Assessment of SLAM-Based Handheld Mobile LiDAR Scanning for Tilt Determination of Circular-Section Structures: A Case Study

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https://doi.org/10.29227/IM-2026-02-02-010

Submission date: *2026-29-06* | Review date: *2026-10-07*

Abstract

This study presents a comparative assessment of two geodetic approaches for determining the tilt deformation of engineering structures with a circular cross-section, including pylons, chimneys, towers, tanks, etc. The investigated object is a freestanding metal advertising pylon with a height of 9.5 m and a smooth cylindrical surface. In geodetic observations, a classical approach with angle-length measurements was applied as a reference method, along selected cross-sections and by using an alignment circle to derive the center and radius of these sections, as well as the spatial position of the structural axis and its deviation from the vertical. In parallel, the structure was surveyed using a SLAM-based handheld mobile LiDAR system (FJD Trion P1). Two independent mobile laser scanning surveys were performed and processed separately to evaluate the repeatability of the method. The tilt deviations determined from the point clouds were compared with the corresponding results obtained from the classical geodetic measurements. The comparison showed differences of 0.6–0.9 cm in the determined tilt magnitude, demonstrating a high level of agreement between the two approaches. The obtained results indicate that SLAM-based handheld mobile LiDAR scanning can provide reliable tilt estimates for the investigated circular-section structure and shows potential for application to similar structures with smooth continuous surfaces.

Keywords: *SLAM, handheld mobile laser scanning, tilt determination, circular-section structures, point cloud analysis, alignment circle by cross-sections*

1. Introduction

Determining the current spatial position of high engineering structures with circular cross-sections, such as pylons, chimneys, towers, and storage tanks, is a common task in engineering geodesy. Particular attention is often given to the determination of deviations from the vertical axis, as these may indicate structural deformations, construction inaccuracies, or long-term operational effects.

Currently, for the implementation of this task, classical geodetic methods have been used, due to their proven reliability and high accuracy [1]. In recent years, advances in LiDAR technology have enabled the development of SLAM-based handheld mobile laser scanning systems, which provide rapid three-dimensional data acquisition. The authors have previously investigated the applicability of terrestrial laser scanning (TLS) for tilt determination of complex engineering structures, demonstrating a high level of agreement with classical geodetic measurements [2]. The present study extends this research by evaluating a SLAM-based handheld mobile LiDAR system, which offers greater flexibility during field data acquisition. As part of the broader process of digital transformation and the implementation of innovative geospatial technologies, handheld mobile laser scanning has found increasingly widespread application in surveying practice [3, 4]. Recent review studies have highlighted the rapid expansion of mobile LiDAR applications across numerous engineering and geospatial fields [5]. Previous studies have demonstrated the applicability of these systems for building documentation, 3D modelling, and other geospatial applications [6, 7], as well as for vegetation surveying and forest inventory applications, where handheld and wearable laser scanning have been evaluated against terrestrial laser scanning [8, 9] and also in the context of vehicle-based mobile laser scanning for large-scale deformation monitoring [10]. The geometric quality and accuracy of point clouds generated by SLAM-based mobile mapping systems have also been investigated through comparisons with reference surveying techniques and multisensor survey approaches [11]. Despite these developments, relatively limited attention has been paid to the use of SLAM-based handheld LiDAR systems for determining the tilt of engineering structures with circular cross-sections.

This study investigates the applicability of SLAM-based handheld mobile LiDAR scanning for determining the inclination of tall structures with a circular cross-section. The results obtained from the mobile laser scanning surveys are evaluated against reference measurements obtained from classical geodetic observations. The experimental investigation was conducted on a freestanding metal advertising pylon with a circular cross-section and a structural height of 9.50 m (Fig. 1). The structure represents a typical example of an engineering facility for which periodic verification of verticality may be required during operation. The object was selected because its simple cylindrical geometry and smooth continuous external surface provide reliable extraction of circular cross-sections from both geodetic measurements and point cloud data.

Fig. 1. Overview of the investigated metal advertising pylon.

Assessment of the accuracy of geodetic determinations.

