Application of Terrestrial Laser Scanning to Study the Geometry of Slender Objects

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Abstract. Slender objects are a special group among the many types of industrial structures. These objects are characterized by a considerable height which is at least several times bigger than the diameter of the base. Mainly various types of industrial chimneys, as well as truss masts, towers, radio and television towers and also windmill columns belong to this group. During their operation slender objects are exposed to a number of unfavourable factors. For this reason, these objects require regular inspection, including geodetic measurements. In the paper the results of geodetic control of geometry of industrial chimney with a height of 120 m has been presented. The measurements were made by means of terrestrial laser scanning technique under rather unfavourable conditions (at night, during snowfall, with low air temperature) which allowed to verify the real usefulness and accuracy of this technique in engineering practice. On the basis of point cloud, the values of deviations from the vertical for main axis of the chimney have been calculated. Using point cloud, the selected horizontal cross sections of chimney were analysed and were compared with the archival geodetic documentation. On this basis the final conclusions about the advantages and limitations of the using of terrestrial laser scanning technique for the control of geometry of high industrial chimneys have been formulated.

1. Introduction

In the last century the intensive industrial development led to the creation of many factories equipped with chimneys for carrying exhaust gases which are producing during manufacturing process. Some of these chimneys are already old and require special supervision. Simultaneously tightening of criteria related to environmental protection has forced the building of higher industrial chimneys. In addition, in our landscape there are a lot of high constructions related to the development of new technologies: telecommunication relays, radio and television masts, wind power plants. All these objects are characterized by high altitude with small dimensions of their base and they are called the slender objects. During their operation the slender objects are exposed to a number of unfavourable factors. The most important of these is variable wind load which causes vibrations and deformation of the structure. The second major factor is the thermal load caused by varying direction of incidence and intensity of sunlight. In the case of industrial chimneys, the thermal load is also connected with a difference of temperatures between the hot exhaust gases inside the chimney and the low ambient temperature (especially in winter). Not without significance is also the stability of the foundation of the object as well as the corrosion of its structural elements. In order to ensure operational safety, the slender objects require regular technical inspections, including regular geodetic measurements. Standard range of geodetic work includes the determination of vertical displacements of the foundation of the chimney.
and determination of deviations of the main vertical axis of the chimney. Apart from the classical methods of measurement, such as precise levelling, photogrammetry and motorized precise tacheometry, the terrestrial laser scanning is increasingly applied. It is undoubtedly a modern and fast measurement technique, but has also some limitations.

2. Terrestrial Laser Scanning
Terrestrial Laser Scanning (TLS) technology provides a wide number of precision spatial data. The characteristic feature of this technique is its high automation at the measurement stage as well as the further processing of its results, including the classification of received data - clouds of the measured points. Thus, measurements using TLS are currently widely used by architects, building and construction engineers as well as surveyors. In simplification, the terrestrial laser scanner can be compared to a tacheometer. However, the efficiency of laser scanner is not possible to reach by the tacheometer. Even the latest motorised tacheometers or scanning tacheometers do not achieve the same measurement speed as laser scanners.

TLS is an active data acquisition system which allows precisely determine the shape and geometric relations between the measured objects. The theoretical basics of TLS and its classification can be found in [1]. The main result of measurement performed using terrestrial laser scanner is a point cloud with known X, Y, Z coordinates of each point in a predefined coordinate system. Most often such a point cloud is subsequently used for creating of spatial models [2-5] and for detection of geometric shape changes in engineering structures [6-9]. From laser scanner we can also obtain high-resolution images of scanned structures as well as additional information which is intensity of laser beam reflection. On the basis of intensity, it is possible to analyse e.g. properties of the scanned surfaces [4, 10, 11].

With regard to the monitoring of geometric state of slender objects the TLS is becoming increasingly popular. However, presently there aren't a great number of scientific papers about application of this technique for control of slender objects. Usually the literature provides examples of using the terrestrial laser scanning in the monitoring of engineering structures such as cooling towers [12] or industrial chimneys [13, 14]. In the case of measurements of high chimneys there are some problems like: very steep sight lines (especially for high chimneys localized among dense infrastructures of industrial plant) and the vibrations or changes of the object's shape during the measurement period. In some situations, the comparison of measurement results from the scanner (quasi-continuous data) with the archival data (usually based on classical techniques which describe the geometry of the chimney in selected measurement levels) can also provide an additional problem. It’s known that the monitoring of geometrical shape and determination of deviations of chimney’s axis from vertical are not sufficient to properly assess the technical condition of the chimney. Additionally, it is necessary to control the settlement of the foundation of the chimney in long period of time by means of precision levelling. Construction works performed in the vicinity of slender objects can also influence adversely. Some examples of dynamic monitoring of old chimney in course of Rapid Impulse Compaction were given in [15] and [16]. Nowadays the integration of various measuring techniques is increasingly being used to provide comprehensive monitoring of building objects. In the author's opinion the terrestrial laser scanning technique is becoming increasingly important in these monitoring systems.

