accuracy – 1.2 mm + 10 ppm; measurement noise – 0.5 mm (distance 50 m);

horizontal and vertical measurements accuracy – 8 sec; target acquisition – 2 mm. These quantities we will use in the next section for preliminary accuracy calculation.

Fig. 1. The first object of research – building of insurance company Deutscher Herold in city Bonn, Germany

For the second case was chosen another type of structures. As we already said, it must be structure with one fixed important parameter. For this aim, we choose the underground section of the metro tunnel. It is a part of metro tunnel in Kiev, Ukraine with length of 85 m (Fig. 2).

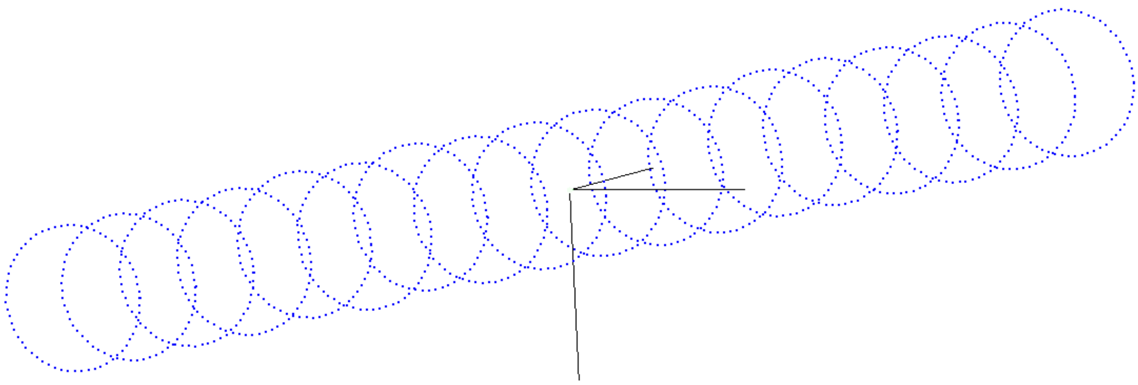

Fig. 2. The underground section of the metro tunnel

TLS was made each 5 m from 15 scan station. For scan stations connection, the eight tie marks were placed for each scan station – four in front and four – behind scan station. The spatial coordinates of marks were determined by total station from points of underground surveying network with spatial accuracy RMS 5.5 mm. For scanning was used Leica ScanStation C10 with next technical characteristics: distance measurement accuracy – 4 mm; horizontal and vertical measurements accuracy – 12 sec; target acquisition – 2 mm. As in previous case, these quantities we will use for preliminary accuracy calculation.

Here we also want to point out that all following researches were done with already filtered and referenced point clouds.

3. THEORY AND RESULTS OF PRELIMINARY ACCURACY CALCULATION OF CONTROL SURVEY BY TLS

In order to know the accuracy of control survey by TLS, we have to take in account the whole amount of errors, which influences on the result. We have to keep in mind that determination of the scan station coordinates is carrying out with reference to the fixed points of survey network (Braun and Štroner 2014). Further, the obtained scan station coordinates will have used as a fixed base for scanning. Thus, final coordinates of point cloud contain three types of errors: errors of initial survey network (or tie marks), errors of scan station coordinates determination and errors of scanning. As can be seen, accumulation of errors and their influence on each other has place. We offer the whole error of control survey write as (Shults et al. 2016):

$$\mathbf{K}_{CS} = \mathbf{K}_{SN} + \mathbf{K}_{SS} + \mathbf{K}_{S}, \tag{1}$$

where: $\mathbf{K}_{SN}$ - covariance matrix of initial survey network errors influence; $\mathbf{K}_{SS}$ - covariance matrix of errors of scan station coordinates determination which computed with errorless initial data (supposition that survey network coordinates do not contain errors); $\mathbf{K}_{S}$ - covariance matrix of scanning with reference to the scan station.