The permissible tolerance for steel structures, according to the current requirements in Bulgaria [12], are presented as a percentage based on the total height:

$$\Delta = \pm 0{,}20\%\ H \tag{1}$$

Based on (1), the permissible tolerance for objects with a height in the range H ≤ 30 meters, expressed by the construction tolerance Δ, were calculated. The acceptable error M_Δ form. (2) was also determined, at t=1.5 or confidence probability P=86.6%.

$$M_\Delta = \frac{\Delta}{t} \tag{2}$$

According to this criterion for the metal part of the structure of the object, according to (1) and (2) we have the permissible tolerance Δ and the total acceptable Root-Mean-Square Error (RMSE) - $M_\Delta \equiv M_\Delta$, as follows:

$$H \leq 10\ \text{m} - \Delta = 2.0\ \text{cm},\ \ M_\Delta \equiv M_Q \leq 1{,}5\ \text{cm} \tag{3}$$

2. Classical approach. Reference measurement.

The reference approach for determining the inclination of facilities is the method of equalizing circles, based on previously selected cross-sections. A detailed theoretical justification of the method described above can be found in [1].

In short, this approach is based on determining the center and radius of a selected cross-section of a facility with a circular shape, using a single measurement from a single station, as well as by Angular or multiple Angle-length Intersections two or more Geodetic points (Fig. 2).

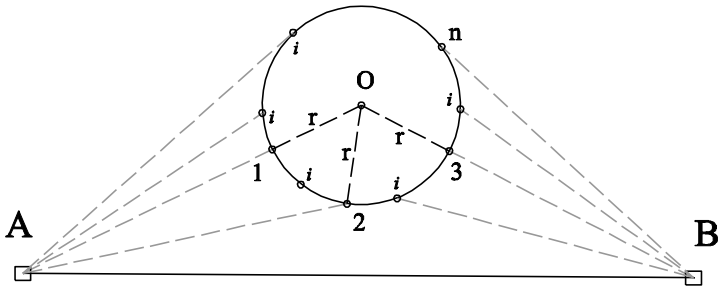

Fig. 2. Scheme of classical geodetic measurements.

The radius r of the circle is calculated as the distance between the centre and any point 1, 2 or 3, i.e.

$$\mathbf{r}_i = \sqrt{(\boldsymbol{X_0} - \boldsymbol{X_i})^2 + (\boldsymbol{Y_0} - \boldsymbol{Y_i})^2} \tag{4}$$

Since in this case the number of points is more than 3, an equalizing circle is used for the set of points. The equation for the corrections at a point in the section can be written as:

$$\mathbf{V_i} = \boldsymbol{a_i}.\boldsymbol{dr} + \boldsymbol{b_i}.\boldsymbol{dx} + \boldsymbol{c_i}.\boldsymbol{dy} + \boldsymbol{l_i}\,, \quad \boldsymbol{p_i} = \mathbf{1} \tag{5}$$

where

$$\boldsymbol{a_i} = \mathbf{1}, \quad \boldsymbol{b_i} = \frac{\boldsymbol{X_i - X_0}}{\boldsymbol{r_i}}, \quad \boldsymbol{c_i} = \frac{\boldsymbol{Y_i - Y_0}}{\boldsymbol{r_i}}\,, \qquad \boldsymbol{l_i} = \mathbf{r_i} - \mathbf{r_o} \tag{6}$$

In (5) it is assumed that all points are determined with equal accuracy and the weights p are unity. In matrix form the correction equations are:

$$\mathbf{V_{n,1}} = \boldsymbol{A_{n,3}}.\boldsymbol{X_{3,1}} + \boldsymbol{l_{3,1}}\,, \quad \boldsymbol{P_{n,n}} \tag{7}$$

The unknowns and the mean square error $\boldsymbol{m_0}$ per unit weight are determined by the formulas:

$$\mathrm{X} = -\,\mathrm{Q.L}, \qquad \boldsymbol{m_0} = \sqrt{\frac{\boldsymbol{V^T.P.V}}{\boldsymbol{n-3}}} \tag{8}$$

The adjusted values of the unknowns are

$$\mathbf{r} = \mathbf{r_0} + \boldsymbol{dr}, \quad \mathbf{x} = \mathbf{x_0} + \boldsymbol{dx_0}, \quad \mathbf{y} = \mathbf{y_0} + \boldsymbol{dy_0} \tag{9}$$

