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ACCURACY IN VERTICAL ASSESSMENT OF TELECOMMUNICATIONS TOWERS THROUGH 3D SCANNING

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Abstract

Telecommunications towers are essential infrastructures that serve various functions, including telecommunications, meteorological data collection, and surveillance. Maintaining their structural integrity and accurate vertical alignment is crucial for ensuring operational efficiency, safety, and long-term durability. However, evaluating the verticality of tall structures presents significant challenges, necessitating the use of modern and precise methods. Traditional techniques, such as manual surveys using level instrument, are often limited by human error, environmental factors, and the complexity of the structures involved. This study investigates the use of LiDAR (Light Detection and Ranging) technology as a modern method for assessing verticality. By employing advanced LiDAR scanning techniques, the research establishes a thorough framework for accurate and efficient structural monitoring. The paper highlights how LiDAR technology outperforms traditional methods in accuracy, speed, and flexibility, providing a safer and more dependable solution for managing the vertical alignment of observation towers.

***Key words**: 3D scanning, vertical assessment, point cloud, surveying accuracy, LiDAR.*

INTRODUCTION

The rapid expansion of telecommunications infrastructure has necessitated precise and reliable methods for assessing verticality and structural integrity in telecommunication towers. Given the increasing demand for high-speed connectivity and the expansion of cellular networks, ensuring the stability and accuracy of tower installations is essential to maintaining service quality, structural safety, and compliance with regulatory standards. The resistance criteria for these kinds of towers are defined based on the current applicable technical standards and within the framework of the conditions specified in the beneficiary's project requirements (Sîrbu et al., 2023).

Recent advancements in three-dimensional scanning technologies (Kantaros et al., 2023) have revolutionized structural assessment by enabling high-resolution, non-contact measurements with enhanced accuracy and efficiency. 3D laser scanning, photogrammetry, and LiDAR (Light Detection and Ranging) have emerged as powerful tools for capturing detailed spatial data of telecommunications towers. These technologies facilitate the generation of precise digital replica, which allow for comprehensive structural analysis, deformation monitoring, and early detection of anomalies (Kaartinen et al., 2022).

This paper focuses on the use of 3D scanning technologies for the vertical assessment of observation towers, aiming to analyse their stability over time. Observation towers, with their large dimensions and complex structures, require precise measurements to ensure their integrity and safety in the long term. The main goal of this paper is to demonstrate the effectiveness of 3D scanning technologies, especially LiDAR systems and laser scanners, in performing accurate vertical assessments that contribute to monitoring the structural condition of the towers.

Traditional methods of vertical assessment, such as manual plumb-line measurements, total station surveys, and inclinometer readings, often suffer from limitations in precision, efficiency, and accessibility. Compared to traditional surveying methods, 3D scanning provides superior data density, automated processing, and enhanced reproducibility, making it a compelling alternative for vertical assessment in telecommunication infrastructure (El-Tokhey et al., 2019).

In the context of observation towers, maintaining verticality is essential for their structural stability, as significant deviation from verticality can lead to safety risks or deterioration. Thus, by using 3D scanning technologies, extremely high precision can be achieved in measuring angles and tower height, allowing the detection of any deformations or changes that may affect its stability. 3D laser scanners are among the most effective tools for three-dimensional monitoring of various types of constructions, including observation towers, as they provide detailed data such as shape, intensity, and colour, which can be used to study crack growth and detect possible structural weaknesses (Mihai et al., 2014).

A recent study by Wang et al. (2024) introduced an automated 3D reconstruction framework for communication towers using TLS point clouds. Their model-driven approach achieved an average root-mean-square error (RMSE) of 1.3 cm in antenna reconstruction and 1.2 cm in tower body reconstruction, demonstrating high accuracy in capturing complex geometries. This high-precision methodology enables improved structural assessment and facilitates better decision-making in maintenance and design processes.

Figure 1 illustrates the scanned object, a tall telecommunication tower, which has been examined using 3D scanning technology.

Figure 1. The study area

The tower features a cylindrical structure with alternating red and white segments; a typical design used for visibility and aviation safety compliance. It stands on a concrete base, which is slightly elevated from the surrounding ground level. The tower is equipped with antennas and transmission equipment at the top, indicating its function in communication and signal transmission.

The height of the tower necessitates multiple elevation perspectives to accurately capture the structural details. Furthermore, consideration must be given to potential obstacles and reflections from metallic surfaces at the top, as these factors may influence the quality of the scanning process.

MATERIALS AND METHODS

The study utilized the Leica BLK360 G2 laser scanner, a high-precision LiDAR system capable of capturing detailed 3D point clouds with a range accuracy of ±4 mm at 10 meters (ArcTron, n.d.). This scanner operates using a combination of infrared scanning and photogrammetry to generate dense and precise spatial data (ArcTron, n.d.). The determination of control points was carried out using a fully robotic total station to establish 12 ground control points (GCPs) at strategic locations surrounding the telecommunications tower. These GCPs were crucial in georeferencing and validating the accuracy of the scan data (Liu et al., 2022). The total station captured accurate spatial data, ensuring alignment between the scan data and real-world references.