Covariance matrix of errors for scan station coordinates determination $\mathbf{K}_{SS}$ is obtained from adjustment of 3D-resection. The structure of this matrix depends on resection geometry, and values of its elements depend from accuracy of distances, vertical and horizontal angles measurements (Osada et al. 2010). This matrix has a following well-known structure:

$$\mathbf{K}_{SS} = \begin{bmatrix} m_{X_{SS}}^2 & k_{X_{SS}Y_{SS}} & k_{X_{SS}Z_{SS}} \\ k_{X_{SS}Y_{SS}} & m_{Y_{SS}}^2 & k_{Z_{SS}Y_{SS}} \\ k_{X_{SS}Z_{SS}} & k_{Z_{SS}Y_{SS}} & m_{Z_{SS}}^2 \end{bmatrix}, \tag{2}$$

where: $m_{X_{SS}}$, $m_{Y_{SS}}$, $m_{Z_{SS}}$ – RMS errors of abscissa, ordinate and applicate of scan station; $k_{X_{SS}Y_{SS}}$ – correlation moments.

To find out covariance matrix of initial survey network errors influence $\mathbf{K}_{SN}$, covariance matrix $\mathbf{K}$ is used, which is obtained from initial survey network adjustment results. Generally, matrix $\mathbf{K}$ is:

$$\mathbf{K} = \begin{bmatrix} m_{X_1}^2 & k_{X_1Y_1} & k_{X_1Z_1} & \dots & k_{X_1Z_n} \\ k_{X_1Y_1} & m_{Y_1}^2 & k_{Z_1Y_1} & \dots & k_{Y_1Z_n} \\ k_{X_1Z_1} & k_{Z_1Y_1} & m_{Z_1}^2 & \dots & k_{Z_1Z_n} \\ \dots & \dots & \dots & \dots & \dots \\ k_{X_1Z_n} & k_{Y_1Z_n} & k_{Z_1Z_n} & \dots & m_{Z_n}^2 \end{bmatrix}, \tag{3}$$

where m_{X_i}, m_{Y_i}, m_{Z_i} – RMS errors of abscissa, ordinate and applicate survey network *i*-th point or tie mark; $k_{X_iY_j}$ – correlation moments; *n* – number of network points or tie marks.

The main issue is how to modify matrix $\mathbf{K}$ to matrix $\mathbf{K}_{SN}$. In general, influence of initial survey network errors can be written as (Kougia et al. 1986):

$$\mathbf{K}_{SN} = \mathbf{BKB}^T, \quad (4)$$

where: $\mathbf{B}$ - matrix of partial derivatives from scan station by fixed points coordinates of initial survey network or tie marks. Generally, matrix $\mathbf{B}$ can be presented as (Kougia et al. 1986):

$$\mathbf{B} = \begin{bmatrix} \frac{\partial X_{SS}}{\partial X_1} & \frac{\partial X_{SS}}{\partial Y_1} & \frac{\partial X_{SS}}{\partial Z_1} & \cdots & \frac{\partial X_{SS}}{\partial X_n} & \frac{\partial X_{SS}}{\partial Y_n} & \frac{\partial X_{SS}}{\partial Z_n} \\ \frac{\partial Y_{SS}}{\partial X_1} & \frac{\partial Y_{SS}}{\partial Y_1} & \frac{\partial Y_{SS}}{\partial Z_1} & \cdots & \frac{\partial Y_{SS}}{\partial X_n} & \frac{\partial Y_{SS}}{\partial Y_n} & \frac{\partial Y_{SS}}{\partial Z_n} \\ \frac{\partial Z_{SS}}{\partial X_1} & \frac{\partial Z_{SS}}{\partial Y_1} & \frac{\partial Z_{SS}}{\partial Z_1} & \cdots & \frac{\partial Z_{SS}}{\partial X_n} & \frac{\partial Z_{SS}}{\partial Y_n} & \frac{\partial Z_{SS}}{\partial Z_n} \end{bmatrix}. \quad (5)$$

To find out partial derivatives in the matrix (5), we will use method of numerical differentiation. Partial derivatives are computed numerically using the following formulas:

$$\frac{\partial X_{SS}}{\partial X_1} \approx \frac{X_{SS}^0 - X_{SS}}{\Delta X_1} = \frac{\Delta X_{SS}}{\Delta}; \frac{\partial Y_{SS}}{\partial X_1} \approx \frac{Y_{SS}^0 - Y_{SS}}{\Delta X_1} = \frac{\Delta Y_{SS}}{\Delta}; \frac{\partial Z_{SS}}{\partial X_1} \approx \frac{Z_{SS}^0 - Z_{SS}}{\Delta X_1} = \frac{\Delta Z_{SS}}{\Delta}. \quad (6)$$