Where r is the value of the radius of the compensation circle, and x, y – coordinates of its centre. For the Root-Mean-Square Error (RMSE) of the unknowns, the following formulas are valid:

$$\boldsymbol{m_r} = \boldsymbol{m_0}\sqrt{\boldsymbol{Q_{11}}}\,, \quad \boldsymbol{m_x} = \boldsymbol{m_0}\sqrt{\boldsymbol{Q_{22}}}\,, \quad \boldsymbol{m_y} = \boldsymbol{m_0}\sqrt{\boldsymbol{Q_{33}}} \tag{10}$$

The described methodology [1] is implemented with algorithmizing of the computational process and applied software, through strict alignment of measurements in the presence of more than three points in a given circular cross-section.

In the specific study, an approach was chosen to determine the inclination of the facilities through angular-length measurements and coordinate determinations for n (6-10) detailed points on selected cross-sections. Subsequently, by applying the method of alignment circle, the coordinates of the central points of the observed sections were calculated. At the base of the facility, as well as from a section under the top of the pylon.

Initial measurements were carried out using a Leica TCR403 total station, featuring an angular accuracy of 10^{cc} and a distance accuracy of $\pm(2 + 2{\cdot}S)$ mm, where S is the measured distance in kilometres

The necessary directions and distances /without reflector/ were measured from two stations (A, B), located in two relatively mutually perpendicular directions, relative to the studied facility.

The coordinates of the two stations and the observed points from each section were calculated. For this purpose, an independent /local/ coordinate system was introduced, oriented along the geographical directions, for each separate object with a centre - the central point of the base.

After strict adjustment (Least Squares Method, [1]) the coordinates of the central points of the base were calculated, and of a point at the top of the pylon (below the advertising sign),

The coordinates of these points were obtained with absolute accuracy (mean square error) in position of $M_p \leq \pm 3$mm.

The theoretical vertical axis of the facilities is realized as a perpendicular to the base plane - from the centre point of the base towards the top.

The deviations of the centre point of the top, relative to the design vertical axis in two mutually perpendicular directions: $+q_x$(north) and $+q_y$(east), as well as the total deviation - Q, have been calculated.

As a result of the practical study of the facility, using the approach described above, the following results were obtained, described in Table 1.

Tab. 1. Advertising pylon.

Description	Elevation	+qX, North (cm)	+qY, East (cm)	Q (cm)	Orientation angle α (degrees)
Base	0.00 m	0.0	0.0	0.0	0.00
Top	+9.50 m	-6.2	+2.4	6.7	159°

The obtained deviations (q_x, q_x, Q) in centimeters and orientation angle (α) in degrees are given relative to the created local coordinate system. The mean square error for the calculated deviations Q, obtained as a function of the measured coordinates at the central points of the top and base is $M_Q \leq \pm 5$ mm.

As can be seen, the accuracy achieved with this approach satisfies the requirements according to the regulatory standards in the Republic of Bulgaria and defined above in (3), and is even much higher than the permissible limits. This gives grounds to use this method as a comparative (reference) for the present study.

3. Mobile Handheld Laser Scanning Measurements.

The investigated structures were surveyed using a SLAM-based handheld mobile LiDAR system in order to evaluate the applicability of this technology for tilt determination of metal structures with circular cross-sections and continuous external surfaces.

Data acquisition was performed using an FJD Trion P1 handheld laser scanning system (Fig. 3). The instrument provides a measurement range of up to 40 m for surfaces with 10% reflectivity and up to 70 m for surfaces with 80% reflectivity. The scanner offers a 360° vertical field of view and a 59° horizontal field of view. The FJD Trion P1 employs a Simultaneous Localization and Mapping (SLAM) algorithm, which enables real-time estimation of the scanner trajectory and generation of a georeferenced point cloud without the need for a pre-established positioning infrastructure. To assess the repeatability of the measurements and the influence of the operator trajectory on the resulting point cloud geometry, two independent surveys were conducted.

Fig. 3. FJD Trion P1 handheld laser scanning system.

