High-precision Verticality Assessment of the Kyiv TV Tower Using UAV-RTK Photogrammetry

Hochgenaue Überprüfung der Vertikalität des Fernsehturms in Kyjiw durch UAV-RTK-Photogrammetrie

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The study of a TV tower, conducted using an unmanned aerial vehicle (UAV) with an RTK module and photogrammetry, significantly increased the accuracy and detail of geospatial measurements, and showed high efficiency in determining the verticality of an infrastructure object. RTK technology, which provides coordinates to the nearest centimeter in real-time, has made it possible to create detailed 3D models that are critical for assessing structural stability. Analysis of the data revealed a slight deviation of the central axis, indicating structural stability at medium elevations and the presence of significant bends in the upper sections, which may be the result of structural damage due to the explosion. The integration of these technologies has provided effective monitoring of the condition of the structure, thereby increasing the safety and reliability of inspection of the facility. Further development of these technologies can significantly improve the monitoring processes of large structures under difficult conditions.

Keywords: Large-scale structures, UAV, photogrammetry, point cloud, 3D modeling, verticality

Die Untersuchung eines Fernsehturms, die mit einem unbemannten Luftfahrzeug (UAV) mit RTK-Modul und Photogrammetrie durchgeführt wurde, hat die Genauigkeit und Detailauflösung der räumlichen Messungen erheblich erhöht und eine hohe Effizienz bei der Bestimmung der Vertikalität eines Infrastrukturobjekts gezeigt. Die RTK-Technologie, die Koordinaten in Echtzeit zentimetergenau liefert, hat es ermöglicht, detaillierte 3D-Modelle zu erstellen, die für die Beurteilung der strukturellen Stabilität von entscheidender Bedeutung sind. Die Analyse der Daten ergab eine leichte Abweichung der Mittelachse, was auf eine strukturelle Stabilität in mittleren Höhen und das Vorhandensein signifikanter Biegungen in den oberen Abschnitten hindeutet, die möglicherweise auf strukturelle Schäden aufgrund einer Explosion zurückzuführen sind. Die Integration dieser Technologien hat eine effektive Überwachung des Zustands der Struktur ermöglicht und damit die Sicherheit und Zuverlässigkeit der Inspektion der Anlage erhöht. Die Weiterentwicklung dieser Technologien kann die Überwachungsprozesse großer Strukturen unter schwierigen Bedingungen erheblich verbessern.

Schlüsselwörter: Großstrukturen, UAV, Photogrammetrie, Punktwolken, 3D-Modellierung, Vertikalität

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1 INTRODUCTION

Large-sized structures such as television, cellular, and electric towers play an important role in providing communication and energy transmission. However, these structures are constantly exposed to natural stresses such as wind, rain, snow, temperature fluctuations, seismic activity or man-made impacts such as war-related attacks. These factors gradually affect structural materials, leading to aging and loss of strength. In addition, improper maintenance of these facilities can accelerate destruction processes, increasing the risk of accidents and the failure of important infrastructure elements.

Diagnostic verticality of such large-sized structures is an important aspect of their maintenance and ensuring safe operation. Deviation from verticality may indicate deformations, subsidence of the foundation, or other structural problems that can lead to the instability of the entire structure. The timely detection and correction of such abnormalities are critical for preventing serious accidents. Today, there are many large-sized emergency facilities in Ukraine that are primarily associated with the war. There is an urgent need for new, more effective, and safer methods for the diagnosis of large structures.

Various methods have been used to determine the verticality of structures, including observations using global navigation satellite systems (GNSS) and three-dimensional ground-based geodetic measurements using total stations, theodolites, inclinometers, and laser scanning systems /Gao et al. 2016/, /Roberts et al. 2004/, /Widerski & Kurałowicz 2014/, /Li et al. 2014/, /Song et al. 2010/, /Wang 2013/. However, in cases where it is necessary to obtain additional information about the geometric parameters of an object or to perform high-precision measurements in complex or remote areas, other approaches need to be introduced. For example, recent studies have highlighted how automated processing of 3D point clouds can be leveraged to assess object verticality and geometry with high accuracy, supporting broader automation in structural diagnostics /Chen et al. 2023/, /Kuschnerus et al. 2024/, /Xu et al. 2023/.