Using obtained from adjustment of scan station coordinates X_{SS}, Y_{SS}, Z_{SS} with condition that network fixed points do not contain errors of initial data, in formulas (6) scan station coordinates $X_{SS}^0, Y_{SS}^0, Z_{SS}^0$ calculated considering the condition that coordinate X_1 of the first fixed point was distorted by adding correction Δ, which can be practically accepted equal to 50 mm. Therefore, gradually changing fixed points coordinates, one by one, all columns of matrix (5) can be computed and meaning of covariance matrix $\mathbf{K}_{SN}$ can be found. When covariance matrix of scan station position is computed, considering the influence of initial data, we can calculate covariance matrix $\mathbf{K}_S$. For this we used the equations of 3D-polar method. Then, formula for matrix $\mathbf{K}_S$ can be written as:

$$\mathbf{K}_S = \mathbf{AMA}^{\mathrm{T}}, \quad (7)$$

Covariance matrix $\mathbf{K}_S$ can be computed by analogy as in (Beshr and Elnaga 2011): where: $\mathbf{A}$ - matrix of partial derivatives from equations for coordinates calculation using 3D-polar method; $\mathbf{M}$ - 3x3 diagonal matrix, where diagonal elements are dispersions of angles measurements and distances measured by terrestrial laser scanner. The matrix $\mathbf{A}$ of partial derivatives will look:

$$\mathbf{A} = \begin{bmatrix} S\cos z\cos\beta & -S\sin z\sin\beta & \sin z\cos\beta \\ S\cos z\sin\beta & S\sin z\cos\beta & \sin z\sin\beta \\ -S\sin z & 0 & \cos z \end{bmatrix}, \quad (8)$$

where: β - horizontal angle; z - zenith distance; S - distance.

Matrix of dispersions of angle and distance measurements without considering of correlation is:

$$\mathbf{M} = diag\begin{bmatrix} m_z^2 & m_\beta^2 & m_S^2 \end{bmatrix}, \quad (9)$$

where: m_z - RMS error of zenith distance measurement; m_β - RMS error of horizontal angle measurement; m_S - RMS error of distance measurement. These values can be taken from scanner specification or again by analogy with total station can be calculated like in (Bird 2009).

We substitute (4) and (7) in (1) and obtain equation for accuracy of control survey by TLS:

$$\mathbf{K}_{CS} = \mathbf{AMA}^{\mathrm{T}} + \mathbf{BKB}^{T} + \mathbf{K}_{FS}\ , \tag{10}$$

Using this equation and specifications from Section 2, we will make the preliminary accuracy calculation of control survey by TLS data. Therefore, taking into account the accuracy of survey network we got:

Case 1.

$m_{X_{CS}}$ = 2.0 mm, $m_{Y_{CS}}$ = 2.0 mm, $m_{Z_{CS}}$ = 2.4 mm and the total RMS $m_{CS_1} = \sqrt{m_{X_{CS}}^2 + m_{Y_{CS}}^2 + m_{Z_{CS}}^2}$ = 3.7 mm;

Case 2.

$m_{X_{CS}}$ = 3.9 mm, $m_{Y_{CS}}$ = 3.9 mm, $m_{Z_{CS}}$ = 4.9 mm and the total RMS $m_{CS_2} = \sqrt{m_{X_{CS}}^2 + m_{Y_{CS}}^2 + m_{Z_{CS}}^2}$ = 7.4 mm.

These accuracies we will have used for checking of different approaches for getting a correct geometrical information from TLS data in the following section.

