PROCESSING OF POINT CLOUDS FOR DEFORATION MONITORING

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Abstract

The weather conditions and the operation load are causing changes in the spatial position and in the shape of engineering constructions, which affects their static and dynamic function and reliability. Because these facts, geodetic measurements are integral parts of engineering structures diagnosis.

The advantage of terrestrial laser scanning (TLS) over conventional surveying methods is the efficiency of spatial data acquisition. TLS allows contactless determining the spatial coordinates of points lying on the surface on the measured object. The scan rate of current scanners (up to 1 million of points/s) allows significant reduction of time, necessary for the measurement; respectively increase the quantity of obtained information about the measured object. To increase the accuracy of results, chosen parts of the monitored construction can be approximated by single geometric entities using regression. In this case the position of measured point is calculated from tens or hundreds of scanned points.

This paper presents the possibility of deformation monitoring of engineering structures using the technology of TLS. For automated data processing was developed an application based on Matlab®, Displacement_TLS. The operation mode, the basic parts of this application and the calculation of displacements are described.

1 Terrestrial Laser Scanning

The technology of Terrestrial Laser Scanning (TLS) in a non-selective method of spatial data acquisition. TLS determines the 3D coordinates of the measured points on the surface of the measured object in a grid, which is defined by regular angular spacing in the horizontal and vertical directions. The result of TLS is an irregular raster of measured points, the so-called point cloud, which documents the measured object (fig. 1). The difference of TLS to conventional surveying methods is that the coordinates of characteristic points are obtained by modelling, respectively by generalization of the main elements of 3D models or the resulting point cloud [1].

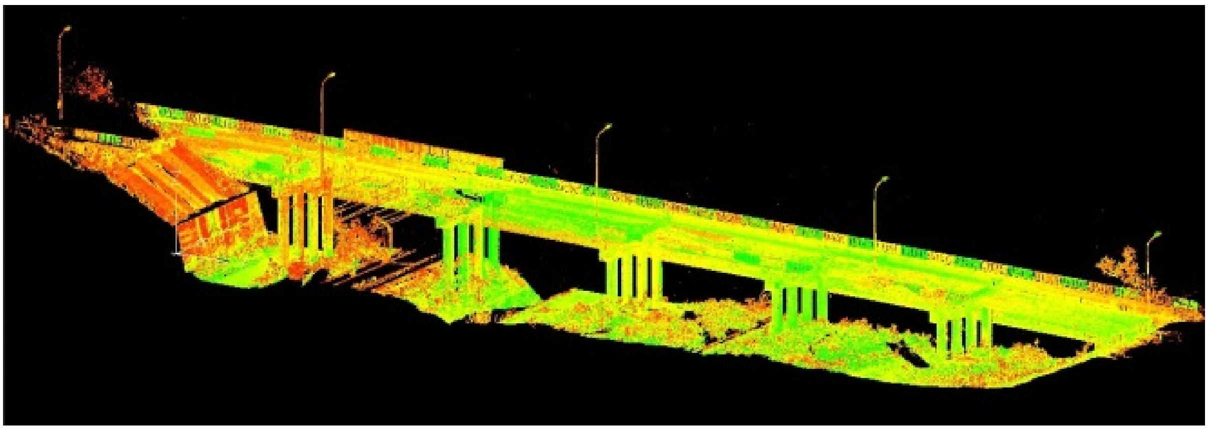

Figure 1: The point cloud of The bridge No. 137, Bojnicka street in Bratislava

Most of the current TLS works on the principle of spatial polar method. The spatial position of measured points are calculated from the measured horizontal and vertical angles and from the measured slope distance (fig.2 left).

The optimal source of radiation of electromagnetic waves for scanning systems are lasers. These are used for contactless measuring of distances. Laser beams are highly monochromatic and have a narrow spectral line width compared to the other sources of radiation.

The deflecting of laser beams is provided by oscillating mirrors, rotating prism, by rotation of the laser source around the horizontal and vertical axis of the instrument or by fiber optics, resp. by combination of the methods mentioned above. The most common used is the combination of rotation of instrument around the vertical axis, and an oscillating mirror.

