Research Article

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Implementation of virtual reference points in registering scanning images of tall structures

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Abstract: The concept of obtaining uniform and high-precision 3D models of large and complex engineering structures based on terrestrial laser scanning surveys highly depends on the accuracy of registering a series of adjacent scans. If it is not possible to place the required number of reference points in the observation scene, and there are no identifiable structural elements that could serve as such reference points, the issue can be solved by using the virtual reference points. The virtual reference points are not marked, but their position can be re-created in the post-processing of the scans on the basis of the geometrical features of the object. In the case of an industrial chimney, these can be the structural axis points determined at arbitrarily selected altitudes. In the solution presented herein, the coordinates of the reference points were independently determined twice: in the geodetic coordinate system using traditional method, in the local system of the scanner using the bisector of the chord of the circle, and by approximation of the circular arc shape of the chimney shell. Both procedures are preceded by the filtration of outliers. The concept of virtual reference points was verified by the measurement of the verticality of the axis and the structural geometry of a steel industrial chimney, which was accessible only on the foundation level.

Keywords: TLS applications, point clouds registration, outliers filtration

1 Introduction

The evolution of scanning technology (TLS), we have seen in recent years, has made this method not only more and more eagerly used in broad-based engineering, but in many applications has given it a leading role [1]. Among its advantages, one should definitely point out the ease and speed of use (up to 1 million points per second); precision (up to mm level accuracy) with a high point density, non-invasive, and remote character of the measurement (also in very low light conditions); and the possibility of remote operation (especially important in life-threatening or health-endangering conditions). All these contribute to the fact that the TLS technique is now applied in as built surveys of buildings and structures for the purpose of documentation of their existing condition and checking compliance with the project [1–4]; creating the precise 3D models of structures of various types for design purposes [5]; documenting historical objects [6,7]; or destruction, deformation, and monitoring of engineering constructions and excavations [3,6,8–12]; surveying of tunnels and rail tracks [13]; calculating volumes; applying building information modeling (BIM) [1,2]; monitoring the stability of the earth's structures [14]; and geotechnical and geological mapping in mining.

From the engineering surveying perspective, one of the most interesting features of this technology is the possibility of obtaining a full model of the surveyed structure [3,9,10]. This contributes to the ability to perform advanced analyses (determination of cross-sections, geometry, volume or displacements and deformations over time) [3,12] as well as to obtain the desired information on the properties or state of an object at any point, not just at selected spots [2,3,9].

Making uniform and precise 3D models for large and complex building structures always involves the necessity of acquiring adjacent scans from multiple locations. As a consequence, we face the problem of proper registration of individual scanning images, which has been widely discussed in many publications [2,8,15–17].

Tall structures are a special case of constructions in the aspect of registering scans and determining their spatial location [12,18]. Most often available only from the ground level, without the possibility of implementing

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targets at the top as well as identification of structural elements that can replace them. As a result, it makes it impossible to create a proper 3D model with the assumed internal accuracy. This publication presents the analysis and solution of this problem through the use of virtual reference points. The method is discussed on a practical example of scanning of an industrial chimney in order to examine its condition and geometry.

The verticality of the industrial chimney axis is usually analysed by measuring the directions of the tangents to the circular sections of the structure. This method is accurate and, depending on the number of stations, makes it possible to assess the deformation of the structure [19]. However, it is only efficient for small portions of the chimney shell. The laser scanning technology is free of such limitations. The advantages of the scanning technology are less obvious in view of the conditions and properties of prismless distance measurements and in particular the issue of precise orientation of the point clouds [16,20].

The use of laser scanning technology for chimney geometry analysis has been widely discussed in the literature of the subject [18,21–25]. The analyses of the shape and verticality are usually conducted on processed data, i.e. on combined point clouds. The analysis consists of visual [22] or analytical alignment of the equation of the circle [18,24] or ellipse for point bands isolated from point clouds. The cloud registration stage is usually omitted.

In the analyses of tall structures, the issue of cloud registration requires particular attention. In each case, the reference points should be distributed throughout the measurement space and projected on individual scans [18,21,25]. With the “cloud-to-cloud” method, the quality of the final effect is determined by the size of the overlapping areas. Curvatures of the chimney sections limit both the choice of reference points and the common areas.