The first survey lasted 3 min 31 s and covered a trajectory length of 78.7 m, while the second survey lasted 4 min 38 s with a total trajectory length of 103 m. During data acquisition, the FJD Trion Scan application was used for real-time monitoring of the scanning process, allowing the operator to verify object coverage, ensure complete data acquisition, and identify potential gross geometric errors during scanning. Both surveys were performed using a closed-loop trajectory, with identical start and end positions, enabling the application of loop-closure optimization during data processing [5, 9, 10].

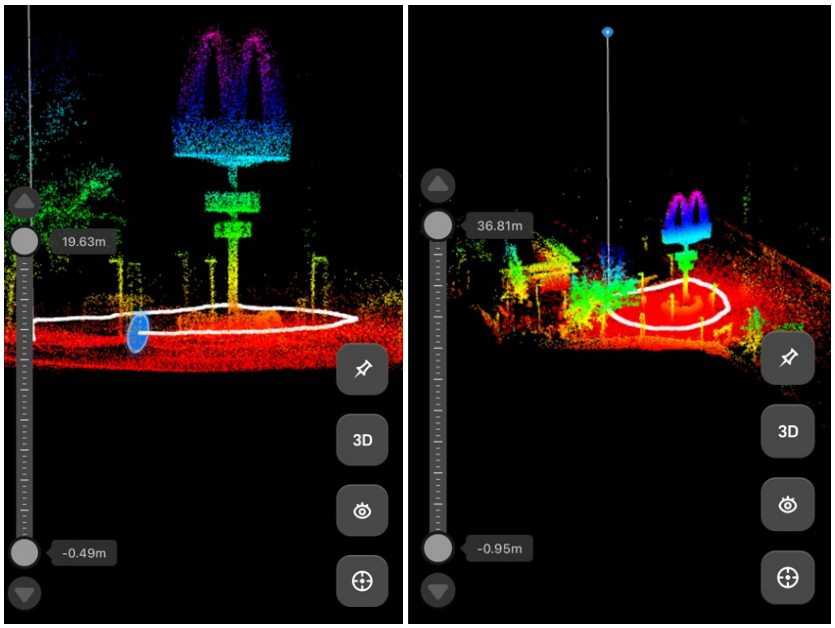

Fig. 4. Real-time monitoring on FJD Trion Scan application.

The acquired data was processed using the manufacturer's software package FJD Trion Model (Fig. 4). The measurement trajectories are presented in Fig. 5. The survey trajectories were designed to remain as close as possible to the structure while considering existing site conditions, including urban traffic corridors, vegetation, and other surrounding obstacles.

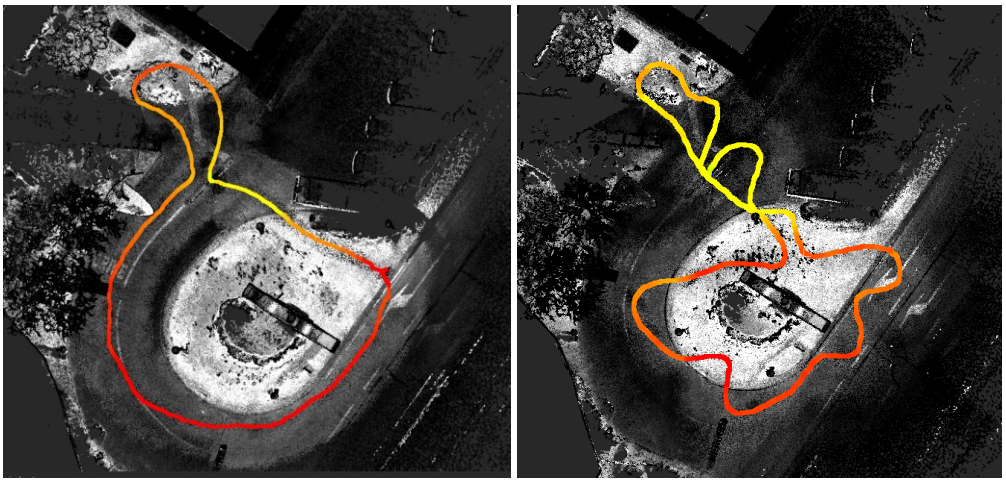

Fig. 5. Survey trajectory.