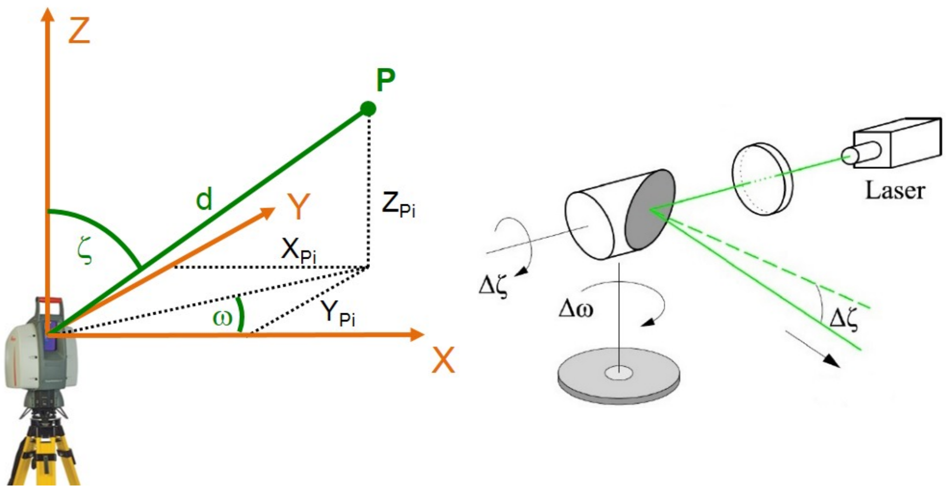

Figure 2: The principle of spatial polar method (left), and the combination of rotating source and oscillating mirror (right)

The process of data acquisition and the modelling using TLS can be divided into three main steps. The first one is the preparation for the measurement (for scanning), recognition of the measured object, the choice of positions for the instrument, signalization of the control points. The second step is the process of scanning and the third one is the processing of data obtained by TLS. The data processing contains:

- Preparation of the point cloud for data processing. This includes initial adjustments of point cloud: error elimination, filtering and data reduction, transformation (between different coordinate systems), elimination of unnecessary points, and coloring of points (assigning the colors according to the intensity of measuring signal or from photographs).
- Processing of data obtained by TLS. Spatial model creation of the measured object or its parts, determination of geometric parameters (e.g. dimensions) and deformations of chosen parts of the measured object.
- Visualization. Rendering of the created model, and creation of animations.

2 Deformation monitoring

The weather conditions and the operation load are causing changes in the spatial position and in the shape of engineering constructions, which affects their static and dynamic function and reliability. Because these facts, geodetic measurements are integral parts of engineering structures diagnosis.

One of the ways of deformation monitoring of engineering structures using TLS is the use of differential models. This method is used to determine the displacements of large surfaces, e.g. surface of the bottom of bridge deck. From the point cloud is created a triangular network at every epoch of measurement. From the differences between them are determined the displacement of the measured structure. These differences are measured in a defined grid in perpendicular direction to the reference plane defined in the epoch of initial measurement [2]. The disadvantage of this method is the less accuracy, because the triangles are created from points determined by accuracy of several millimeters (depends on the accuracy of chosen instrument).

To increase the accuracy of results, chosen parts of the monitored structure can be approximated by single geometric entities using regression. In this case the position of measured point is calculated from tens or hundreds of scanned points. Vertical displacements of measured points on the bottom part of chosen structures can be determined as the difference between the Z coordinates of these points in every measurement epoch. Their position is modelled by regression planes using orthogonal regression.

Figure 3: Vertical displacement determination of part of the Harbor Bridge in Bratislava

Orthogonal regression is calculated from the general equation of plane:

$$a \cdot X + b \cdot Y + c \cdot Z + d = 0 \qquad (1)$$

where: a, b and c are the parameters of normal vector of the plane,

X, Y and Z are the coordinates of the point lying in the plane,

d is the scalar product of the normal vector of the plane and the position vector of any point of the plane.

The orthogonal distance of a point from a plane is calculated by:

$$d_{P,\rho} = \frac{|a \cdot X_P + b \cdot Y_p + c \cdot Z_P + d|}{\sqrt{a^2 + b^2 + c^2}} \qquad (2)$$

The requirement of orthogonal regression is that the sum of the orthogonal distances have to be minimal, so:

$$\sum_{i=1}^{n} \frac{|a \cdot X_i + b \cdot Y_i + c \cdot Z_i + d|}{\sqrt{a^2 + b^2 + c^2}} = \min \qquad (3)$$

where: *n* is the number of points used for the calculation of the plane.

Partial derivation of (3) with respect to *d* leads to:

$$2 \cdot \sum_{i=1}^{n} \frac{|a \cdot X_i + b \cdot Y_i + c \cdot Z_i + d|}{a^2 + b^2 + c^2} = 0 \qquad (4)$$

According to the previous formula for the parameter *d* can be formulated as:

$$d = -(a \cdot X_0 + b \cdot Y_0 + c \cdot Z_0) \qquad (5)$$

And the formula for the general equation of plane becomes:

$$a \cdot (X_i - X_0) + b \cdot (Y_i - Y_0) + c \cdot (Z_i - Z_0) = 0 \qquad (6)$$

where: $(X_i - X_0)$, $(Y_i - Y_0)$ and $(Z_i - Z_0)$ are the coordinates of point cloud reduced to centroid.