In addition, micro-electro-mechanical system (MEMS) sensor calibration methods are used, which take into account the initial position of the inclinometer and correct the data with a total station from a single reference point, which increases the accuracy and stability of measurements /Chiriac & Ciclicci 2020/. In the case of diagnostics of the Millennium Tower in San Francisco, California, the effectiveness of three-dimensional analysis was demonstrated to control changes in the verticality of the structure, which includes monitoring of foundation subsidence, lateral deviations and changes in groundwater level in dynamics /Stewart et al. 2023/.

Although laser scanning methods provide high detail and accuracy in creating three-dimensional models, they require significant financial and technical resources, which limit their use in solving engineering problems. In addition, they do not always guarantee the required positional accuracy, which is critical for some applications. GNSS technologies, on the other hand, are noted for their effectiveness over large areas, but the accuracy of these measurements often exceeds a few meters, which is insufficient for engineering solutions. As demonstrated by /Hesse et al. 2006/, neither laser scanning nor GNSS alone can provide reliable and stable deformation parameters for dynamic structures, since each technique suffers from specific limitations such as signal interruptions, ambiguity issues, or sensitivity to environmental conditions.

With the development of technology, unmanned aerial vehicles (UAVs) have rapidly become an integral part of the remote control of infrastructure facilities, and their use continues to grow rapidly /Duque & Seo 2018/, /Ham et al. 2016/, /Albeaino et al. 2019/, /Onososen et al. 2023/, /Lobanov et al. 2023/, /Panigati et al. 2025/. UAVs are effectively used to determine the tilt of towers by analyzing images collected during overflights /Lu et al. 2021/.

However, it is equally important to integrate these modern methods with other technologies that can significantly expand the possibilities of remote diagnostics. In particular, the improvement of data processing algorithms and automation of processes contribute to increased accuracy and efficiency of monitoring the state of infrastructure facilities. This is especially important for determining the verticality of structures, where high requirements for monitoring accuracy and efficiency are crucial, especially in difficult terrains or hard-to-reach places, which emphasizes the relevance of further research in this direction.

The Kyiv TV Tower is the tallest structure in Ukraine (385 m) and the world's tallest all-metal lattice construction. Built in 1973 for television and radio broadcasting, it is listed in the Register of Architectural and Urban Planning Monuments and holds the status of a cultural heritage site. On March 1, 2022, Russian forces carried out two targeted missile strikes on the tower. The unique structure withstood the attack, but the control room and the transformer substation powering the tower were damaged.

2 METHODOLOGY

To determine the verticality of the lower tier of the Kyiv TV Tower, a series of experimental measurements were carried out using the DJI Mavic 3 Enterprise UAV with RTK module. The purpose of the study was to provide high-precision measurement of the spatial coordinates of the object for further processing and analysis.

The survey was carried out taking into account the optimal shooting parameters, which included the choice of the appropriate flight altitude, angle of photography, as well as taking into account weather conditions to minimize errors. Data collection was performed by conducting a series of flights around the TV tower at the minimum possible distance from the object, which made it possible to increase the resolution and clarity of the images obtained.

One of the key tools to achieve high accuracy of the exterior orientation parameters of each shooting position is the use of real-time kinematics (RTK). RTK is a method of high-precision positioning based on GNSS. RTK technology uses a differential approach, in which corrective data from a stationary reference station is transmitted to a mobile receiving station via radio, the internet, or mobile networks. The use of an RTK receiver onboard the UAV enables the correction of satellite signals in real time, providing centimeter accuracy in determining the coordinates of the shooting positions.

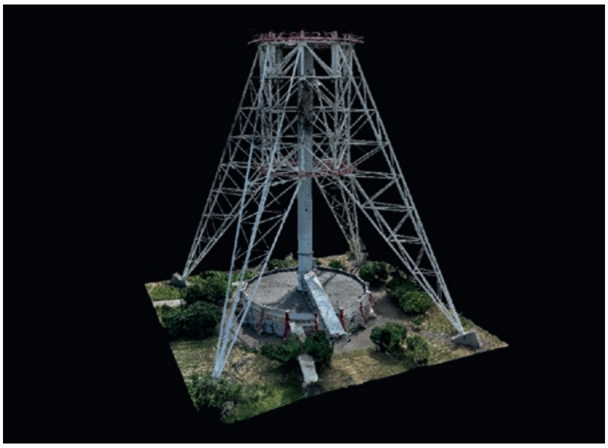


Fig. 1 | Textured mesh of the Kyiv TV Tower generated in 3DF Zephyr at the final stage of the photogrammetric workflow