As a device similar in structure and mode of operation to total station, the terrestrial laser scanner is susceptible to similar errors. Instrument errors, levelling errors, unfavourable angles of reflection of the laser beam, and the type of the reflective surface disrupt the uniformity of data accuracy. This impact grows with the height of the scanned structure. In the case of an industrial chimney, this becomes a significant issue due to additional conditions of the structure, namely:

- the reference points cannot be placed evenly across the structure; as a result, the scans are correctly aligned only on the foundation level,
- scanning is performed from a number of adjacent stations usually located in highly developed areas,
- the chimney shell lacks details which could be used as reference points and

- relatively small diameters of the structures and the low number of scanning stations result in limited overlapping areas which are used to register the scans using the cloud-to-cloud method [15,26].

In the currently used solutions, the axes are determined by aligning the circles with the point clouds which represent the entire or a substantial section of the chimney’s circumference [18,21,27]. For structures with small diameters, correct registration is conditional upon the large number of scanner stations.

In consideration of the above, the authors propose that the reference points can be replaced or supported with virtual reference points. These are not installed on the structure surface and are not physically present in the measurement space. Their coordinates can be determined on the basis of the geometrical properties of the structure or a segment thereof. In the case of the industrial chimney, the natural choice is the axis points located on specific levels. Solving the task requires determining the coordinates of the chimney axis in the local point cloud system and in the geodetic coordinate system. The former is performed using the scan point approximation method and the latter by geodetic method used for analysing slender structures. The same point is determined in the scanner’s local system on the basis of the curvature of the chimney shell captured on the scan. The resulting pairs of points serve as the basis for the spatial transformation which adjusts less accurate results of interpretation of scanned images to much more precise traditional measurements. The elements of the structure’s surroundings are ignored when the scanned images are registered.

In the event of an analysis of single scans covering only small sections of the arch, filtration of outliers and the approximation method are crucial. In the processing of scanned images, the curvature is determined with the assumption that the analysed sections of the chimney shell are circular sectors. In this context, the outcome of alignment of conventional observations of the control network points is an important input. The determined mean errors and the error ellipse of the circle centre coordinates indicate the importance of the irregularity of the circular shape on specific levels.

2 Characteristics of the structure and the measurement works

The proposed method of using virtual reference points was verified by the measurement of an industrial

chimney located in Kielce Power Station. The steel chimney is 80 m high and has the diameter of 0.90–1.40 m. It was commissioned in 2016. The chimney is operated year-round and discharges the flue gas from the biomass boiler. Chimney renovations are performed outside the heating season. The structure has a uniform steel colour and is composed of eight segments joined with bolts. Access to the chimney is difficult due to the extensive infrastructure of the power station, such as belt conveyors, internal traffic routes and biomass storage yards (Figure 1).

The measurement was performed on seven levels of the chimney using the method of tangent directions from four measurement control stations (Figure 2). The measurement was performed using a Topcon GPT-3007N total station ($m_k = 7''$, $m_d = 2 + 2 \text{ mm}$). The angular and linear observations were adjusted using the least square method in the local coordinate system. The coordinates of the control points and their mean errors are summarized in Table 1. Scanning was performed with a TLS Stonex X300 scanner, with the range of 300 m, scan rate of 40,000 points/sec, and the distance

Figure 1: Object of measurement.

Figure 2: Angular-linear control network on which the measurement with ambient tangents was based.

measurement error $m_d = 0.02\text{--}0.04 \text{ m}$. The origins of the individual scans were determined using a GNSS SOKKIA GRX1 receiver and Real Time Kinematic (RTK) method, with the accuracy of 0.02 m horizontally and 0.05 m vertically which was comparable to the conventional measurement results (ca. 0.02 m). Direct measurement of the above-mentioned coordinates was made possible with a dedicated Stonex mount adapter.

Scanning was performed on five stations: stations 1–5 (of which four were eventually used to build the final model) were located in the immediate vicinity of the structure. The reference points were marked by 10 scanning targets distributed on the ground around the structure.