The total station used belongs to the class of high-precision total stations, providing angular accuracy of up to 1” (one second) and distance measurement accuracy of 2 mm + 2 ppm (Stonex, n.d.). The angular measurement system includes a dual-axis compensator, offering stability and an angular accuracy of 1” or 2” with a resolution of 0.1” (Stonex, n.d.). Distance measurements in prism mode reach up to 5000 m with an accuracy of 2 mm + 2 ppm, while reflectorless measurements can extend up to 1000 m with an accuracy of 3 mm + 2 ppm, depending on surface reflectivity (Stonex, n.d.). Initially, the total station was set up at a known reference point or a strategically chosen temporary setup point, with its exact position pre-established using high-precision GNSS (Global Navigation Satellite System) collected survey data. At the location of the control point, a prism or reflector was positioned to serve as the target for the total station's measurements. The total station employed electromagnetic distance measurement (EDM) technology to precisely calculate the slant distance between the total station and the prism, while simultaneously recording the horizontal and vertical angles to the target. The total station's integration with an Android-based software interface further enhanced this process, enabling real-time data collection, immediate calculations, and seamless display of results either on the instrument itself or through connected devices (Stonex, n.d.). Data processing and analysis were conducted using AutoCAD CIVIL 3D for technical drawing and structural modelling, while CloudCompare was used for point cloud processing, alignment, and accuracy assessment.

Data acquisition involved scanning the telecommunications tower using the Leica BLK360 G2 at 17 scan stations, ensuring full coverage from multiple vantage points. Between these positions, 77 connections were established, each representing an overlap between data acquired from two different perspectives, contributing to the overall coherence of the point cloud. For a detailed evaluation of the coverage and measurement consistency, a data presence matrix was generated (Figure 2).

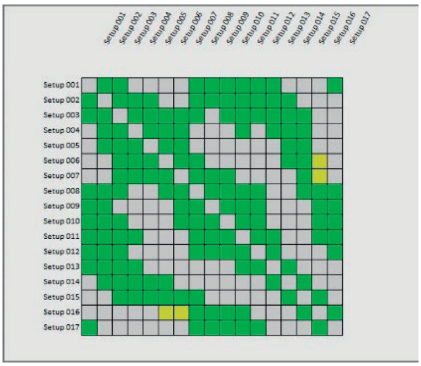

Figure 2. Distribution of overlaps between scanning stations - 3D scan coverage matrix

This matrix indicates the degree of connectivity between scanning stations and helps identify areas where the measurements can be considered reliable for verticality analysis. Cells that are filled indicate the presence of valid data and useful overlaps, while empty or unevenly marked cells point to potential gaps in data capture or regions where accuracy is reduced due to blind spots or obstacles.

The scanning process included pre-scan calibration to ensure measurement precision, positioning the scanner at pre-determined points for optimal visibility of the tower's vertical structure, capturing 3D point clouds using a full panoramic scan, and utilizing the scanner's built-in camera to supplement the LiDAR data with high-resolution images.

Ground control and georeferencing were established by placing GCP markers at fixed, stable locations around the base of the tower, measuring their coordinates using the total station with centimetre-level accuracy, and integrating the GCPs into the point cloud during post-processing to align the scan data with real-world coordinates (Figure 3).

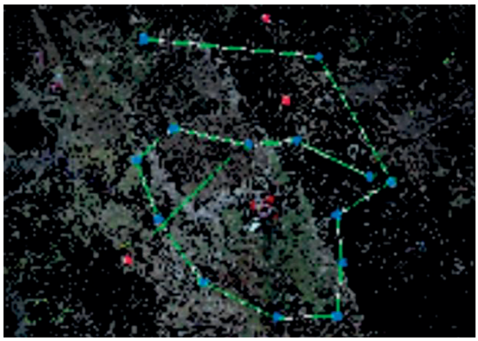

Figure 3. Ground Control and Georeferencing Using GCP Markers

Point cloud processing began with preliminary data cleaning in CloudCompare (Figure 4), where noise reduction and outlier removal were performed to eliminate erroneous data points.

Multi-scan registration was conducted using iterative closest point (ICP) algorithms to align the multiple scan stations into a unified 3D dataset. The total station-derived GCPs were used to refine the spatial accuracy of the point cloud through georeferencing. To determine the vertical accuracy of the telecommunications tower, the central vertical axis of the tower was extracted from the point cloud by identifying key structural elements, followed by a vertical

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deviation analysis that compared the actual scanned position of the tower elements with their expected theoretical positions based on the AutoCAD structural model. Statistical assessment was conducted using CloudCompare's cloud-to-cloud distance measurement tool to quantify vertical misalignments.