Fig. 2 | Central trunk (elevator shaft) extracted from the textured mesh of the Kyiv TV Tower and used to define the region of interest for verticality analysis

After collecting data from the UAV, the information was processed using photogrammetry. This method allows creating a three-dimensional point cloud based on images obtained from different viewing angles /Luhmann et al. 2023/, /Toldo et al. 2015/. To process the data obtained and create a three-dimensional model of the TV tower, the 3DF Zephyr 7 software was used. The time required to generate a point cloud and 3D mesh by the program depended on the number of photos, selected modes, and parameters for the accuracy of the generated results. The process of forming the model was automated. For correct scaling, 100 % of the photos were used as keyframes, the coordinates of which were obtained using the RTK module installed on the UAV.

To build a model, 2497 photos with a size of 5 280 × 3 956 pixels and focal length of 12 mm were acquired from a drone. The Vertical Structure build mode of the 3DF Zephyr software was used on the workstation with the following technical characteristics: Intel Core i7-13700K 3.4 GHz processor, 64 GB of RAM and SSD storage 2 TB, NVIDIA Quadro RTX A4000 graphics card. Based on the obtained 3D model of the TV tower (*Fig. 1*), the central trunk was determined, which is a key part of the structure in the verticality analysis (*Fig. 2*).

Although the final output of the photogrammetric workflow is presented as a textured mesh for visualization, all quantitative analyses in this study were performed on the underlying dense point cloud prior to surface meshing. This approach avoids geometric smoothing and interpolation effects introduced during mesh generation and ensures metric consistency of the extracted cross-sections.

DJI Mavic 3E camera is factory calibrated, the photogrammetric processing in 3DF Zephyr included an internal self-calibration during bundle adjustment. The predominantly longitudinal geometry of UAV acquisition did not cause instability in the interior orientation parameters: the estimated focal length was 3 994.79 px, the principal point was located at (2 686.55, 1 975.37) px, while radial and tangential distortion parameters remained within typical values for the Mavic 3E sensor. The final bundle adjustment yielded a mean reprojection error of 1.05 px, with a reference variance of 0.42 px, indicating a consistent and geometrically stable camera model. No artificial coded targets were deployed in the field; all tie points (587 609 points in total) were extracted from natural features of the tower structure. The average Ground Sampling Distance (GSD) of the dataset was 0.0118 m/pixel (1.18 cm/pixel).

To determine the position of the central axis of the TV tower, segmentation of the point cloud was performed, which was the result of the photogrammetric analysis. This stage involves dividing the point cloud into separate segments, each representing a specific cross-section of the structure (*Fig. 3*).

For each segment of the point cloud with coordinates (x_i, y_i) the least-squares method (LSM) was applied to approximate the geometric shape of the section as an ellipse /Fitzgibbon et al. 1996/. The basics of LSM and adjustment calculations can be found in literature (e.g. /Niemeier 2002/, /Schwarz 2024a/, /Schwarz 2024b/).

The mathematical model of the LSM is represented by the following equation:

Fig. 3 | Central trunk (elevator shaft) – division of the elevator shaft into sections

$$\boldsymbol{Xp} = 0,$$

$$\text{where } X = \begin{bmatrix} x_1^2 & x_1y_1 & y_1^2 & x_1 & y_1 & 1 \\ x_2^2 & x_2y_2 & y_2^2 & x_2 & y_2 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_n^2 & x_ny_n & y_n^2 & x_n & y_n & 1 \end{bmatrix}, \qquad (1)$$

with n denoting the number of points. The parameter vector $\boldsymbol{p}$ consists of the unknown coefficients of the standard ellipse equation

$$Ax^2+Bxy+Cy^2+Dx+Ey+F=0,$$

$$\boldsymbol{p} = [A \;\; B \;\; C \;\; D \;\; E \;\; F]^{\mathsf{T}} \qquad (2)$$

The objective of LSM is to minimize the quadratic norm $\|\boldsymbol{Xp}\|_2$. An unweighted least-squares formulation was adopted, assuming equal accuracy of all points within each segment; therefore, explicit stochastic model or weighting scheme wasn't applied. The solution is obtained through singular value decomposition (SVD) of the matrix $\boldsymbol{X}$, where the vector $\boldsymbol{p}$ corresponds to the smallest singular value. From the derived coefficients A, B, C, D, E, and F the center of the ellipse is determined as:

