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DEVELOPMENT OF A METHOD FOR DETERMINING THE TILT OF TOWER-TYPE ENGINEERING STRUCTURES

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Abstract. *This paper investigates modern approaches to determining the tilt of tower-type engineering structures using unmanned aerial vehicles (UAVs) and digital photogrammetry techniques. The relevance of the research is driven by the growing need to improve the accuracy, efficiency, and safety of geodetic monitoring of high-rise engineering structures subjected to natural and anthropogenic influences throughout their operational life. A geodetic methodology for determining the tilt of industrial chimneys is proposed, based on UAV aerial image acquisition followed by photogrammetric processing of digital images using the Digitals software package. The study describes the principal stages of the proposed methodology, including flight mission planning, image acquisition, photogrammetric data processing, three-dimensional reconstruction of the structure, determination of the coordinates of characteristic points, and calculation of the tilt magnitude. Experimental investigations confirmed the effectiveness and reliability of the proposed approach, demonstrating its capability to provide accurate geometric characteristics of the structure and to assess its spatial position with a high degree of precision. The obtained results indicate that UAV-based photogrammetric surveying significantly reduces fieldwork duration, decreases labor intensity, enhances personnel safety during inspections of inaccessible structures, and lowers operational costs compared with conventional geodetic surveying methods. The practical significance of the research lies in the development of a universal geodetic methodology for tilt determination of tower-type engineering structures that can be effectively applied for operational inspection, technical condition assessment, deformation monitoring, and the timely detection of hazardous changes in the spatial position of high-rise engineering facilities. The proposed methodology provides an efficient, reliable, and economically feasible solution for modern engineering surveying and structural health monitoring applications.*

Keywords: *unmanned aerial vehicle (UAV); quadcopter; aerial photogrammetric survey; digital photogrammetry; structural tilt; industrial chimney; Digitals software; geodetic monitoring.*

Introduction

The diversity of tower-type structures has led to the development of numerous construction methods that depend on the structural design, geometric parameters, construction materials, and site conditions. Significant foundation loads, wind effects, and thermal impacts cause deformations that must be taken into account during the construction of tower structures.

Temperature gradients, mechanical loads, and high humidity in aggressive environments may cause vertical and horizontal cracking and brickwork delamination in load-bearing structures. Design errors and inappropriate assumptions adopted in the structural analysis of the chimney shaft may also significantly contribute to such damage.

Modern technologies for producing topographic and cadastral maps are primarily based on the use of digital aerial imagery. However, the cost of using manned aircraft and helicopters for local large-scale surveys is considerably higher. Therefore, an effective alternative is the use of unmanned aerial vehicles (UAVs), which enable rapid and cost-effective aerial surveys of relatively small areas for the production of cadastral maps and orthophotos.

Analysis of recent research and publications

The problem of determining the tilt of tower-type engineering structures is primarily investigated using electronic total station surveying, terrestrial laser scanning, photogrammetry, and integrated automated monitoring systems. Current research is focused on shifting from observations of individual control points to the development of three-dimensional models of structures and the determination of their geometric axes at different height levels.

In the study by Ž. Pleterski, G. Rak, and K. Kregar [1], a method for determining chimney non-verticality from terrestrial laser scanning data was proposed. The authors divide the point cloud into narrow horizontal cross-sections, remove outliers using the RANSAC algorithm, fit circles or ellipses to the section contours by the least-squares method, and determine the spatial position of the chimney axis from the displacements of the section centres. An advantage of this method is its ability to analyse local structural deviations at different heights.

M. Zhou et al. [2] developed an automated approach for determining the tilt of industrial chimneys from LiDAR point clouds. The method involves generating horizontal cross-sections, determining their geometric centres, fitting the central axis, and calculating the tilt angle and direction. The researchers also integrated LiDAR, GNSS positioning, and remote data transmission, thereby increasing the level of automation in the monitoring process.

In the study by Ji, Ren, Fu, Zhang, and Li [3], a method for determining the dynamic displacements of monopole communication towers was proposed by integrating data from accelerometers and strain gauges using a Kalman filter. This approach provides continuous assessment of the structural deformation state; however, it requires the installation of specialized sensors directly on the structure.

The potential of unmanned aerial vehicles for the technical inspection of structures was demonstrated in the study by J. Bae et al. [4]. The proposed system combines aerial imaging, thermography, machine-learning algorithms, and three-dimensional point-cloud generation to detect cracks and structural deformations. The study confirms the feasibility of using UAVs for the non-contact inspection of hard-to-reach parts of engineering structures.

