THE USE OF TERRESTRIAL LASER SCANNING TECHNIQUES TO EVALUATE INDUSTRIAL MASONRY CHIMNEY VERTICALITY

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ABSTRACT:

This paper presents a strategy to measure verticality deviations (i.e. inclination) of tall chimneys. The method uses laser scanning point clouds acquired around the chimney to estimate vertical deviations with millimeter-level precision. Horizontal slices derived from the point cloud allows us to inspect the geometry of the chimney at different heights. Two methods able to estimate the center at different levels are illustrated and discussed. A first solution is a manual approach that uses traditional CAD software, in which circle fitting is manually carried out through point cloud slices. The second method is instead automatic and provides not only center coordinates, but also statistics to evaluate metric quality. Two case studies are used to explain the procedures for the digital survey and the measurement of vertical deviations: the chimney in the old slaughterhouse of Piacenza (Italy), and the chimney in Leonardo Campus at Politecnico di Milano (Italy).

1. INTRODUCTION

Industrial masonry chimneys appeared in many European countries in the 19th century. Their popularity was strictly connected to the industrial revolution since the primary function was to remove the smoke of combustion caused by industrial processes. Industrial chimneys are related to the invention and production of steam boilers, in which fuel is burned in the boiler to produce steam.

To reduce construction costs, it was normal practice for different factories to share a single chimney, which often meant that the structures had a big size. Chimney height was very various. It depended on many factors such as wind, type of goods manufactured, nearness to towns, topography, etc. For this reason, chimney height is extremely variable: from a few tens of meters (20-50 m) up to hundred meters or more.

The shape used for a chimney is usually conical. During the period of industrial expansion, large numbers of chimneys were built in many cities, forming typical skylines during the 19th and 20th centuries. After WW2, changes in industrial processes and urban expansion have put an end to many of these industries situated in the heart or outskirts of towns and cities. Many factory buildings have disappeared, or they have been transformed into constructions for other uses, but many chimneys have been conserved and now constitute part of the urban scene of many cities.

Many chimneys have been declared protected buildings for their social and historic value. However, once they became outdated in industrial processes, many chimneys were neglected for several years, causing rapid degradation. For this reason, the assessment of the state of conservation has primary importance for further interventions and preservation plans.

From a static point of view, one of the most important parameters to inspect during a stability assessment of a tall chimney is the inclination of the main body. In many cases, this is related to differential expansions of the masonry joints affected by mortar sulfation, faulty construction methods, foundation problems, or, differences in mortar drying on different sides due to the action of the prevailing wind.

The evaluation of the inclination of a chimney with traditional techniques can be a difficult task. In this paper, we present a method for the evolution of industrial masonry chimney inclination using terrestrial laser scanning (TLS, Vosselman and Maas, 2010) point clouds. Laser scanning is a popular solution to evaluate structural stability for many constructions (Erdélyi et al. (2016), Głowacki, et al.(2016), Muszyński (2014), Pandžić et al. (2016), Pesci et al. (2011), Vezočnik et l. (2011)). Examples of previous work with TLS applied to the survey of chimneys are Bajtala et al. (2011), Kregar et al. (2015).

Two case studies are illustrated and discussed in this paper: the chimney in the old slaughterhouse of Piacenza (Italy), and the chimney in Leonardo Campus at Politecnico di Milano (Italy).

The paper describes the methods used to collect metric information on-site as well as the procedures and algorithms used to assess vertical deviations. In the first case study, a manual approach was used. In the second one, a novel automated procedure was implemented, resulting in a method able to provide statistical parameters for quality check.

2. THE CHIMNEY OF THE S. ANNA COMPLEX, PIACENZA, ITALY

2.1 Brief description

The chimney is located in the C. Guidotti pavilion of the former municipal slaughterhouse of Piacenza (Figure 1), which is bounded by via Scalabrini, Vicolo Moroni, stradone Farnese, and via Caccialupo. A high brick wall facing East and South encloses the entire complex.