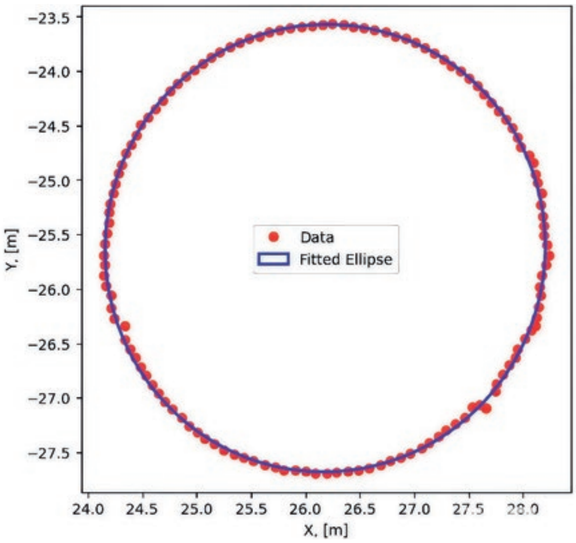


Fig. 4 | Calculation of center coordinates of an elevator shaft section

$$x_0 = \frac{BE-2CD}{4AC-B^2}, \quad y_0 = \frac{BD-2AE}{4AC-B}. \qquad (3)$$

This made it possible to obtain the most accurate values for the centers of the sections by minimizing the (squared) deviations of the points from the ellipse. The main parameters that have been determined are the coordinates of the center of the mine relative to the X-axis (east-west), Y-axis (north-south), radius, and standard deviation (*Fig. 4*).

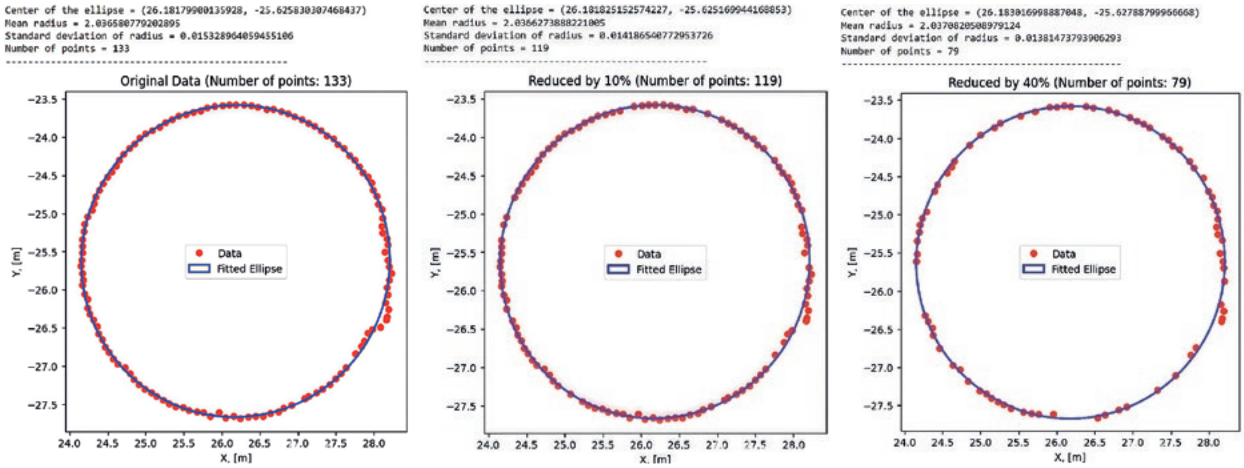
With the help of GNSS, data can obtain a coordinate accuracy of approximately 3 m in the presence of a sufficient number of satellites /Magiera et al. 2022/. The use of RTK technology yields a camera positioning accuracy of approximately 20–50 mm /Baybura et al. 2019/, /Elhassan 2017/. This accuracy refers to the geotagging of the UAV camera centers and does not directly correspond to the accuracy of individual points in the photogrammetric point cloud. The analysis showed that the standard deviation of the estimated parameters corresponds to the RTK-based positioning accuracy (*Tab. 2*).

During the calculations to determine the coordinates of the central axis of the TV tower, the number of experimental points was analyzed. The 3DF Zephyr v.7 software offers different processing modes for building a 3D model: the "Deep" mode provides the highest quality but is time-consuming, while the "Default" and "Fast" modes offer faster processing with basic parameters and reduced photo resolution, respectively.