4. RESEARCH OF DIFFERENT APPROACHES FOR GETTING A CORRECT GEOMETRICAL INFORMATION FROM TLS DATA

4.1. Deutscher Herold building control survey

The task of control survey of Deutscher Herold building appeared due to necessity in some reconstruction works. As was known from previous results, the central part of building facade has deviation from ideal plane. These deviations are results of errors during building construction process. In order to determine these deviation TLS was held. As we already discussed, we tried to compare the CAD model, which was known from archive data, with another three models, which were got from TLS data. Therefore, we have three comparison results, which we will present in graphical form below.

Fig. 4. The deviations field for comparison CAD and point cloud model

The first comparison we made in the most traditional way. It is comparison between CAD model and point cloud. The results of this comparison is presented on fig. 3 in the form of deviations field.

For better understanding the results, which we were got, we constructed a deviations histogram and found main statistical characteristics. The histogram of deviations distribution presented on Fig. 5.

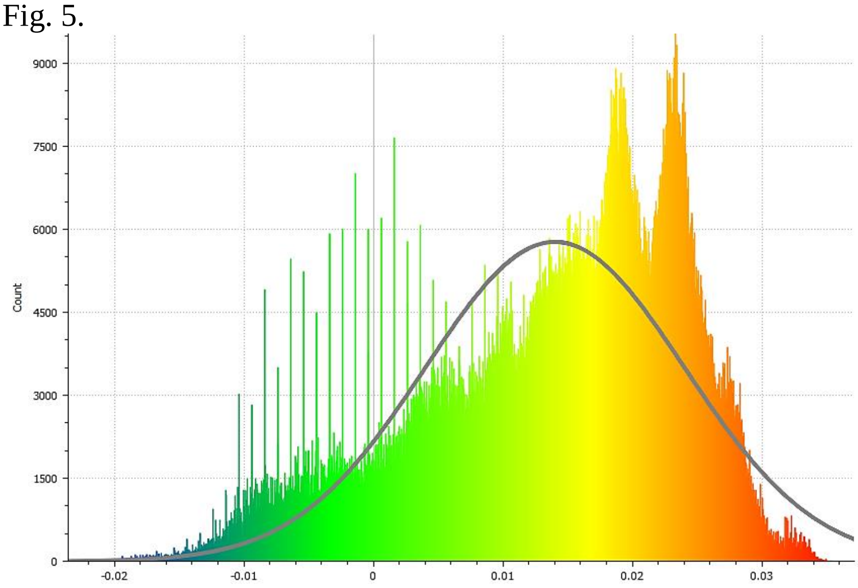

Fig. 5. The histogram of deviations distribution between CAD model and point cloud until blunders exclusion

As we can see, the deviations do not have a Normal distribution. We excluded all blunders and after statistical analysis, we got a systematic shift on the level 20 mm and standard deviation - 10 mm with mean value 14 mm. The max and min meanings are in range from – 30 mm to + 30 mm.

The second comparison we made between CAD model and TIN model. The results of this comparison is presented on fig. 6.

Fig. 6. The deviations field for comparison CAD model and TIN model

For better understanding the results which we were got, we constructed a deviation histogram and calculated main statistical characteristic. The histogram of deviations distribution presented on fig. 7.

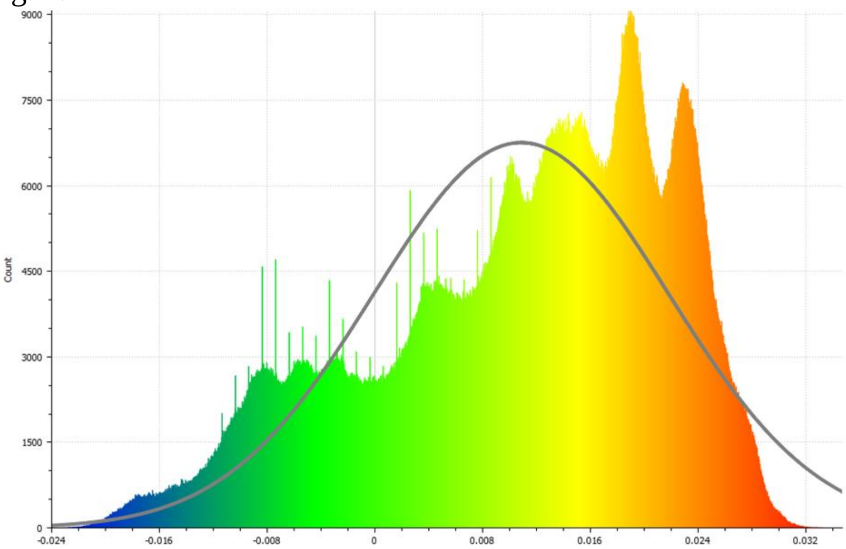

Fig. 7. The histogram of deviations distribution between CAD model and TIN model until blunders exclusion