For each point of point cloud is possible to write a formula according to (6) and the design matrix of the system of equations has the form:

$$\mathbf{A} = \begin{pmatrix} (X_1 - X_0) & (Y_1 - Y_0) & (Z_1 - Z_0) \\ (X_2 - X_0) & (Y_2 - Y_0) & (Z_2 - Z_0) \\ \vdots & \vdots & \vdots \\ (X_n - X_0) & (Y_n - Y_0) & (Z_n - Z_0) \end{pmatrix} \tag{7}$$

The orthogonal regression is calculated by applying of Singular Value Decomposition:

$$\mathbf{A} = \mathbf{U\Sigma V}^{T} \tag{8}$$

where: **A** is the design matrix, with dimensions *nx3*, and *n* is the number of points used for the calculation. The column vectors of $\mathbf{U}^{nxn}$ are normalized eigenvectors of matrix $\mathbf{AA}^{T}$. The column vectors of $\mathbf{V}^{3x3}$ are normalized eigenvectors of $\mathbf{A}^{T}\mathbf{A}$. The matrix $\mathbf{\Sigma}^{nx3}$ contains eigenvalues on the diagonals. Then the normal vector of regression plane is the column vector of **V** corresponding to the smallest eigenvalue from **Σ** [3].

The position of the observed points in XY plane is defined as fixed. The advantage of this procedure is that the position of observed points does not change, with the thermal expansion of the construction. Heights of observed points are calculated by projecting the points into regression planes using formula:

$$Z_P = -\frac{a \cdot X + b \cdot Y + d}{c} \tag{9}$$

Their mean errors are obtained using law of propagation of uncertainty, from the mean error of transformation and the mean error of regression planes, calculated from the orthogonal distance of points from these planes:

$$\sigma_{Z_P} = \sqrt{\sigma_{T_Z}^2 + \sigma_\rho^2} \tag{10}$$

where: σ_{T_Z} is the vertical error of the data transformation and σ_ρ is the standard deviation of the calculated regression plane.

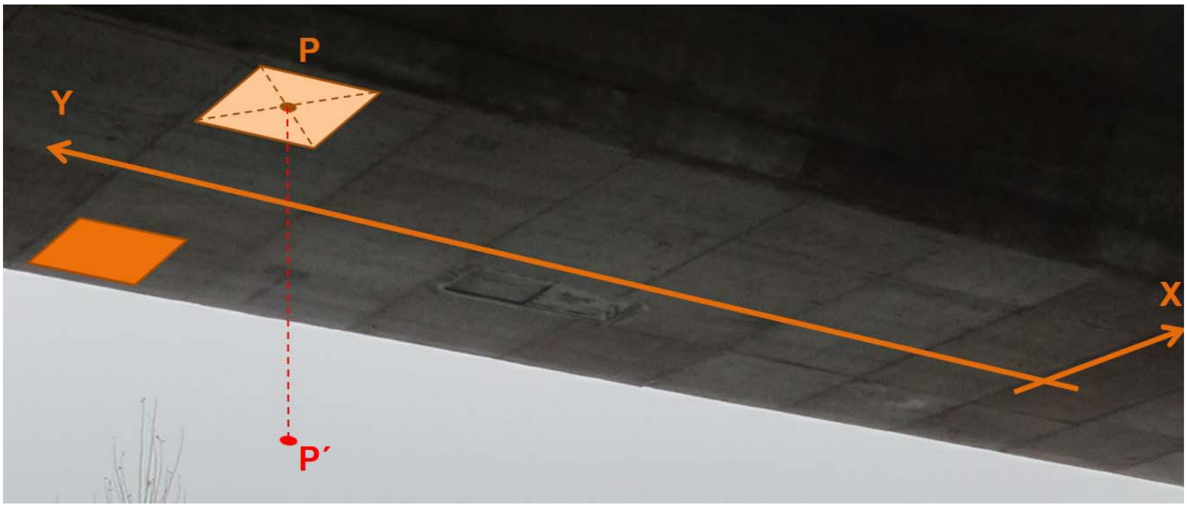

Figure 4: Determination of the height of measured points

3 Displacement_TLS application

The proposed procedure to determine the vertical displacements, depending on the number of the points of the point cloud, takes high demand on computing, used for the data processing, as well as the operator itself (definition of large number of fences, export/import the data, regression calculation, etc.). For the partial automation of the above mentioned procedure, a computing application

“Diplacement_TLS” was developed (fig.5). The application is based on computational software Matlab® by MathWorks®.