An experiment was conducted to construct a defined volume of an object in these three modes using 183 photos (*Tab. 1*). To

Mode	Fast	Default	Deep
Point Count	30 698	44 010	47 231
Point Count	65 %	93 %	100 %

Tab. 1 | Number of points obtained in different processing modes of the 3DF Zephyr software



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Center of the ellipse = (26.18179900135928, -25.625830307468437)
Mean radius = 2.036580779202895
Standard deviation of radius = 0.015328964059455106
Number of points = 133
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Center of the ellipse = (26.181825152574227, -25.625169944168853)
Mean radius = 2.0366273888221005
Standard deviation of radius = 0.014186540772953726
Number of points = 119
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Center of the ellipse = (26.183016998887048, -25.62788799966668)
Mean radius = 2.0370820508979124
Standard deviation of radius = 0.01381473793906293
Number of points = 79
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a) 100 % of points b) 90 % of points c) 60 % of points

Fig. 5 | An example of determining the coordinates of the center of section of an elevator shaft with a different number of points: a) 100 % points, b) 90 % points, c) 60 % points

analyze the object's verticality, it was necessary to generate dense point clouds, from which sections could be extracted. The original photos of the Kyiv TV Tower, captured with UAVs, were used, ensuring a consistent dataset while yielding a unique number of points for each processing mode.

Based on the data analysis, subsequent research focused on the following point densities: "Deep" – 100 % of points, "Default" – 90 % of points, and "Fast" – 60 % of points. For each section extracted from the "Deep" mode point cloud, approximately 120–150 original key points were used. To simulate the effect of lower density point clouds, the number of these original points was reduced randomly for the "Default" and "Fast" modes (*Fig. 5*).

The obtained coordinates of the centers were used to further calculate the verticality of the structure. The use of the least-squares method in this context allows for accuracy and reliability of measurements, which is necessary for conducting detailed structural analyses and assessing the quality of structures.

3 RESULTS AND DISCUSSION

The central axis varies by 30 mm at altitudes ranging from 40 m to 72 m. *Fig. 6* illustrates the relationship between the central axis coordinates and height, where the *X* coordinate represents the east-west direction, and the *Y* coordinate represents the north-south direction.

Analysis of the central axis deviation graphs reveals a bend in the elevator shaft at altitudes between 50 m and 65 m. This bend may be a result of damage to the lattice structure of the TV tower trunk caused by an explosion at a height of 58 m and the subsequent destruction of the support unit. Importantly, systematic errors cannot account for the bending observed in the model due to the symmetrical nature of the tower structure. Systematic errors would affect all measurements uniformly, resulting in consistent shifts rather than the directional bending evident in our findings. The clear observation of a bending curve, despite the small magnitudes of the deviations, indicates that the actual measurement accuracy is significantly

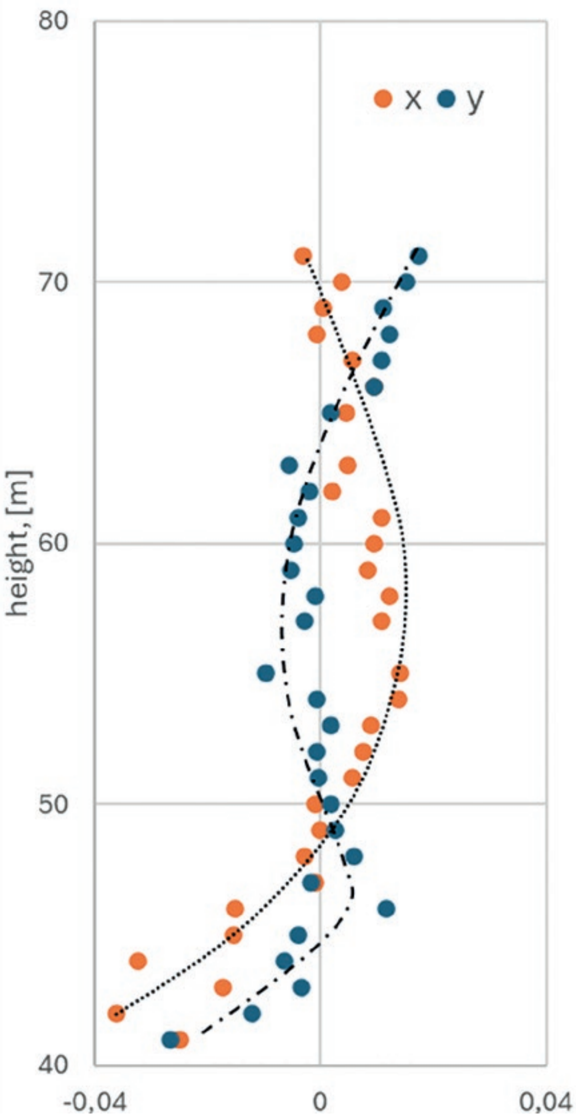

Fig. 6 | Dependence of the central axis coordinates on height between 40 m and 72 m