3 The outcome of registering scanned images using reference points located on the foundation level of the structure

The point clouds were processed in CloudCompare software using the reference points. The resulting structure model is correct but only at the foundation level of the structure. This is confirmed by minor errors of coordinates of the tie points which were determined on the basis of the spatial transformation outcomes (Figure 3). The outcome of registration on top of the chimney is unacceptable even by visual assessment (Figure 4).

Table 1: Coordinates of the control points and the chimney centres

Station no.	Survey control network				Chimney axis		
	X [m]	Y [m]	m_p [m]	Level	X [m]	Y [m]	m_p [m]
1	67.774	191.840	0.012	A	74.351	82.507	0.007
2	186.919	92.647	0.007	B	74.336	82.511	0.007
3	0.000	54.219	0.008	C	74.322	82.529	0.007
4	0.000	0.000	0.000	D	74.314	82.537	0.007
5	64.182	63.908	0.010	E	74.302	82.545	0.007
6	193.083	20.069	0.010	F	74.307	82.543	0.007
7	188.657	171.832	0.011	G	74.352	82.531	0.007

As expected, installing the reference targets on the foundation level of the structure in its nearest vicinity failed to produce the desired results. According to the conclusions of the study [12], the system of reference targets should form an irregular spatial solid with the span comparable to the size of the structure which, in the case presented, was impossible to meet due to the highly developed surroundings. The error of the showcased outcome model, which increases with height can, however, be eliminated by using virtual reference points.

4 Virtual reference points

In the task discussed herein, it was assumed that the scanned images would be registered using virtual reference points determined on B, E, and G levels and the scanned image origins, as determined by RTK-GPS

(scanner stations). The calculations were performed in the local coordinate system. According to the proposed virtual reference point method, the following steps should be taken when processing the point clouds:

- filter out the reference points which do not represent a circular section and
- determine the coordinates of circle centres separately for each section.

The need to filter out outliers arises from the fact that some of the points do not actually represent the analysed structure [6]. Those points appear as a result of the laser beam's reflection from other objects, of approaching the angular threshold of measurement, of the changes in the chimney surface albedo, or the local imperfections of the structure. In the example presented herein, filtering out was performed using robust statistics. Outlier points, which were not located on the chimney surface, were identified and rejected if the radius value calculated on their basis exceeded 5 cm.

Figure 3: Example of registration of scanned images. **Figure 4:** The outcome of registration of scanned images on the top of the chimney.

The circle centres were determined separately for each section following the selection of the set. It should be noted that each of the analysed sets applies to a single scanned image, i.e. covers a small section of the arch. The size of the arch decreases with the chimney diameter, i.e. with the increasing altitude of the analysed section and also the angular threshold of measurement. In the presented example, the impact of the latter made it necessary to discard points located on the edges of the scanned image. The task was solved using the method of approximation of the circle equation.

The centre of the circular arch was determined using two methods. The first one was based on the least squares approximation of data. However, when applying the least squares method, it should be borne in mind that this method is susceptible to gross errors. Significant outliers distort the result of the analysis, with high outlier values eliminating the correct results from the set. It should also be noted in this context that the emergence of outliers in the point clouds is a specific feature of the scanning technology.

The chimney axis points were determined by aligning the circle with the cloud points for 10 cm wide bands. The result of the approximation was the determination of the coordinates of the circle centre x_0 , y_0 , and the radius R in the equation:

$$(x - x_0)^2 + (y - y_0)^2 = R^2 \quad (1)$$

In the observation equations,

$$2(x_0^0 - 2x_i)dx_0 + 2(y_0^0 - 2y_i)dy_0 - 2R_0^0dR + (x_i - x_0^0)^2 + (y_i - y_0^0)^2 - (R_0^0)^2 = v_i \quad (2)$$

the approximate values of vector $X_0 = [x_0^0, y_0^0, R_0^0]$ of the variables sought were adopted on the basis of the outcomes of the conventional measurement.

The results of the circle centres approximation are provided in Table 2. The demonstrated differences in radiuses, as determined in independent approximation processes, are minor. Their order of magnitude coincides with the measurement accuracy characteristic for the scanner used (Stonex X300).

The differences in radii determined in the independent approximation processes are small, which proves the correctness of the method. High conformity also indicates that the structure sections are regular.