As we can see again, the deviations do not have a Normal distribution. We excluded all blunders and after statistical analysis, we got a systematic shift on the level 20 mm and standard deviation 11 mm with mean value 11 mm. The max and min meanings are in range from – 20 mm to + 30 mm.

The third comparison we made between CAD model and solid model. The results of this comparison is presented on fig. 8.

Fig. 8. The deviations field for comparison CAD model and solid model

The histogram of deviations distribution presented on fig. 9.

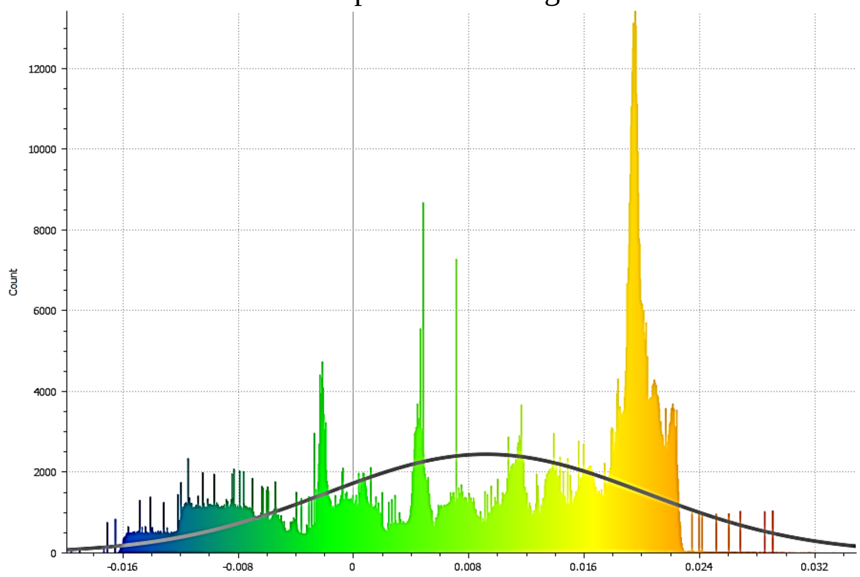

Fig. 9. The histogram of deviations distribution between CAD model and solid model until blunders exclusion

The deviations do not have a Normal distribution. We excluded all blunders and after statistical analysis, we got a systematic shift on the level 15 mm and standard deviation 11 mm with mean value 9 mm. The max and min meanings are in range from – 15 mm to + 22 mm.

For all approaches, such values correspond to preliminary calculated accuracy.

Based on these results we can make a preliminary conclusion. From the all models, the most real results were got from comparison with solid model. One of the reason of this result is that on solid model we have, in the most cases, the same elements, as on CAD model and thus, it is most exact comparison, without any redundant elements.
However, what will be if we do not have CAD model or when it is hard to compare this model with measurements data? Let's investigate such case in the next subsection.

4.2.Metro tunnel section control survey

Here we are presenting project as a good example what to do if we do not have CAD model. For such research, we choose the underground section of the metro tunnel (Fig. 10).