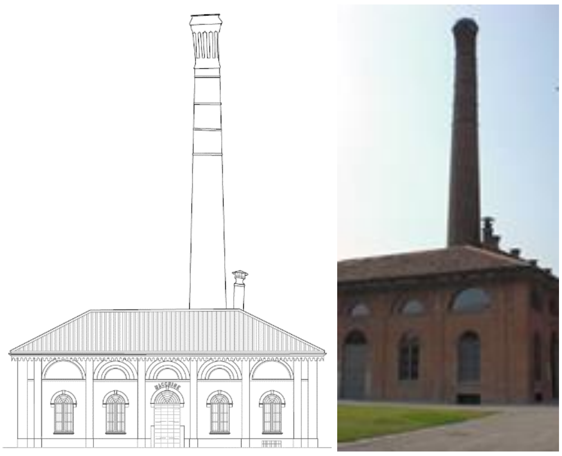

Figure 1. The chimney in the C. Guidotti pavilion of the former municipal slaughterhouse of Piacenza.

The slaughterhouse of S. Anna (Figure 2) was built in the years 1892 - 1894. The decision to build a new slaughterhouse was motivated by the choice of the Municipality of Piacenza to replace the old Carmine slaughterhouse (built in 1805), which was closed at the end of the nineteenth century because of its limited size. In addition, the Italian regulation for all cities with more than 6,000 inhabitants made compulsory to build a slaughterhouse for the needs of local inhabitants.

Figure 2. The S. Anna complex in Piacenza.

2.2 The digital survey

The survey was conducted using terrestrial laser scanning technology coupled with total station measurements. A closed traverse was measured around the Guidotti pavilion with a Leica 1203 total station. Scans were acquired with a Faro Focus 3D X130 HDR.
The scheme of the network is visible in Figure 3. It is made up of 4 station points, from which several laser scanning targets (checkerboards) where measured. Some targets were measured multiple times from different stations, obtaining redundant observation schemes that improved network adjustment. Least squares adjustment was carried out fixing the coordinates of two points (1 station point and an orientation target). The number of observations (distances, horizontal and vertical angles) is 408, whereas the unknowns (3D coordinates) are 98. The precision from the variance-covariance matrix provided an average point precision of about ±2-3 mm.

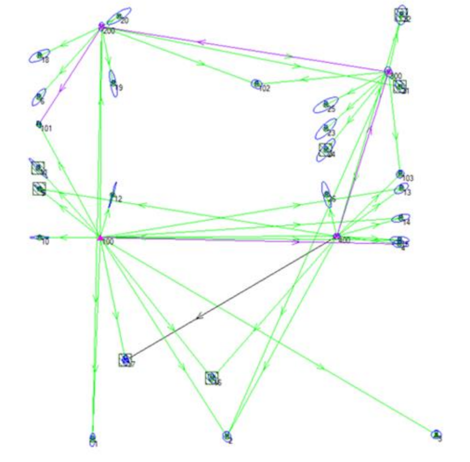

Figure 3. The network around the building.

A set of scans was then collected with a Faro Focus 3D HDR X130, using a resolution of 44 million points / scan. Scans were taken moving the scanner around the building. Registration was carried out using the checkerboard targets already measured with the total station, and additional sphere-to-sphere correspondences used to connect consecutive scans. The registration gave an average precision of about ±2-3 mm, which seems sufficient for the next phases of the work, i.e. the evaluation of chimney verticality. Some images of the registered point clouds are shown in Figure 4.

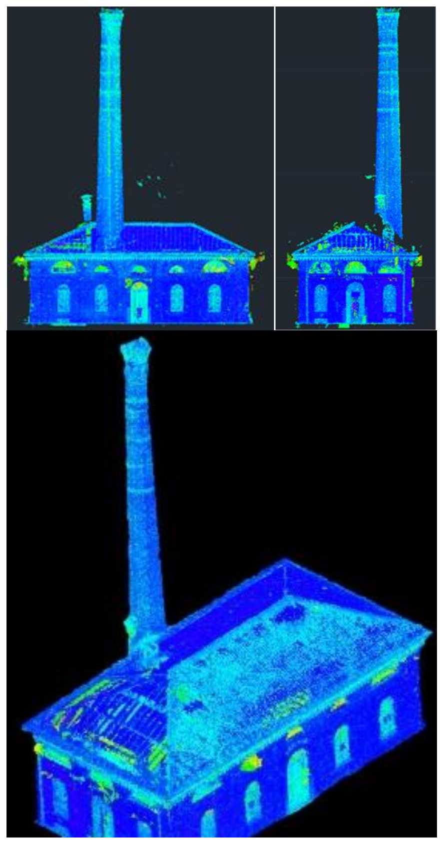

Figure 4. Some images of the registered point clouds in Autodesk Recap.