3. Industrial chimney as an example of slender object
The object of study was a reinforced concrete industrial chimney with a height of 120 m, which is situated in heat and power plant located in central Poland (figure 1). Last two measurements controlling the deviations of chimney’s axis from vertical were conducted in 1996 and 2004. Classic techniques of measurement using the tangent method were applied during those measurements and the obtained results have been presented in table 1. It is visible that for each measurement, different measuring levels on the chimney were selected. In result, it was impossible to directly compare values of deviations between these years. Within the framework of researches, in 2013 the authors of this work conducted measurements of the chimney geometry with the use of terrestrial laser scanner. For this purpose, a geodetic control network consisting of 6 points (figure 1a) was established. Four of these points, with
the following numbers: 1, 3, 4, 6, were used as stations of an impulsive laser scanner Leica ScanStation C10. The measurements were taken at night in winter season. It was snowing and the temperature was slightly above 0°C. Because of unfavourable measurement conditions, point clouds were unclean, mostly due to reflections of laser beam from snowflakes (figure 2a, 2b). Additionally, snow limited effective range of scanner measurement. Although sight axes did not exceed the distance of 132 m, the top part of the chimney was not scanned entirely, which caused empty spaces in point clouds (figure 2b). Point clouds, obtained from particular stations, were combined in a special software Leica Cyclone. Mean Absolute Error of the registration, conducted on the basis of HDS targets, was equal to 2.3 mm. Point cloud view after combining is presented on figure 2a and 2b. The next step was cutting the point cloud in such a manner that it would show the chimney only and, subsequently, it was purified of noise and unnecessarily scanned elements of infrastructure attached to the chimney (figure 2c).

![Figure 1. Location of geodetic control network (a) and view of the bottom part of the chimney’s corpus (b)](image)

**Table 1. Archival documentation concerning deviation of the chimney's axis from the vertical.**

| Height [m] | 1996 year | 2004 year |
|-----------|------------|-----------|
|           | Deviation in north direction [mm] | Deviation in east direction [mm] | Total deviation [mm] | Height [m] | Deviation in north direction [mm] | Deviation in east direction [mm] | Total deviation [mm] |
| 0         | 0          | 0         | 0             | 0          | 0          | 0             | 0             |
| 22        | 17         | -7        | 18            | -          | -          | -             | -             |
| 45        | 2          | 46        | 46            | 30         | -9         | 30            | 31            |
| 60        | -14        | 72        | 73            | -          | -29        | 63            | 69            |
| 80        | -4         | 93        | 93            | 60         | -29        | 63            | 69            |
| 114       | -33        | 166       | 169           | -          | -63        | 182           | 193           |

![Figure 1](image)
Figure 2. The view of point cloud: before cutting – top view (a) and the view from south (b), after cutting and purifying (c), and after cutting into slices (rings) (d)

4. Results and discussions
In order to compare data from scanner to results of archival measurements from 1996 and 2004, rings with the width of 25 mm were cut out of point cloud (in CloudCompare software) on adequate levels (figure 2d). In places, where points density in the cloud was not sufficient, the width of rings was increased, up to 0.5 m at the extreme case (table 2). Next, segment of vertical cylinder was fitted into every ring with the use of the least squares method and then x, y coordinates of cylinder axes and mean error of adjustment were calculated. By comparing x and y coordinates on higher levels to coordinates on the lowest level, deviations of the chimney’s axis from vertical were calculated (table 2). Results obtained from scanner measurement were compared to the results of previous measurements (conducted with the use of classic methods), which is presented in the form of charts (figure 3, 4). Figure 3 also shows mean errors of deviations from verticality for last measurement (2013 year). Unfortunately, the accuracy evaluation of previous measurements is not available.