The analysis conducted shows that terrestrial laser scanning provides highly detailed reconstruction of the geometry of tower-type structures, whereas automated sensor systems enable continuous monitoring. However, laser scanners and permanent monitoring systems are associated with high costs and complex deployment. Therefore, the development of a more accessible non-contact method for determining the tilt of industrial chimneys using a quadcopter, digital imagery, and the Digitals software package remains highly relevant. The proposed approach is based on determining the centres of the upper, lower, and intermediate cross-sections of the structure, constructing its geometric axis, and calculating both the linear and angular tilt.

The aim of this study is to develop and experimentally validate a method for determining the tilt of tower-type engineering structures using unmanned aerial vehicles and digital photogrammetry in order to improve the accuracy, efficiency, and safety of geodetic monitoring of their structural condition.

Methods and research data

New technical solutions for structural systems, equipment, products, and materials must be accompanied by confirmation of their suitability for use in the construction and operation of high-rise buildings in accordance with DBN V.1.3-2:2010 [5], approved by the Cabinet of Ministers of Ukraine.

Due to the technical complexity of high-rise buildings, geodetic surveying should be performed by specialized organizations licensed to carry out this type of work and in accordance with DSTU-N B V.1.2-18:2016 [6]. For the construction of high-rise buildings, it is recommended that a permanent geodetic team be established for the entire construction period of the project.

For unique buildings and structures, as well as in monitoring applications requiring continuous acquisition of measurement data, the use of automated monitoring systems is recommended. Deformation monitoring of buildings and structures in service should be carried out when unacceptable cracks, joint openings, or significant changes in the operating conditions of the structure are observed.

Tilt is the most characteristic indicator of the overall deformation of tall structures. In such structures, which are highly sensitive to foundation soil deformations, tilt induces an additional bending moment that, in turn, promotes further tilting and may ultimately lead to structural instability [1, 7–8].

Therefore, tower-type structures, including industrial chimneys, distillation columns, granulation towers, and radio and television antenna masts, belong to the category of engineering structures with a high level of responsibility.

During construction or operation, structures may undergo deformation due to differential settlement and the effects of other factors. In addition, owing to their structural characteristics, torsional and bending deformations may occur as a result of non-uniform solar heating or wind loading. These effects may cause the structures to tilt, that is, to deviate from the vertical [3].

Such deformations may lead to structural instability. Therefore, the periodic determination of structural deformations (monitoring) is of particular importance [9]. Based on the results of these measurements, preventive measures may be developed, when necessary, to eliminate structural tilt and ensure the safe operation of the structure.

Current trends in the assessment of the deformation state of engineering structures are focused on the development of automated continuous monitoring systems based on high-precision Global Positioning System (GPS) technology, robotic total stations, high-precision inclinometers (e.g., Leica Nivel210/Nivel220) with an angular measurement accuracy of 0.09 arcseconds, and the GeoMoS software platform (Leica Geosystems) [10–14].

A substantial proportion of the high-rise engineering structures currently in service in Ukraine were commissioned several decades ago and have since been exposed to the long-term effects of natural and anthropogenic factors. During operation, such structures are subjected to differential foundation settlement, temperature fluctuations, wind loads, vibrations, and other influences that may alter their geometric position, cause tilt, and lead to the development of deformations. In this context, the implementation of modern geodetic monitoring methods is of particular importance, as they enable the timely detection of deviations from the design position and provide an objective assessment of the technical condition of the structures.

Most conventional methods for determining the tilt of tower-type structures are based on high-precision angular and linear measurements performed using electronic total stations, theodolites, or other geodetic instruments. Although these methods provide highly accurate results, they require the establishment of a geodetic control network, unobstructed intervisibility between observation points, and considerable time for field measurements. Furthermore, geodetic surveys at industrial facilities are often complicated by restricted access to the structure and the need to comply with stringent safety requirements.

According to the current regulatory documents [6], the spatial position of high-rise engineering structures should be monitored throughout their entire service life. For newly constructed structures, geodetic observations of tilt and foundation settlement are recommended at least twice a year during the first two years of operation. Thereafter, the frequency of observations is determined by the technical condition of the structure and the intensity of deformation processes. Once foundation settlement has stabilized, monitoring measurements may be carried out at longer intervals in accordance with the applicable regulatory requirements.

In recent years, unmanned aerial vehicles (UAVs) have become widely adopted as an effective tool for engineering geodetic surveys and the technical inspection of high-rise structures. The use of multirotor UAVs equipped with high-resolution digital cameras and satellite navigation systems enables the rapid acquisition of photogrammetric data from hard-to-reach parts of a structure without the need for hazardous work at height. Modern UAVs support 4K photo and video acquisition, automatically record the coordinates of camera exposure stations, and generate datasets suitable for the production of orthophotos, digital terrain models (DTMs), and three-dimensional models of engineering structures [1, 3, 8, 15–16].