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2.3 Manual extraction of sections

The procedure for the estimation of verticality deviations is based on the creation of several horizontal sections from the point cloud. Starting from the level of the ground, a set of horizontal slices every 3 m was automatically extracted from the registered point clouds. A limited thickness (2 cm) was chosen to obtain slices with enough points.

Starting from every section, a set of circles was manually fitted in AutoCAD. The user traced the circumferences using three points, checking the distance between the point cloud slices and the achieved circumferences. Then, the center of each section can be easily computed. The deviation is given by the difference between the center at ground level and the remaining ones. The achieved result is visible in Figure 5. Obviously, this is a manual procedure.

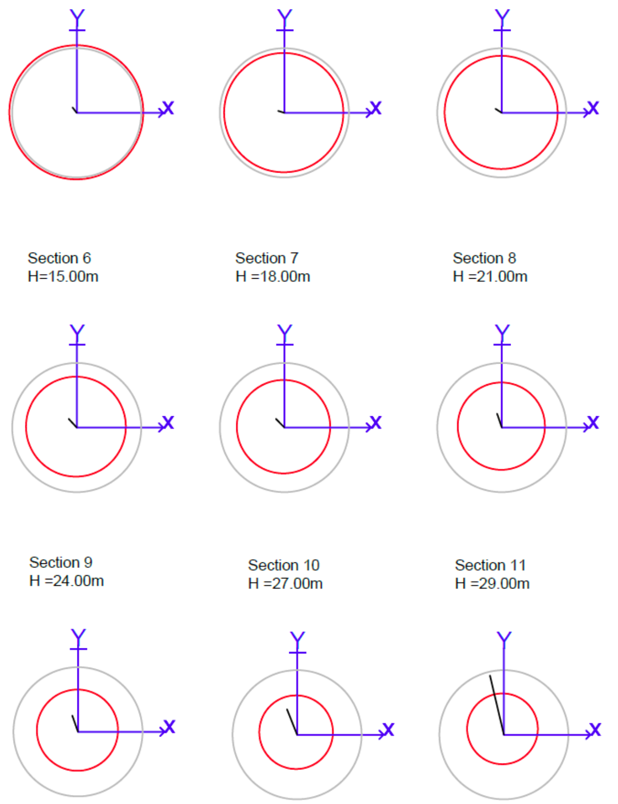

Figure 5. Some images of the schemes used to represent verticality deviations. Original images also have numerical information about the displacement. Numerical results are omitted in this paper.

3. THE CHIMNEY OF LEONARDO CAMPUS AT POLITECNICO DI MILANO

3.1 Brief description

The chimney is located in the Leonardo Campus of Politecnico di Milano (Italy). The chimney was built by Costruzioni Edili Speciali di Milano, that completed the construction in 1927. The chimney was inaugurated the same year with the rest of the buildings belonging to the historical nucleus of the university in Piazza Leonardo da Vinci in Milan.

Nowadays, the chimney is no longer in use. It has a height of 56 meters and has a solid brick structure. The internal section of the chimney is "double-barreled" for the first section of about 26 meters, after which it continues up to the top with a single conduit. A water tank is installed around the chimney and was used in the past for scientific experiments.

The chimney was subjected to consolidation and restoration in the initial double-barreled part in the years 2012-2013. In the same intervention, the structure was equipped with a system of anchors necessary to perform future inspections or interventions by specialized staff.

Figure 6. An image of the chimney in Leonardo Campus at Politecnico di Milano, Milan, Italy.

3.2 The digital survey

The survey started with the creation of a geodetic network around the chimney, considering the requirements of the laser scanning project. In fact, the chimney is in a courtyard, which provides limited distances between the chimney and the buildings. Such distances do not allow the collection of laser scans capturing the top of the chimney.

For these reasons, the scanner was moved in other areas beyond the buildings, resulting in a larger geodetic network. The total station is a Leica TS30, and the network is made up of 8 stations (Figure 7). Laser scanning targets (chessboard) were placed during the creation and measurement of the network, so that they were directly measured without repositioning the tripods.