Table 2. Results of calculations conducted on the basis of data from terrestrial laser scanning.

| Height [m] | Deviation in north direction [mm] | Deviation in east direction [mm] | Total deviation [mm] | No. of points | Width of slice [m] | Radius from fitting [m] | Sigma [m] |
|------------|-----------------------------------|---------------------------------|----------------------|---------------|-------------------|------------------------|----------|
| 0          | 0                                 | 0                               | 0                    | 1914          | 0.050             | 5.133                  | 0.012    |
| 22         | -8                                | 12                              | 14                   | 988           | 0.025             | 4.503                  | 0.012    |
| 30         | -13                               | 14                              | 19                   | 988           | 0.025             | 4.352                  | 0.015    |
| 45         | -14                               | 40                              | 42                   | 763           | 0.025             | 4.032                  | 0.017    |
| 60         | -31                               | 43                              | 53                   | 787           | 0.025             | 3.746                  | 0.015    |
| 63         | -27                               | 71                              | 76                   | 526           | 0.025             | 3.703                  | 0.019    |
| 80         | -13                               | 92                              | 93                   | 109           | 0.050             | 3.589                  | 0.028    |
| 90         | -76                               | 122                             | 144                  | 90            | 0.200             | 3.440                  | 0.021    |
| 98         | -61                               | 138                             | 151                  | 192           | 0.500             | 3.360                  | 0.009    |
| 114        | -72                               | 157                             | 173                  | 1155          | 0.200             | 3.797[^a]              | 0.020    |
| 117        | -103                              | 183                             | 210                  | 1563          | 0.200             | 4.094[^a]              | 0.027    |

[^a] with railing
Figure 3. Deviations of chimney’s axis from vertical in the vertical projection for south-north and west-east directions

Figure 4. Deviations of chimney’s axis from vertical [mm] in a horizontal projection (for red points the heights H [m] are given)
Terrestrial laser scanning was used in this work in order to calculate deviations of chimney’s axis to vertical. Reliability of results depends on several factors. The most important one is a good quality of obtained point cloud. In this case, restricted availability of the construction as well as adverse weather conditions during conduct of measurements, reduce the quality of point cloud considerably. It concerns especially the top part of the chimney, where substantial fragments of construction were not scanned appropriately. Arduous process of cleaning the point cloud was additionally hindered by numerous elements of technical infrastructure attached to the corpus of the chimney: ladders, platforms, wiring, antennas of mobile telecommunications, etc. Uneven density of the cloud on higher level has forced an increase of rings width applied to fitting of cylinder segments, which has decreased the precision of results. Alternative solution could be an application of robust estimation method [17] instead of the least squares method, which would decrease the potential influence of outliers. Moreover, for adjustment of wider rings (cut-outs from point cloud), instead of cylinder segment, a cone side could be used, which describes the shape of the chimney’s corpus more precisely. Simplified assessment of accuracy, which was conducted in the work, makes it able to conclude that deviations of the chimney’s axis from vertical were determined with the accuracy no worse than 30 mm. This is relatively low precision, nevertheless, in case of the examined point cloud it is satisfactory. Comparing the determined deviations with the results from previous measurements, a considerable accordance can be noticed, especially in west-east direction. In south-north direction, the actual deviations are more similar to results from the previous measurement (from 2004 year) then from 1996 year. Comparing deviation values, it should be kept in mind that environmental conditions during measurement conducting should be also taken into consideration, especially in case of insolation.

5. Conclusions
Terrestrial laser scanning is sometimes applied to examination of geometry of slender objects. A typical problem which tends to occur are adverse reflection angles of scanner laser beam. Typical slender objects and, in particular, industrial chimneys are normally found in vicinity of dense industrial buildings which prevents stepping away to an appropriate distance and thus limits the required visibility of the object. Another problem which occur in engineering practice are limited range of laser measurement (because some slender objects have the height above 300 m) and adverse properties of object surface which hinder laser beam reflection (i.e. moisture, concrete corrosion, black paint coatings). The purpose of the hereby works was to verify the usefulness of laser scanner for assessment of industrial chimney geometry, conducted in real and adverse conditions. Despite thoroughly performed measurement, the obtained point cloud was incomplete and required time-consuming cleaning. The applied method of determining inclination of chimney’s axis from vertical allows for obtaining satisfactory accuracy. The greatest advantage of laser scanning is however the possibility to obtain detailed data regarding geometry of the entire object. In the discussed case, this allowed to compare results of scanning with each of the two previous measurements of inclination. Formerly, these measurements could not be compared together, because they were conducted for different places (measurement levels) on the chimney. For comprehensive analysis of geometrical state of this chimney it might be beneficial to conduct measurements of vertical displacements of chimney foundation.