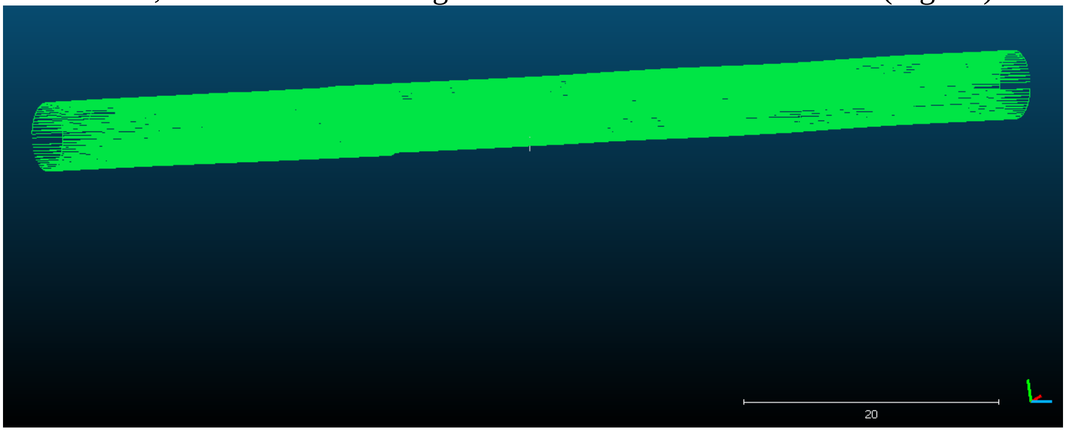

Fig .10. Underground tunnel TIN model

As we can see, it is a cylinder surface. For this tunnel, we know the geometric entities and their characteristics but CAD model is unknown. From the other hand, we have many demands to tunnel geometry. The first of them and the most important is tunnel radius. For this tunnel, the real radius must be exactly 2.690 m. Thus, in order to make a control survey of the tunnel we have to perform direct comparison between surveying results and real tunnel radius, instead of tunnel surface modelling. For resolving such task we offer to make transformation TLS data in such way that to make them more simple for comparison. One of the better way is perform involution of scanning data on the plane. This involution performed in equidistant projection. This projection does not have distortion, since the distance projection on the tangent plane is equal to distance on the surface of the cylinder (Fig. 11).

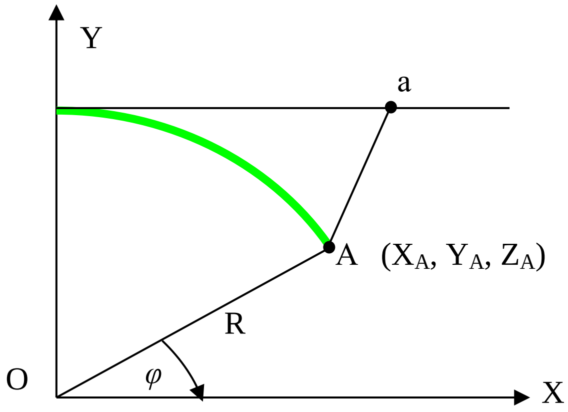

Fig. 11. The projection of tunnel surface on the plane in equidistant projection

For coordinate transformation, we using the next equations:

$$X_a = R\phi_A; \quad Y_a = R = \sqrt{X_A^2 + Y_A^2}; \quad Z_a = Z_A. \qquad (11)$$

The symbols in these equations is clear from fig. 11.

After applying this transformation to TLS data we got the picture of deviations which is presented on fig. 12.