The second method of processing the scanning results was based on determining the population of circle centres using the method of intersection of bisectors of the chords based on three points. The points

Table 2: The results of the approximations of circle centres on the scanned images acquired from four scanning sites

Scanned image		Top (level G)	Middle (level E)	Bottom (level B)
Station 1	R	0.881	0.867	1.424
	X	4.717	5.010	5.381
	Y	44.995	45.640	46.530
	Z	71.303	47.409	11.474
Station 2	R	0.887	0.880	—
	X	36.023	35.434	—
	Y	−25.894	−26.207	—
	Z	70.473	46.552	—
Station 3	R	0.910	0.911	1.418
	X	−32.747	−32.263	−31.647
	Y	20.464	20.909	21.370
	Z	69.918	45.915	9.982
Station 4	R	0.893	0.886	1.420
	X	−29.172	−28.704	−28.061
	Y	40.299	40.540	40.884
	Z	66.286	42.319	6.403

were selected to ensure that the distance between them is approximately one third of the length of the arc of the circle projected on a single scanned image, as shown in Figure 5. This assumption reduced the analysed set of circle centres to one third of all points. The coordinates of the central point were determined as the median of the population of coordinates of circle centres. One of the advantages of this method is the property of the median which is more resistant to outliers. The circle radius was determined in a similar way, i.e. as the median of the distance of individual cloud points from the central point. The set was filtered by eliminating the points for which the determined radius differed from the median by more than 5 cm.

The outcome of filtration of outliers, as shown in Figures 5 and 6, indicates that the method based on the median of bisectors of the chord yields slightly better results than least squares approximation of the circle. On the basis of the results presented in Table 3, it is not possible to unequivocally determine which of the applied chimney centre approximation methods is more beneficial, although the least squares method shows a lower value of errors. The largest difference in coordinates of the circle centre (5 cm) was observed in the highest level of the structure (level G). The cause of the increased RMSE error value was most likely the unfavourable scanning angle, which was close to the threshold limit, and the lower cloud resolution. The solution to this problem is extending the width of

Figure 5: Circle centres determined with two methods.

the band, however, this is not ideal too due to the potential impact of [20]:

- deviation in the verticality of the chimney axis,
- the setting up of the scanner or the operation of the compensator; the measurement is affected by collimation and inclination errors and
- conical geometry of the chimney shell.

The impact of the first two factors can be seen in Figure 7, which shows the point cloud of a 1 m wide band projected on a horizontal plane.

In general, point clouds should be approximated by the lateral surface of the cylinder. For chimneys with a simpler structure, as in the case at hand, the surface of a cylinder with axis conforming to O_z axis is described by the equation:

$$f(X, Y, Z) = \begin{cases} X^2 + Y^2 - R^2 = 0 \\ Z = Z \end{cases} \quad (3)$$

Since the results of the measurement are saved in the local coordinate system of the scanner, aligning the cylinder side wall requires transforming the coordinates of the cloud points. The transformation involves the following:

- moving the starting point of the local coordinates system (scanner) to the central point of the axis of the approximated cylinder at the base level and
- making two turns around O_x and O_y axes.

The transformation was performed using the following formulas:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos \beta & 0 & -\sin \beta \\ -\sin \alpha \sin \beta & \cos \alpha & -\sin \alpha \cos \beta \\ \cos \alpha \sin \beta & \sin \alpha & \cos \alpha \cos \beta \end{bmatrix} \times \begin{bmatrix} x - x_0 \\ y - y_0 \\ z \end{bmatrix} \quad (4)$$

where x , y , and z – coordinates in the local system of the scanner; X , Y , and Z – transformed coordinates.

α – angle of rotation around axis O_x , β – angle of rotation around axis O_y , and x_0 and y_0 – coordinates of the vector of the coordinates system translation.

Figure 6: The results of point filtration (a) with the median of the bisectors of the chord and (b) by the least squares method.