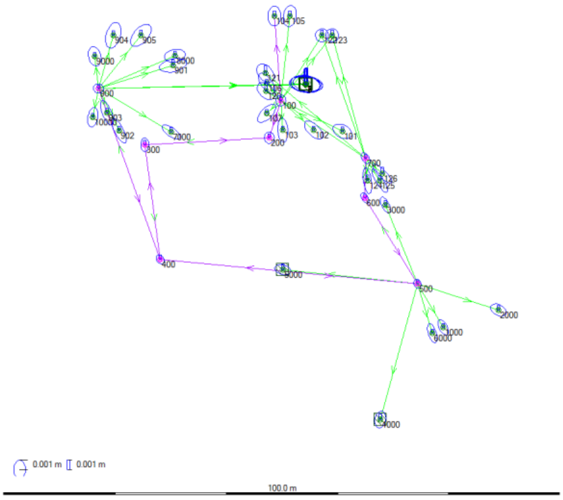

Figure 7. The scheme of the geodetic network around the chimney.

Figure 8 shows an image of the consolidated point cloud after data registration. Some scans were acquired from the roof of the buildings in the area. This was necessary to capture also the top part of the chimney. Here, points have a lower density and result in a slightly worse estimation of the inclination.

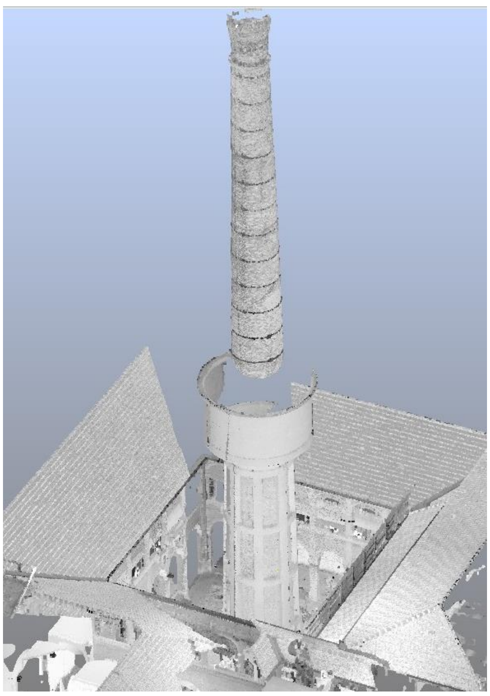

Figure 8. An image of the registered point clouds.

3.3 Automatic evaluation of verticality

The automatic evaluation of center coordinates at different levels is carried out using circumferences automatically fitted via least squares. A set of thin slices (usually 1-2 cm) is extracted at different elevations, then center and radius are calculated as follows.

Let's consider the equation of a circumference:

$$x^2 + y^2 + ax + by + c = 0 \tag{1}$$

For a point A we can write

$$ax_A + by_A + c = -(x_A^2 + y_A^2) \tag{2}$$

where the terms a, b and c are unknowns. These parameters are also linked to the position of the center of the circle and the radius. Indeed, the center of the circle is given by:

$$x_0 = -\frac{a}{2}; y_0 = -\frac{b}{2} \tag{3}$$

While the radius is given by:

$$r = \sqrt{x_0^2 + y_0^2 - c} \tag{4}$$

By using the least squares method, the unknown vector X can be written as:

$$X = \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{5}$$

and the design matrix can be defined as:

$$A = \begin{bmatrix} x_A & y_A & 1 \\ x_B & y_B & 1 \\ \dots & \dots & \dots \end{bmatrix} \tag{6}$$

while the vector of measurements is obtained as

$$l = \begin{bmatrix} x_A^2 + y_A^2 \\ x_B^2 + y_B^2 \\ \dots \end{bmatrix} \tag{7}$$

The precision of parameters a, b, c is extracted from the variance-covariance matrix $C_{abc} = \sigma_0^2 N^{-1}$.

The accuracy of the geometric parameters x_0, y_0 and r can be calculated using matrix notation as:

$$C_{xyr} = J_c\, C_{abc} J_c^T \tag{9}$$

Taking into consideration Eq.3 and Eq.4 the elements of the Jacobean matrix J_c are:

$$\begin{gathered} j_{11} = \frac{\partial x_0}{\partial a} = -\frac{1}{2} \\ j_{12} = \frac{\partial x_0}{\partial b} = 0 \\ j_{13} = \frac{\partial x_0}{\partial c} = 0 \\ j_{21} = \frac{\partial y_0}{\partial a} = 0 \\ j_{22} = \frac{\partial y_0}{\partial b} = -\frac{1}{2} \\ j_{23} = \frac{\partial y_0}{\partial c} = 0 \end{gathered} \tag{10}$$

$$j_{31} = \frac{\partial r}{\partial a} = 0.5 \frac{2a}{2\sqrt{x_0^2 + y_0^2 - c}} = \frac{a}{4r}$$

$$j_{32} = \frac{\partial r}{\partial b} = 0.5\frac{2b}{2\sqrt{x_0^2 + y_0^2 - c}} = \frac{b}{4r}$$
$$j_{33} = \frac{\partial r}{\partial c} = 0.5\frac{-4}{2\sqrt{x_0^2 + y_0^2 - c}} = -\frac{1}{r}$$