Height	Δ *Xc*	Δ *Yc*	Δ *Xc*	Δ *Yc*
	point cloud density 90 %		point cloud density 60 %	
36 m	0.018 mm	–0.249 mm	0.415 mm	–0.236 mm
51 m	1.071 mm	–0.877 mm	0.400 mm	1.988 mm
54 m	0.553 mm	–0.760 mm	0.164 mm	0.250 mm
60 m	–0.211 mm	–0.338 mm	–0.262 mm	0.106 mm
65 m	–0.075 mm	–0.452 mm	–2.870 mm	–0.142 mm
68 m	–1.423 mm	0.226 mm	–1.907 mm	2.842 mm
70 m	–0.217 mm	–0.138 mm	–0.972 mm	2.535 mm
Max. deviations	1.423 mm	0.877 mm	2.870 mm	2.842 mm

Tab. 2 | Central axis coordinate deviation based on point cloud density

higher than 50 mm. This precision is achieved by considering hundreds of data points for each cross-section, which substantially reduces the random error in the coordinate measurements.

Each cross-section consisted of approximately 100 – 150 points. To evaluate the repeatability of the results, random subsampling was performed multiple times for representative cross-sections. The point density was reduced to 90 % and 60 % of the original set using different random selections. The deviations in the estimated center coordinates remained small and consistent across repeated trials. As illustrated in *Tab. 2* for selected cross-sections, the maximum deviations did not exceed 1.4 mm for 90 % density and 2.9 mm for 60 % density. These variations are within the expected statistical variability of a least-squares estimate and indicate that the proposed method is robust and repeatable with respect to random point selection and point cloud density.

Thus, the integration of UAV, RTK, and photogrammetry data not only enabled the precise detection of coordinates but also provided a high level of accuracy in assessing the structure's verticality, which is critical for further evaluation of the condition and safety of infrastructure facilities. This demonstrates the significant potential of combining these technologies for efficient and reliable structural health monitoring. The high accuracy achieved allows for the early detection of even minor deviations from the vertical, which can be indicative of underlying structural issues before they become critical. This approach offers a valuable tool for proactive maintenance and risk mitigation in infrastructure management, potentially leading to reduced costs and enhanced safety.

4 CONCLUSIONS

This research successfully integrated data from an UAV equipped with an RTK module and processed using photogrammetry to generate a high-precision point cloud and detailed three-dimensional model of the case study TV tower. The resulting model enabled a quantitative assessment of the structure's verticality, revealing the presence of bends within the altitude range of 40 m to 72 m. Furthermore, a systematic evaluation of the influence of point cloud density on coordinate estimation demonstrated that a 10 % random reduction of points led to deviations at the millimeter level (≤ 1.5 mm), while a 40 % reduction increased the variability of the estimated center coordinates to approximately 3 mm. These deviations remain consistent with the expected statistical behavior of least-squares estimation and do not indicate a loss of methodological reliability. This finding underscores the importance of data density for achieving accurate geometric representations and highlights the potential for error propagation in situations with reduced data coverage, where precision is crucial for detecting small but critical structural deformations. The outcomes of this study validate the efficiency of the combined UAV-RTK photogrammetry approach for the precise monitoring of infrastructure facility verticality, demonstrating its potential as a valuable tool for proactive maintenance and structural health management.

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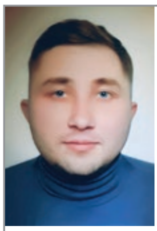

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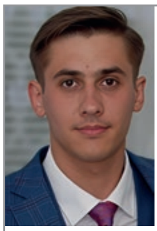

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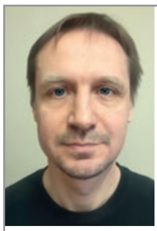

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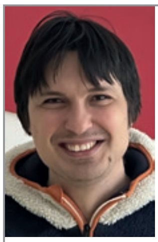

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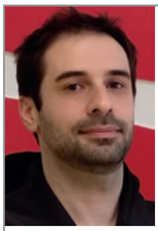

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