Table 3: Results of approximation of the chimney centre using approximation method and intersection of bisectors method

Scanned image no.	Approximation method				Intersection of bisectors method			
	<i>R</i>	<i>X</i>	<i>Y</i>	RMSE	<i>R</i>	<i>X</i>	<i>Y</i>	RMSE
Station 1 level B	1.424	5.381	46.530	0.004	1.414	5.379	46.503	0.006
Station 3 level B	1.418	−31.647	21.370	0.004	1.411	−31.640	21.364	0.008
Station 4 level B	1.420	−28.061	40.884	0.003	1.405	−28.058	40.872	0.007
Station 5 level B	1.409	25.856	−0.147	0.003	1.396	25.837	−0.145	0.005
Station 1 level E	0.867	5.010	45.640	0.007	0.883	5.000	45.662	0.016
Station 3 level E	0.911	−32.263	20.909	0.007	0.932	−32.280	20.923	0.017
Station 4 level E	0.886	−28.704	40.540	0.012	0.867	−28.687	40.527	0.021
Station 5 level E	0.882	26.395	0.250	0.011	0.892	26.406	0.246	0.020
Station 1 level G	0.881	4.717	44.995	0.017	0.886	4.716	44.991	0.031
Station 3 level G	0.910	−32.747	20.464	0.010	0.867	−32.701	20.433	0.032
Station 4 level G	0.893	−29.172	40.299	0.150	0.863	−29.132	40.273	0.310

Figure 7: Plan view of the cloud points – the inclination of the chimney shell image is visible.

Cylinder surface area equation:

$$f(x_0, y_0, \alpha, \beta, R) = \begin{cases} (\cos \beta \cdot (x - x_0) - \sin \beta \cdot z)^2 + \\ + (-\sin \alpha \sin \beta \cdot (x - x_0) + \cos \alpha \cdot (y - R^2 \\ - y_0) - \sin \alpha \cos \beta \cdot z)^2 \\ = 0 \\ Z = \cos \alpha \sin \beta \cdot (x - x_0) + \sin \alpha (y - y_0) \\ + \cos \alpha \cos \beta \cdot z \end{cases} \quad (5)$$

after linearization

$$\begin{aligned} & (-2x \cos \beta + 2y \sin \alpha \sin \beta) dx_0 + (-2y \cos \alpha) dy_0 \\ & + (2y(-\cos \alpha \sin \beta(x - x_0) - \sin \alpha(y - y_0) \\ & - \cos \alpha \cos \beta \cdot z)) d\alpha \\ & + (2x(-\sin \beta(x - x_0) - \cos \beta \cdot z) \\ & + 2y(-\sin \alpha \cos \beta(x - x_0) + \sin \alpha \sin \beta \cdot z)) d\beta \\ & - 2R dR + f_0 = 0 \end{aligned} \quad (6)$$

was used to approximate the cylinder surface area using the least squares method. The results of the analysis of the 1 m wide bands are summarized in Table 4.

5 Verification of the applied methods

The applied method was verified by cloud orientation and demonstrated transformation errors – in this particular case, distributed across the vertical profile of the model (Figure 8).

An objective measure of efficiency is also provided by comparing the measurements of the chimney axis with the results of conventional measurements.

The applied measurement method was verified on levels D and F which had not been included in the transformation task. The differences between the values

of the virtual coordinates acquired by conventional method and scanning method fall within the range of 0.03–0.06 m. The deviations correspond to the accuracies obtained for the reference points used for proper registration of point clouds (Figure 10).

The individual scans, once registered using the virtual reference points, correctly project the shape of the structure. The axis of generated model differs from the axis determined by the conventional method within the error margins typical of the equipment used. Scanning provides additional information on the condition and shape of the chimney shell.

6 Discussion

The dynamic development of measuring instruments and methods in the TLS area has contributed to the fact that we are using this method in newer and newer applications and also in the field of high-precision engineering surveying. However, very advanced accuracy parameters of the devices themselves do not guarantee uniform and correct 3D models of large and complex structures. They usually require multisite observations carried out in very unfavourable spatial and environmental conditions. It is necessary to merge the acquired data sets supplemented with accuracy analysis. The issue of registration of scan sets and their spatial orientation is widely discussed in literature [2,12,16]. It may seem that nowadays this problem has been solved or significantly minimized. There are, however, objects for which the standard, developed methods do not succeed. A good example is the tall objects, especially those located in a highly urbanized environment, which prevents proper spatial distribution of reference points necessary to perform a registration of high precision.