The trajectory of the first survey followed an approximately circular path around the structure, with observation distances ranging from 5.5 m to 12.0 m and an average distance of approximately 7.0 m. In contrast, the second survey employed a more irregular trajectory with larger variations in the distance between the scanner and the object. An additional deviation in the northwestern section of the trajectory was introduced to capture supplementary surrounding features near the starting point.

To eliminate the influence of transformation-related errors, all analyses were performed directly within the local coordinate system of each point cloud. Consequently, two independent point clouds were generated and processed separately (Fig. 6). The deviations obtained from each dataset were subsequently compared in order to evaluate the consistency and repeatability of the mobile laser scanning approach.

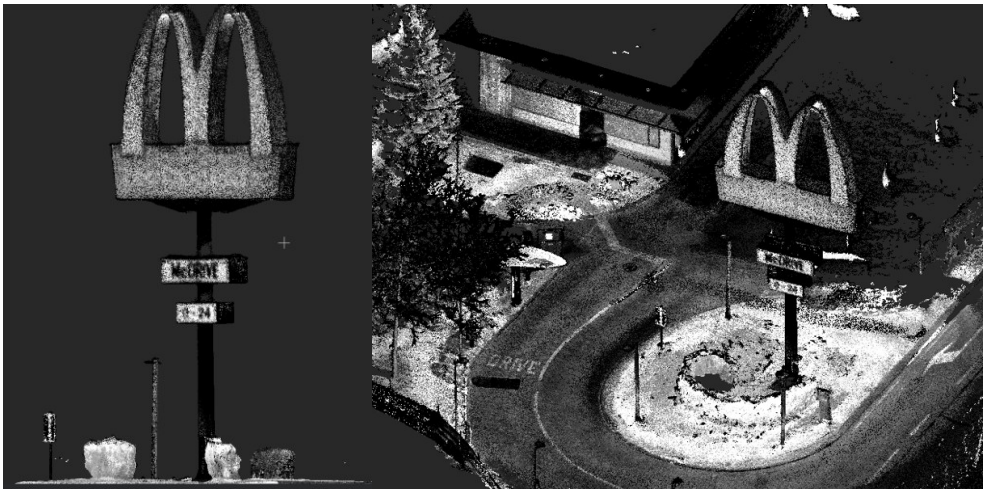

Fig. 6. Final point cloud.

For tilt determination, horizontal cross-sections were extracted at the base and at the top of the structure. Circular features were then fitted to the visible point distributions within each cross-section (Fig. 7). The displacement was determined as the horizontal distance between the centre of the fitted circle at the base section and the centre of the corresponding circle at the top section. This displacement represents the deviation of the structure from its vertical axis.