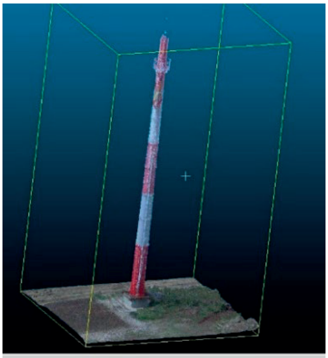
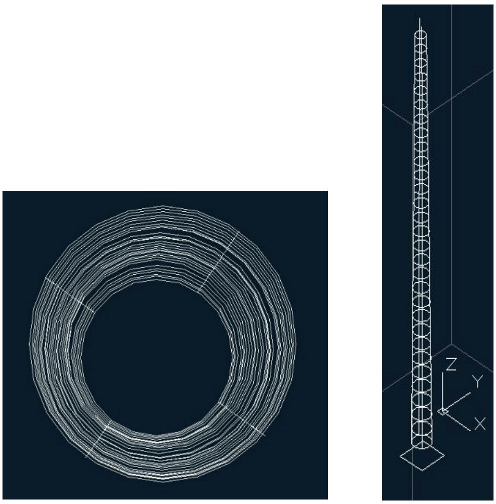


Figure 4. Point Cloud Cleaning and Noise Reduction using CloudCompare

Cross-sections were generated at regular intervals along the height of the tower, providing detailed sectional views that allowed for precise assessment of deviations and misalignments (Figure 5).



a) b)

Figure 5. a) Top-view cross-section b) 3D-view cross-section of the telecommunication tower

These cross-sections were analysed to compare the actual tower profile with its designed specifications. Measurements were taken at multiple points along each section to identify any lateral displacements or distortions in the structure. Additionally, vertical alignment was assessed by projecting reference lines along the tower's intended axis and calculating the deviations at different heights (Figure 6).

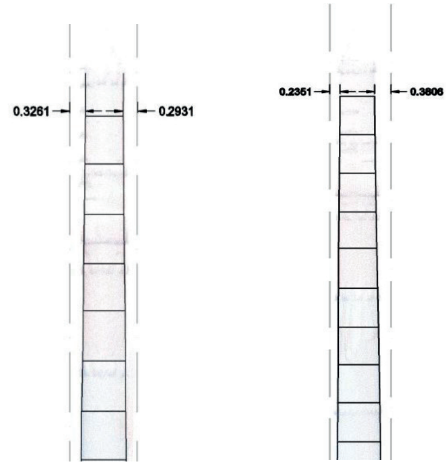


Figure 6. Vertical Alignment Assessment Using Reference Lines

Upon completion of the analysis, final data outputs were generated providing a comprehensive visualization of structural integrity and alignment. Although the overall coverage was 48% and the coherence of the connections between positions was 25%, these values proved sufficient for measuring verticality. The accuracy of the data was confirmed by the very low global errors reported in the technical registration analysis, as follows in Table 1.

Table 1. Summary of mean error values

Type of Error	Mean Value (m)
Global bundle adjustment error	0.004
Bundle error	0.006
Cloud-to-cloud error	0.008
Target registration error	0.004

RESULTS AND DISCUSSIONS

The assessment of vertical accuracy in telecommunications towers through 3D scanning provided detailed insights into structural alignment, deviations, and potential deformations. The use of terrestrial laser scanning (TLS) and point cloud analysis allowed for a precise evaluation of the tower's verticality by identifying misalignments and detecting subtle structural shifts that could impact long-term stability. The findings of this study are categorized into different aspects of analysis, including point cloud processing, vertical alignment evaluation, deformation analysis, and implications for structural integrity.

In terms of point cloud processing, advanced computational techniques were employed to generate an accurate 3D representation of the tower. The data was carefully filtered and processed to eliminate noise and ensure precise modelling. This step was crucial in providing a reliable reference for further analysis, particularly in assessing deviations from the ideal structural alignment. However, at the top of the tower, the point cloud was not as dense due to the increased distance from the scanner to the top. Despite the scanner's capability to collect information up to 35 meters, the data density decreased with height, leading to reduced detail in the uppermost sections.

Regarding vertical alignment evaluation, a series of precise measurements were conducted and compared against an ideal perfectly vertical tower. The results indicate that the actual inclination of the structure deviates by approximately ±0.3 meters from the theoretical vertical alignment (Figure 7). This minor deviation is considered negligible in practical terms, as it falls well within acceptable construction tolerances and does not pose any structural or functional risks to the stability of the tower.