The proposed method of virtual reference points, in the case of an industrial chimney, proves to solve this problem.

	X	Y	Z	Error
A0	116.415	103.672	98.043	0.016
A1	74.316	82.506	108.305	0.026
A2	74.302	82.533	144.254	0.048
A3	74.362	82.543	168.158	0.051

	X	Y	Z	Error
R0	103.667	116.406	98.031	0.016
R1	82.511	74.336	108.300	0.026
R2	82.545	74.302	144.230	0.048
R3	82.531	74.352	168.200	0.051

Figure 8: Example of registration of point clouds using the virtual reference points.

In the authors' opinion, it can be used for all structures with circular and elliptical cross-sections for cylindrical, spherical, or conical surfaces. Not only for tall constructions, but in an industrial environment saturated with pipe installations as well (i.e. mining oil and gas industry).

The possibilities of developing the method of virtual reference points are to be found in several areas. The most significant is the creation of algorithms that give the possibility of implementation in specialized software (i.e. CloudCompare freeware software), which could significantly speed up and simplify the workflow process, introduce additional methods of data filtration or provide the ability to optimize the calculation task. The next is to explore the possibility of increasing the accuracy of registering adjacent scanning images by using a scanner with higher precision parameters and lower image noise as well as by creating a, respectively, superior reference system of higher accuracy (used targets and measurement with redundant observations and least squares method network alignment).

Table 4: Results of approximation of point cloud bands with cylinder surface area

No.		Radius	X [m]	Y [m]	Z [m]	α [g]	β [g]
Station 1 level G	Value	0.889	4.733	44.971	71.200	−1.7988	−0.6751
	RMSE	0.004	0.001	0.005		0.0984	0.1729
Station 2 level G	Value	0.861	35.954	−25.863	70.420	0.6713	0.8043
	RMSE	0.005	0.004	0.004		0.1108	0.1148
Station 3 level G	Value	0.853	−32.673	20.416	69.912	−1.3736	−1.4356
	RMSE	0.005	0.004	0.004		0.1136	0.0931
Station 4 level G	Value	0.898	−29.158	40.264	66.286	−0.5982	−1.4208
	RMSE	0.002	0.002	0.002		0.0534	0.0622

Figure 9: Examples of check point errors.

Research studies on these issues are currently being conducted at the Faculty of Environmental, Geomatic and Energy Engineering of Kielce University of Technology.

chimney eliminates the disadvantages of the prismless measurement as well as the instrument errors of the scanner.

7 Final remarks and conclusions

The determined pairs of virtual reference points increase the accuracy of the generated model, since all individual clouds undergo spatial transformation using the same group of reference points. In the task discussed herein, these were points B, E, and G and scanner centres on individual scanning stations (Figures 5 and 6). The errors on the alignment points after the transformation discussed herein fall within the range of 0.02–0.04 m (Figure 7).

The example presented in this article is relatively complicated. With a very small diameter, the structure has no discernible details on the shell as well. The steel shell, especially in the upper levels of the structure, contributed to the intensification of the reflections, which distorted the shape of the object in these scanned areas. Those factors reduce the accuracy of determination of the chimney centre points on the scanned image (Figure 9).

8 Conclusions

- The method of aligning scanned images with conventional measurement in the case of an industrial

Figure 10: Final image after registering scanned images using the virtual reference points.

- On the stage of filtering out outlier points, the method of the median of bisectors of the chord is more effective than the approximation method.
- For determining the centre of the section, the circle approximation method is preferable to the method of the median of bisectors of the chord.
- For the topmost section of the chimney, isolating wider bands is necessary. For the analysed structure, good results were obtained for 1 m wide bands.
- The more regular the circular cross-section, the better the effect of the applied method. The impact of circular section deformations can be mitigated by using a higher number of scanner stations. In each case, regardless of their number, the stations should be arranged symmetrically around the structure.
- The impact of the inclination and the non-vertical axis of the could be reduced by approximation with cylinder side wall or cone. This solution requires much wider bands in order to ensure the convergence of the subsequent iterations.

The method presented herein is a practical implementation of the concept of reliability measurements, which is based on independent measurement and mutual control. On the other hand, due to the need to perform additional measurements and data processing, it is relatively labour consuming.

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