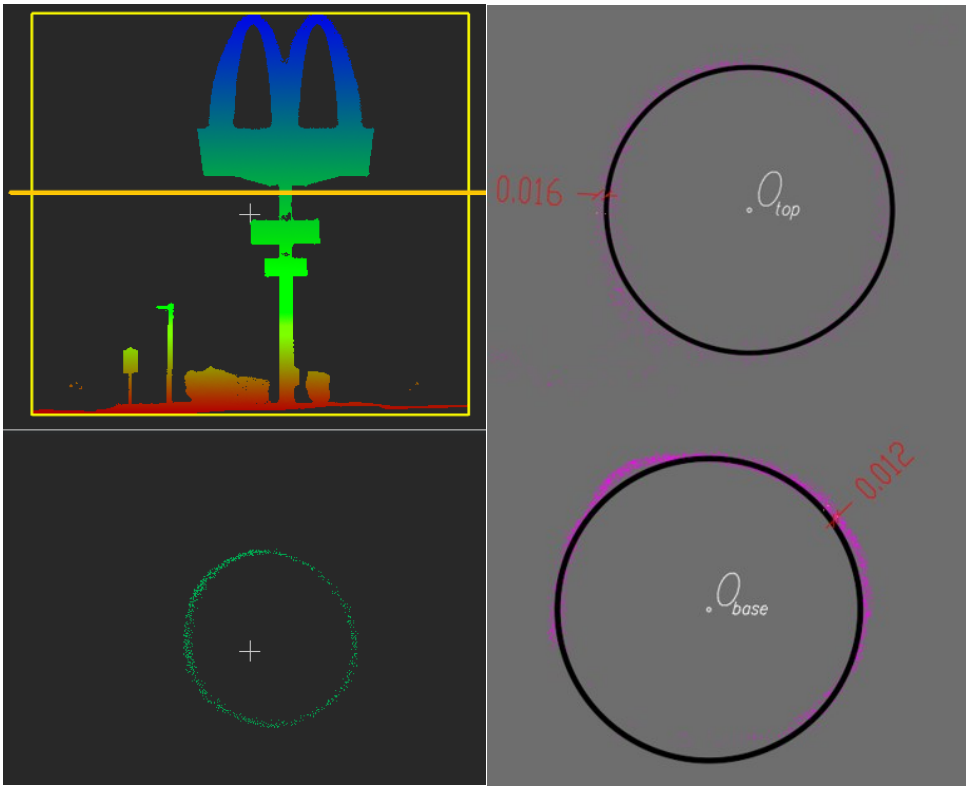

Fig. 7. Circular sections at the base and at the top.

4. Accuracy Assessment of the Point Cloud-Based Tilt Determination

The extracted circular cross-sections demonstrate a point dispersion of approximately 2 cm at the base of the structure, increasing to about 3.3 cm at the top section (Fig. 8). After filtering and removing gross outliers, the point dispersion within the analysed cross-sections remained within approximately 3.0 cm, corresponding to an estimated uncertainty of approximately ±1.5 cm in the determination of the fitted circle centre.

Despite this dispersion, the determination of the section centre is based on the approximation of a circular feature using a large number of points. Therefore, the estimated centre position is less sensitive to local point cloud dispersion than the position of any individual point. Assuming a conservative uncertainty of ±1.5 cm for the determination of each fitted circle centre, the maximum possible uncertainty of the computed displacement between the base and top sections would be approximately ±3.0 cm under a worst-case scenario.

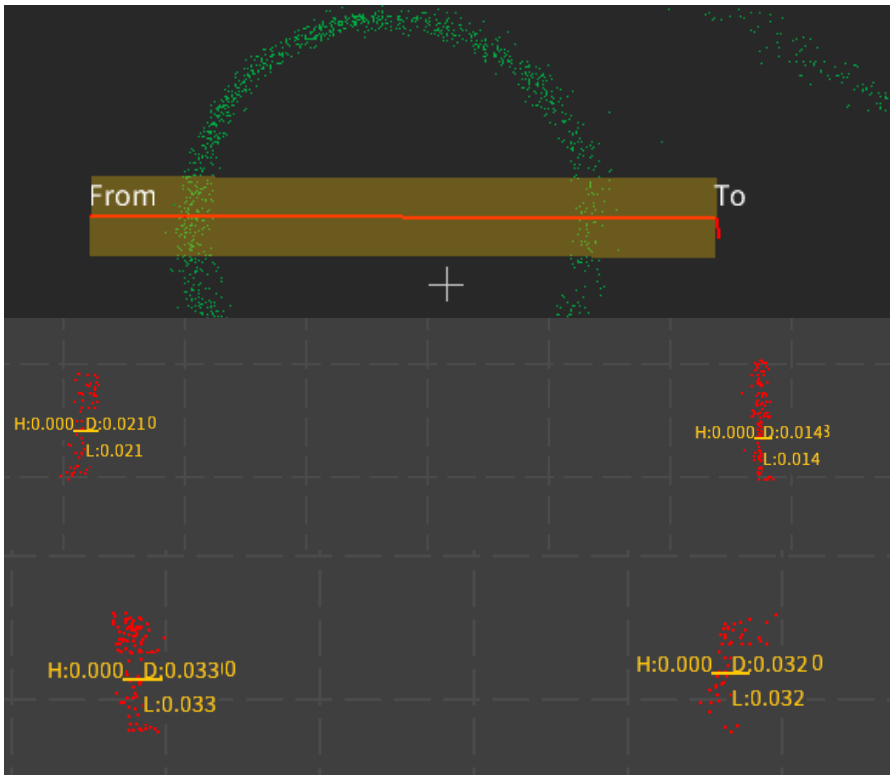

Fig. 8. Point dispersion within the analysed cross-sections.