Deformation analysis was conducted to identify any structural deformations beyond simple inclinations. The results reveal that while minor deformations exist, they are primarily localized and do not compromise overall structural integrity. Potential causes for these deformations include environmental factors such as wind loads, thermal expansion, and material aging. The findings suggest that these minor deformations are within acceptable engineering limits and do not warrant immediate corrective action. Additionally, the local axis misalignment (Figure 8, Figure 9) was verified, and it was concluded that there are no fabrication or installation irregularities.

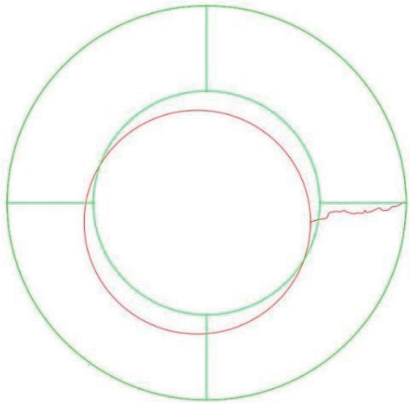


Figure 7. Comparison of Actual (red) and Theoretical (green) Tower Inclination

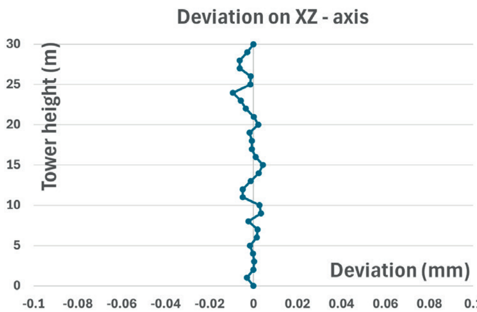


Figure 8. Deviation on XZ axis

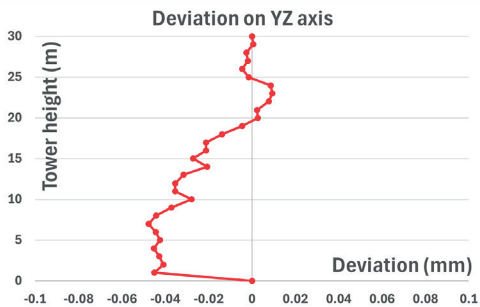


Figure 9. Deviation on YZ axis

Furthermore, deformations might influence long-term stability. The results confirm that the tower maintains a high level of structural reliability and that its slight inclination does not impact on its overall performance or safety. However, the observed deviation may be attributed to minor settlement effects, material deformations, or external environmental influences, all of which remain within industry-accepted limits. These results reinforce the reliability of the construction techniques used and confirm that the tower's alignment remains well within the anticipated engineering standards.

CONCLUSIONS

The assessment of vertical accuracy in telecommunications towers through 3D scanning has proven to be a significant advancement in structural evaluation and maintenance. This study has demonstrated that 3D scanning technology, particularly LiDAR, provides highly precise and reliable data for measuring tower verticality, structural integrity, and component alignment.

A key observation from this research is the detection of slight local axis misalignments that, while measurable, fall within acceptable tolerance limits and are not attributed to fabrication errors. These minor misalignments are typically the result of external factors, such as foundation settlement, small environmental forces or slight variations in installation, which are common in large structures. The environmental factors identified, while seemingly minor at first, have the potential to significantly impact the structural stability of the telecommunication tower over time through cumulative effects, particularly if not consistently and properly monitored. Uneven foundation settlement can lead to a progressive tilting of the structure and the development of additional stresses in load-bearing elements, while repeated environmental actions, such as wind or temperature fluctuations, can induce material ware. Furthermore, even slight deviations in the tower's axis can cause uneven load redistribution, generating unwanted moments and eccentric forces that place extra stress on the structure. In addition, the natural aging of materials, if not countered by proper maintenance, contributes to the decline in overall durability and resistance. Therefore, given that a residential neighbourhood and a public park are planned to be developed in the immediate proximity of the tower, it is essential that comprehensive geodetic measurements and structural evaluations be conducted at intervals of no more than four years, in order to ensure both the integrity of the structure and the safety of the surrounding community. The precision of 3D scanning allows for the identification of these deviations, which, although present, do not pose any immediate structural risk and are well within the industry standards for alignment tolerance.

The ability to quantify such minor misalignments is crucial, as it helps engineers confirm that the tower's alignment remains structurally sound, even when there are small deviations from the ideal vertical. This finding suggests that such misalignments are not a result of poor fabrication or manufacturing defects but rather natural, expected variations that occur during the installation and aging process of the tower.

In conclusion, 3D scanning provides a reliable method for assessing vertical alignment, ensuring that any misalignments are accurately identified, even when they are small and within acceptable limits. This technology allows for proactive monitoring without the need for immediate intervention, promoting the long-term health and operational efficiency of telecommunications towers. As scanning technology continues to improve, future research could focus on further refining the detection of misalignments that could influence tower stability over time, particularly in dynamic environmental conditions.

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