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References
[1] G. Vosselman, and H. G. Maas, “Airborne and Terrestrial Laser Scanning”, Whittles Publishing, 2010.
[2] J. Armesto, J. Roca-Pardiñas, H. Lorenzo, and P. Arias, “Modelling masonry arches shape using terrestrial laser scanning data and nonparametric methods”, Engineering Structures, vol. 32, pp. 607-615, 2010.
[3] J. Pandžić, M. Pejić, B. Božić, and V. Erić, “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.

[4] A. Pesci, G. Casula, and E. Boschi, “Laser scanning the Garisenda and Asinelli towers in Bologna (Italy): Detailed deformation patterns of two ancient leaning buildings”, Journal of Cultural Heritage, vol 12, pp. 117-127, 2011.

[5] S. Pu, G. Vosselman, “Knowledge based reconstruction of building models from terrestrial laser scanning data”, ISPRS J. of Photogrammetry and Remote Sensing, vol. 64, pp. 575-584, 2009.

[6] M. Alba, L. Fregonese, F. Prandi, M. Scaiioni, and P. Valgoi, “Structural monitoring of a large dam by terrestrial laser scanning”, Proceedings of the International Society for Photogrammetry and Remote Sensing, Commision V Symposium Image Engineering and Vision Metrology, Dresden, 2006.

[7] M. Bačić, P. Bruncčák, J. Kubinec, M. Lipták, and Š. Sokol, “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, pp. 77-82, 2011.

[8] B. Riveiro, H. González-Jorge, M. Varela, and D.V. Jauregui, “Validation of terrestrial laser scanning and photogrammetry techniques for the measurement of vertical underclearance and beam geometry in structural inspection of bridges”, Measurement, vol. 46, pp. 784-794, 2013.

[9] G. Vosselman, B. G. H. Gorte, G. Sithole, and T. Rabbani, “Recognising structure in laser scanner point clouds”, International archives of photogrammetry, remote sensing and spatial information sciences, vol. 46, pp. 33-38, 2004.

[10] D. Wujanz, M. Burger, M. Mettenleiter, and F. Neitzel, “An intensity-based stochastic model for terrestrial laser scanners”, ISPRS Journal of Photogrammetry and Remote Sensing, vol. 125, pp. 146-155, 2017.

[11] J. Zaczek-Peplinska, and P. Falaciński, “Evaluation of possibilities to apply laser scanning for estimation of conditions of concrete”, Report on Geodesy, No. 1 (91), pp. 539-546, 2011.

[12] T. Glowacki, P. Grzempowski, E. Sudol, J. Wajs, and M. Zając, “The assessment of the application of terrestrial laser scanning for measuring the geometrics of cooling towers“, Geomatics, Landmanagement and Landscape, vol. 4, pp. 49-57, 2016.

[13] K. Kregar, T. Ambrožič, D. Kogoj, R. Vezočnik, and A. Marjetič, “Determining the inclination of tall chimneys using the TPS and TLS approach”, Measurement, vol. 75, pp. 354-363, 2015.

[14] G. M. T. Rădulescu, A. T. Gh. M. Rădulescu, “Surveying works of Structural monitoring under cinematic regime on a chimney of 351.5 m high at the industrial platform of Baia Mare, Romania”, Recent Researches in Applied Economics and Management, vol. 2, Proceedings of the 5th International Conference on Applied Economics, Business and Development (AEBD ’13), Chania, Crete Island, Greece, August 27-29, pp. 228-234, 2013.

[15] J. Rybak, and A. Tamrazyan, “Calibration of rapid impulse compaction on the basis of vibration velocity control”, Proceedings of the 16th International Multidisciplinary Scientific GeoConference (SGEM 2016), vol. 1, Geology, hydrogeology, engineering geology and geotechnics, Albena, Bulgaria, 30 June-6 July, pp. 715-722, 2016 (http://dx.doi.org/10.5593/SGEM2016/B11/S02.090).

[16] A. Herbut, and J. Rybak, “Guidelines and recommendations for vibration control in the case of rapid impulse compaction”, Advances and trends in engineering sciences and technologies II, Proceedings of the 2nd International Conference on Engineering Sciences and Technologies (ESatT 2016), High Tatras Mountains, Tatranské Matliare, Slovak Republic, 29 June - 1 July, pp. 761-766, 2016 (http://dx.doi.org/10.1201/9781315393827-129).

[17] Z. Muszyński, “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, pp. 65-72, 2014.