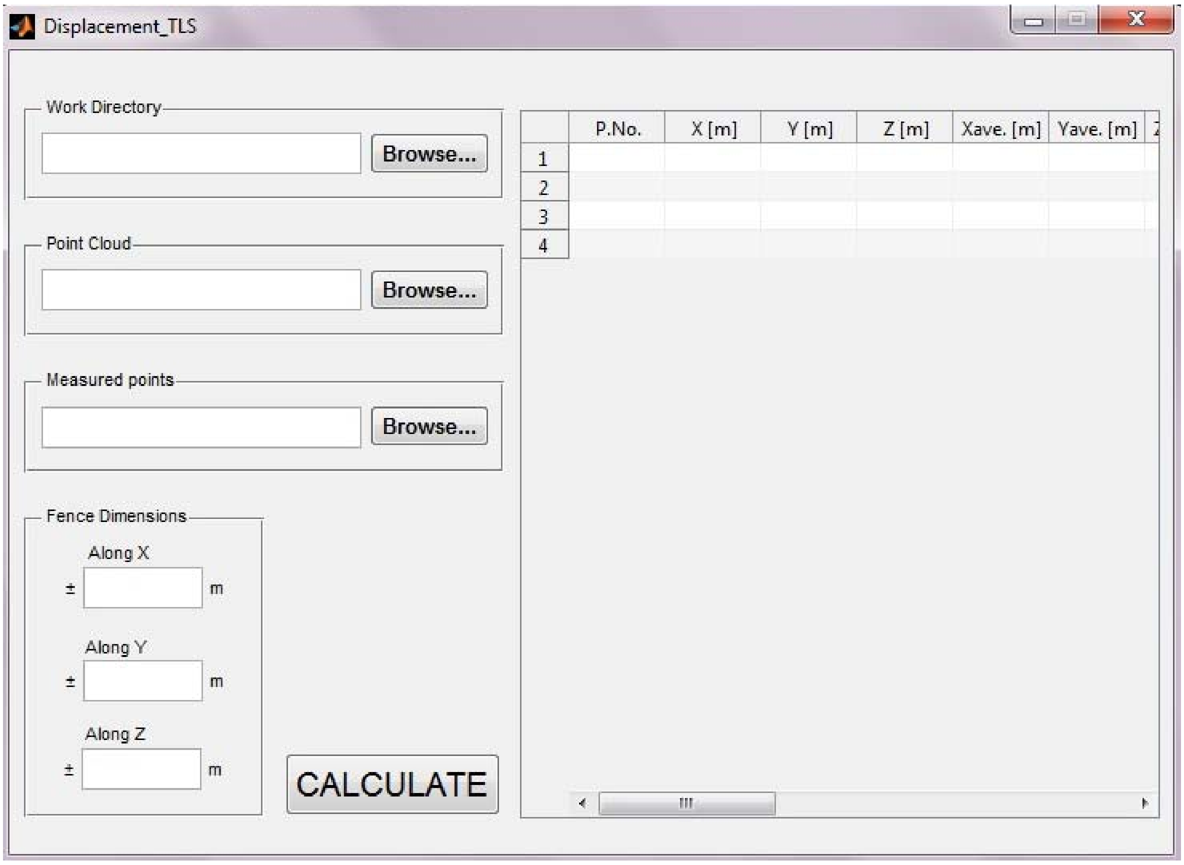

Figure 5: Dialog box of application Displacement_TLS

The application allows to load the coordinates of point cloud in text format (*txt). From the loaded points selects the points nearby the measured points, defined by X, Y and Z coordinates, based on the dimensions of the fences (points lying in the blocks defined by the coordinates of measured points and dimensions of fences). These blocks define approximately the same set of points in each measurement epoch. From these selected points are calculated the regression planes and their standard deviations.

The measured points are then projected into the regression planes and their Z coordinates are determined. The application shows the results of calculation in a table and register them into an *xls file. The results are the coordinates of the measured points, the coordinates of the centroids of selected parts of point cloud, the parameters of the general plane equation *a*, *b*, *c* and *d*, and the standard deviation of regression planes.

Vertical displacements are calculated as height difference of measured points between the initial and the current measurement epoch. The statistical significance of displacements is determined on the base of statistical analysis using interval estimates. The vertical displacements can be transformed into perpendicular displacements (in the case of slope surfaces) using the parameters of normal vectors of regression planes.

4 Conclusion

The issue of inspection of safety operation of engineering structures is always current and closely joined with the activities of surveyors. One of the most important tasks is the determination of the displacements of chosen parts of these structures using different surveying methods [4].

This paper presents the possibility of deformation monitoring of engineering structures using the technology of TLS. To increase the accuracy of results, chosen parts of the monitored structure should be approximated by single geometric entities using regression algorithms. TLS allows deformation monitoring of structures built by any construction methods, from any materials allowing passive reflection of measuring signal for distance measurements (laser beam). The measurements can be performed during full operation of the monitored structure, which significantly increase the economic efficiency of the deformation monitoring. For automated data processing was developed an application based on Matlab®, Displacement_TLS.

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