So, the Jacobean matrix can be defined as:

$$J_c = \begin{bmatrix} -\frac{1}{2} & 0 & 0 \\ 0 & -\frac{1}{2} & 0 \\ \frac{a}{4r} & \frac{b}{4r} & -\frac{1}{r} \end{bmatrix} \tag{11}$$

Starting from the covariance matrix, it is also possible to calculate the error ellipse of the center position. Indeed, the axes of the ellipse are given by the square root of the eigenvalues of the matrix C_{xy}

$$C_{xy} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} \tag{12}$$

while the counter-clockwise rotation (θ) of the ellipse is given by:

$$\theta = \frac{1}{2}\, tan^{-1}\left[\frac{2\sigma_{xy}}{\sigma_x^2 - \sigma_y^2}\right] \tag{13}$$

The previous formulation allows one to compute center coordinates and their precision. The inclination can be estimated using the difference of center coordinates at different levels.

Figure 9 shows the achieved precision of center coordinates estimated as $\sqrt{\sigma_x^2 + \sigma_y^2}$. The graph illustrated that the precision is worse for sections taken on top of the chimney. Indeed, such sections have less points for the longer laser-object distance, resulting also in a worse precision in terms of range measurements. It is interesting that the worse section shows a precision better than 2 mm, which is a value much smaller than the computed inclination. Such statistics are useful to evaluate the metric quality of the computed inclination.

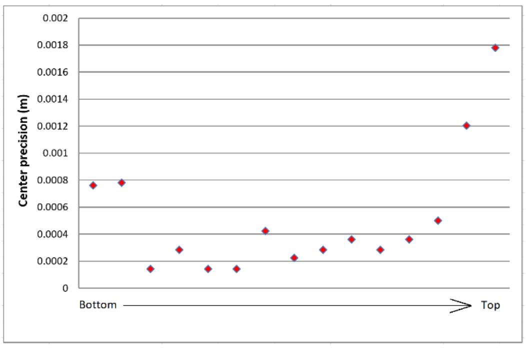

Figure 9. The precision of center coordinates for different sections, from bottom to top of the chimney.

Finally, Figure 10 shows a graphic representation of the inclination of the chimney. Numerical results are omitted and an overall indication is illustrated.

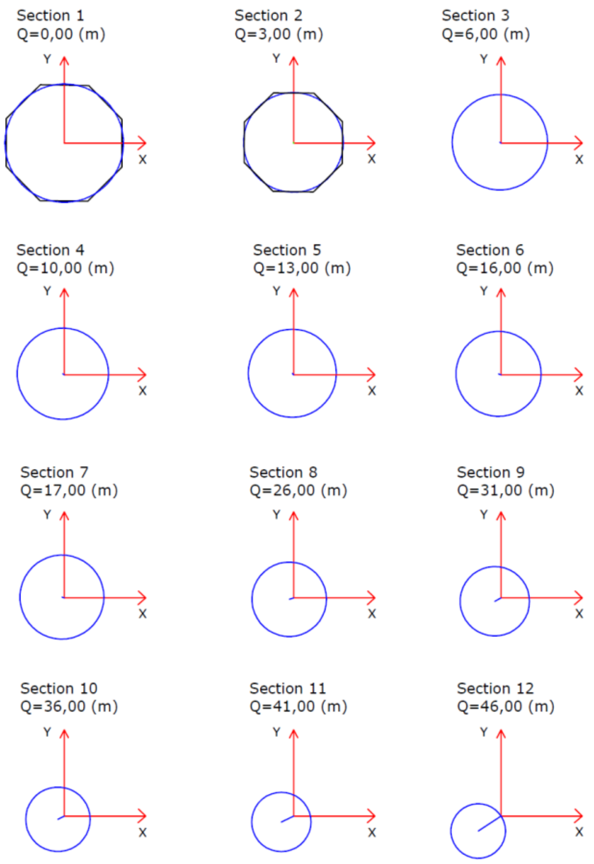

Figure 10. Some images of the schemes used to represent verticality deviations. Original images also have numerical information about the displacement. Numerical results are omitted in this paper.