The obtained results indicate that the point cloud quality is sufficient for reliable determination of the structural axis and its deviation from the vertical direction. The use of circular fitting significantly reduces the influence of local point cloud noise and provides a robust estimate of the centre position for each analysed cross-section.

Table 2 presents the tilt deviations determined from the handheld mobile laser scanning measurements.

Tab. 2. Tilt Deviations Determined from SLAM-Based Handheld Mobile LiDAR Scanning.

Parameter	Survey 1	Survey 2
Total height, (m)	9.5	9.5
Tilt deviation (Q_i), (cm)	7.6	7.3
Orientation angle (α), (°)	187°	196°

5. Comparison of the Obtained Results

As discussed in the introductory section, classical geodetic measurements were adopted as the reference method due to their proven reliability and higher measurement accuracy. Therefore, the results obtained from the SLAM-based handheld mobile LiDAR surveys were evaluated by comparison with the corresponding values determined from the classical geodetic observations. A comparison with the results obtained from the classical geodetic survey shows differences of less than 1 cm, confirming the practical applicability of the proposed methodology for tilt determination of cylindrical metal structures.

Table 3 presents the differences between the tilt parameters obtained from the two independent handheld mobile LiDAR measurements and the corresponding reference values. The differences were calculated as:

$$\begin{aligned} \Delta Q &= Q^{SCAN} - Q^{REF} \\ \Delta\alpha &= \alpha^{SCAN} - \alpha^{REF} \end{aligned} \tag{11}$$

Tab. 3. Comparison of Tilt Deviations Obtained from Different Measurement Methods.

Parameter	Survey 1	Survey 2
Difference ΔQ, (cm)	0.9	0.6
Difference Δα, (°)	28°	37°

The differences between the handheld mobile LiDAR results and the reference geodetic solution remained below 1 cm for both independent measurements, indicating a high level of agreement between the two methods. Larger discrepancies were observed in the orientation angle (28° and 37°, respectively), indicating that the SLAM-based handheld LiDAR system reproduced the magnitude of the tilt more reliably than its exact orientation. However, considering the relatively small magnitude of the measured tilt (approximately 7–8 cm), the observed angular differences correspond to position differences of only a few centimetres at the top section of the structure.

6. Conclusion

The analysis of the point cloud data revealed a point dispersion of up to approximately 3 cm within the investigated cross-sections. Based on this observation, a conservative engineering estimate suggests an uncertainty of approximately ±1.5 cm in the determination of the centre position of an individual cross-section and up to 3 cm in the determination of the displacement between two sections.

Despite this conservative uncertainty assessment, the comparison with the reference classical geodetic measurements demonstrated substantially better agreement. The differences between the tilt deviations determined from the SLAM-based handheld mobile LiDAR surveys and those obtained from the classical geodetic method ranged from 0.6 cm to 0.9 cm.

The obtained results indicate that, for the investigated metal advertising pylon with a height of 9.5 m and a smooth cylindrical surface, handheld mobile LiDAR scanning provides tilt estimates comparable to those derived from classical geodetic measurements. The method therefore represents a practical and efficient solution for rapid assessment of the spatial position and verticality of similar circular-section structures.

It should be noted that the conclusions of the present study are valid for structures of comparable height and for objects characterized by simple geometry and smooth continuous surfaces, which facilitate reliable SLAM-based point cloud reconstruction and circle fitting. The results should not be interpreted as a general validation of handheld SLAM-based LiDAR scanning for all cylindrical structures. The presented findings are limited to the investigated 9.5 m metal advertising pylon and should be regarded as a representative case study.

Further investigations are required to assess the performance of the method for taller structures, more complex geometries, and less favourable surface characteristics.

Acknowledgments

The authors would like to express their sincere gratitude to Geovara Ltd., the official representative of FJDynamics in Bulgaria, for their technical support and valuable assistance in the operation of the FJD Trion P1 handheld mobile LiDAR system and the associated software.

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