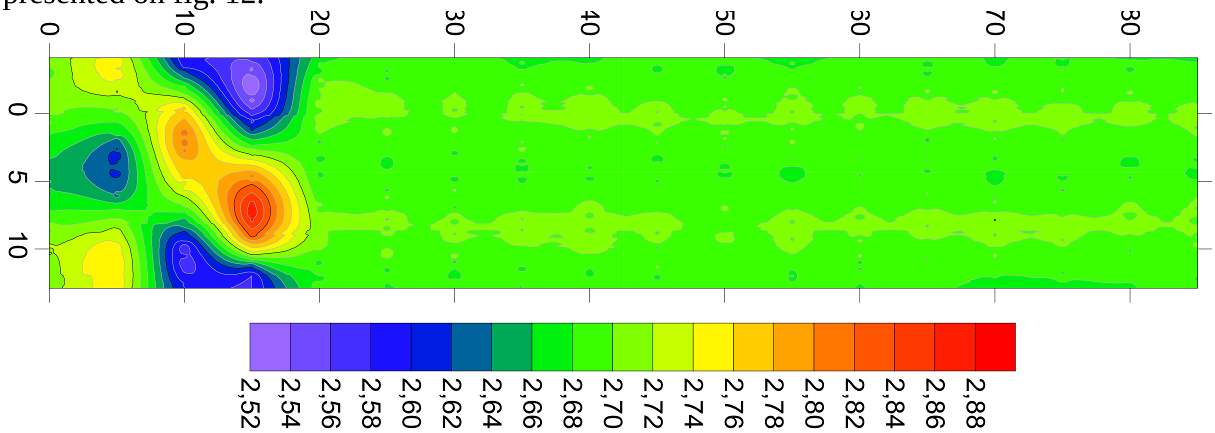

Fig. 12. The projection of tunnel surface on the plane

As we can see, the result of transformation is plane. The deviations from this plane clearly showing discrepancies between project tunnel radius and measured radius in any point. We can identify that in the part of tunnel between 5 m and 20 m there are biggest deviations from project radius. In order to assessing our results, we constructed histogram of deviations distributions (see fig. 13).

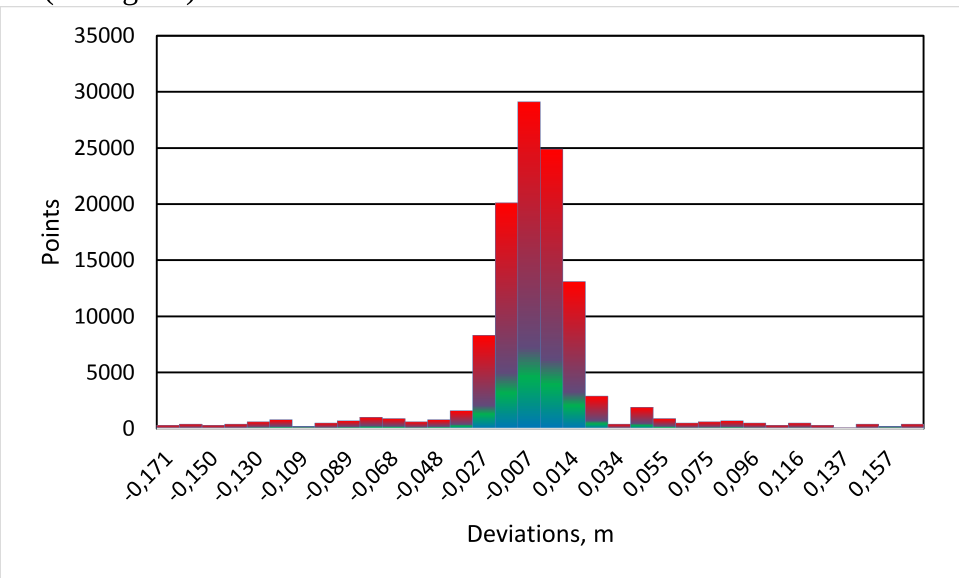

Fig. 13. The histogram of deviations distribution between project and measured radius

Using these deviations, we made statistical calculations and got: mean value – 3 mm; standard deviation 37 mm; max value 169 mm; min value – 181 mm. The reason of such big deviations

is on instantaneous deformation of tunnel constructions immediately after building works finishing.
At the end of these researches, we want to point out that in both cases, the accuracy of TLS measurements did not distort the accuracy of control survey since measurements were performed in 4-5 times accurately than values of deviations.

5. CONCLUSIONS

The first conclusion is that we have to choose right model for comparison according to circumstances. Sometimes, will be enough only point cloud. In another cases we will need a surface modelling with follow comparison. In any case, we have to account TLS accuracy in order to be confident that, our measurements do not distort our control survey. We would like to recommend use solid model for control survey, if we have CAD model for comparison. From the other hand if we do not have CAD model, one of the possible way just use point cloud. In addition, we again want to point out that all control surveys must be done with already filtered and referenced point clouds.
The second, our results are preliminary estimates. They require further investigation. It is necessary to investigate the influence of the point cloud density and mathematical algorithms for the models constructing on the quality and accuracy of control survey. We also must remember that different models are source of different information. For example, a solid model, as a TIN model allows to determine deviations in sections, while the geometric model allows to compare mathematical models of different elements.

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