4. CONSIDERATIONS AND CONCLUSIONS

The work presented in the previous sections was carried out combining laser scanning and total station measurements. The combined use of both technologies allowed us to gather dense point clouds around the chimney. The use of total station targets simplified the data registration phase, and it provided an additional check about scan registration quality. It is extremely important to have scans oriented in a reference system where Z represents the vertical axis. Although the Faro Focus 3D laser scanner used has an internal compensator able to level the acquired scans, the use of a total station provides an additional way to check the accuracy of the solution.

It is also recommended to place some targets (with known coordinates) far from the laser scanner. This allows better control on the registration of the scans, avoiding “tilted scans” resulting in a wrong estimation of chimney inclination. In the case of the Faro Focus 3D, some big chessboard targets were used.

Additional considerations are related to the use of photogrammetry (Luhmann et al., 2006) for such projects. The authors decided to use laser scanning technology for the opportunity to place and measure targets around the chimney. Photogrammetry would require a good distribution of control points also on the chimney, especially for the need to identify the vertical axis. This is not a simple task, which requires expert operators (e.g., qualified climbers) to reach the top of the chimney.

It is also interesting that the magnitude of the measured inclination is significantly larger than the precision achieved with the implemented method. The opportunity to use statistical indexes (precision of center coordinates in this case) confirmed that the obtained results are more than sufficient to evaluate chimney inclination. At the same time, small residuals indicate that the estimated sections are circular.

The same survey repeated at different epochs could become a solution for monitoring. Scans have to be registered in the same reference system, which is not a complicated operation if some control points are placed in stable areas around the chimney.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Erdélyi, J., Kopáčik, A., Lipták, I., Kyrinovič, P., 2016. Automation of point cloud processing to increase the deformation monitoring accuracy. Applied Geomatics, 9(2), 105-113.

Bajtala, M., Brunčák, P., Kubinec, J., Lipták, M., Sokol, S., 2011. Exploitation of Terrestrial Laser Scanning in Determining of Geometry of a Factory Chimney. Proceedings of the 5th International Conference on Engineering Surveying (INGEO 2011), Brijuni, Croatia, September 22-24, p. 77- 82

Głowacki, T., Grzempowski, P., Sudoł, E., Wajs, J., Zając, M., 2016. The assessment of the application of terrestrial laser scanning for measuring the geometrics of cooling towers", Geomatics, Land management and Landscape, vol. 4, p. 49-57.

Kregar, K., Ambrožič, T., Kogoj, D., Vezočnik, R., Marjetič, A., 2015. Determining the inclination of tall chimneys using the TPS and TLS approach, Measurement 75, 354-363, DOI:10.1016/j.measurement.2015.08.006

Luhmann, T., Robson, S., Kyle, S., Harley, I., 2006. Close range photogrammetry. Principles, methods and applications, Whittles Publishing, Dunbeath, Scotland, 87–88.

Muszyński, Z., 2014. Application of robust estimation methods to calculation of geometric distortions of a cooling tower shell. Proc. of the 14th Int. Multidisc. Scientific GeoConference (SGEM 2014), vol. 2, Geodesy and mine surveying, Albena, Bulgaria, 17-26 June, p. 65-72.

Pandžić, J., Pejić, M., Božić, B. and Erić, V., 2016. TLS in Determining Geometry of a Tall Structure Engineering Geodesy for Construction Works, Industry and Research, Proceedings of the International Symposium on Engineering Geodesy (SIG 2016), Varaždin, Croatia, 20–22 May, pp. 279- 290, 2016.

Pesci, A., Asula, G., Boschi, E. 2011. Laser scanning the Garisenda and Asinelli towers in Bologna (Italy): Detailed deformation patterns of two ancient leaning buildings", Journal of Cultural Heritage, vol 12, p. 117-127.

Vezočnik, R., 2011. Analysis of terrestrial laser scanning technology for structural deformation monitoring (PhD thesis), University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana.

Vosselman, G. and Maas, H.G. (2010). Airborne and Terrestrial Laser Scanning. Whittles Publishing.

https://doi.org/10.5194/isprs-archives-XLII-2-W11-173-2019