In this study, aerial photography of a tower-type engineering structure was carried out using a DJI Phantom 4 Pro unmanned aerial vehicle (UAV) equipped with a digital camera featuring a 1-inch 20 MP CMOS sensor, a lens with an actual focal length of 8.8 mm (24 mm equivalent in the 35 mm format), and a mechanical shutter to minimize geometric distortions during image acquisition. The spatial referencing of the photogrammetric model was performed without the use of high-precision RTK positioning. The spatial position of the model was determined based on data acquired during UAV aerial surveying and subsequent photogrammetric processing of the digital images. Camera calibration was performed automatically during photogrammetric processing using self-calibration of the internal camera parameters. This approach enabled the generation of a spatial model of the engineering structure with sufficient accuracy to determine its geometric parameters and assess the magnitude of its tilt within the objectives of the study. RTK positioning was not used in the experimental study; therefore, its effect on the accuracy of the spatial referencing of the photogrammetric model was not evaluated.

Vertical imaging of the chimney top was performed from a height of approximately 7 m above the uppermost point of the structure. Under these conditions, the ground coverage of a single image was approximately 10.5 × 7.0 m, while the calculated ground sampling distance (GSD) was about 1.9 mm/pixel. The selected flight height ensured that the chimney top was entirely located within the central part of the image, providing a sufficient margin around its contour for accurate determination of the geometric center of the upper cross-section.

Since the proposed tilt determination method is based on the independent analysis of individual images, image overlap was not required. The theoretical minimum number of images required for a single tilt measurement is four: two images acquired from opposite directions along each of the two mutually perpendicular axes, X and Y (Fig. 2). To improve the reliability and accuracy of tilt determination, the measurement procedure should be repeated several times, followed by averaging of the obtained results.

Results and Discussion

To investigate the tilt of the thermal power plant chimney, as a representative tower-type structure, a DJI Phantom 4 Pro unmanned aerial vehicle (UAV) was used. The UAV aerial survey workflow included the preparation of the launch site, flight path planning with due consideration of existing obstacles and meteorological conditions, and the selection of both primary and alternate landing sites.

Before image acquisition, baselines are established on the ground surface adjacent to the chimney in two mutually perpendicular directions, defining a local X, Y coordinate system. Photo and video acquisition of the chimney is then performed sequentially along these directions, ensuring complete coverage of the structure's geometry.

The photograph in Figure 1 shows the chimney of the district heating plant in the Tsentralno-Miskyi District of Kryvyi Rih, Ukraine. The inspection was carried out in 2021. The baselines are indicated in Figure 2 by red dashed lines. Their actual lengths, measured on the ground surface, are as follows:

$$S_X = 16.482 \text{ m}, S_Y = 20.261 \text{ m}. \tag{1}$$

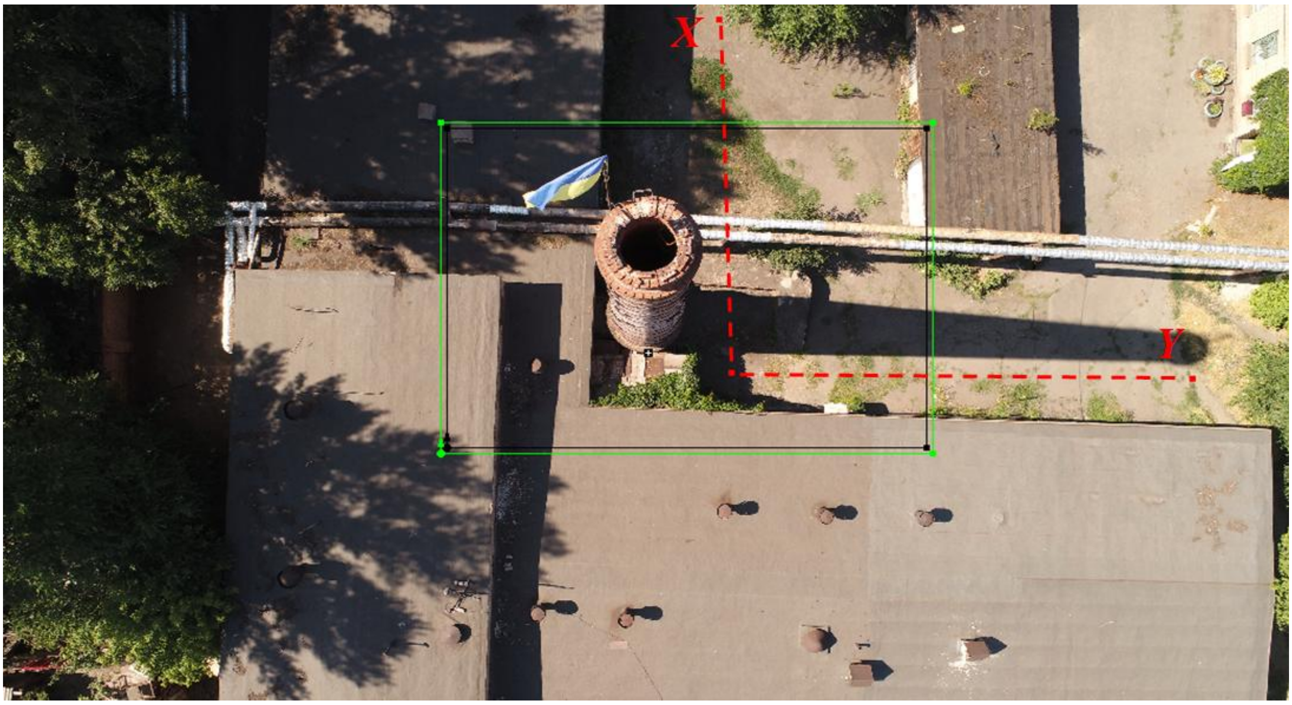


Figure 1. Local coordinate system defined by two mutually perpendicular baselines used for the UAV survey of the district heating plant chimney (2021).

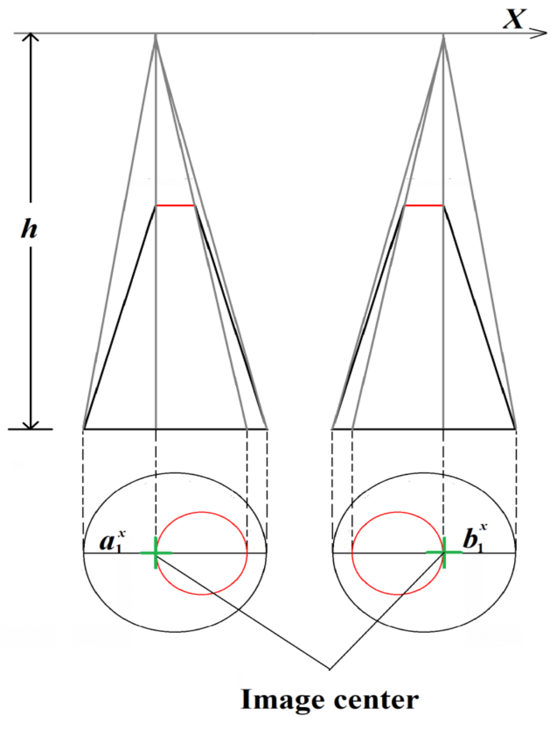
At least two photographs of the chimney are acquired along each baseline during a single image acquisition session. Figure 2 illustrates the two positions of the chimney during image capture. The lower cross-section of the chimney is shown schematically in black, while the upper cross-section is shown in red. The images are acquired so that the center of the image frame is successively aligned with the upper edge of the chimney: first in the position shown in Fig. 2a and then in the position shown in Fig. 2b.

In the acquired images, the distances between the upper and lower circular edges of the chimney are measured. The first difference, measured along the direction of the quadcopter's motion, is denoted by a, and the second by b. The total tilt along each axis is calculated using the following formulas:

$$\Delta x_i = a_i^x - b_i^x, \quad (2)$$

$$\Delta y_i = a_i^y - b_i^y, \quad (3)$$

where a_i^x, b_i^x are the differences between the lower and upper circular edges of the chimney along the X-axis, while a_i^y, b_i^y are the corresponding quantities along the Y – axis; i denotes the i-th tilt measurement cycle.



a) b)

Figure 2. Schematic representation of the chimney positions in the vertical plane during image acquisition and the corresponding images of its lower and upper cross-sections: (a) the image center is aligned with the upper edge of the chimney in the first position; (b) the image center is aligned with the upper edge of the chimney in the second position.

A minimum of two pairs of images acquired along two mutually perpendicular axes is required to determine the tilt angle. Such a dataset is sufficient for calculating the tilt; however, the accuracy of the result is limited by the errors associated with the individual measurements.

To improve the accuracy and reliability of tilt determination, it is advisable to perform a series of independent measurements, for example, two sets of four images (two image pairs in each set). Averaging the resulting tilt estimates reduces the influence of random errors, measurement system noise, and variations in image acquisition conditions, thereby providing a more accurate and reproducible determination of the tilt angle.

Before photogrammetric processing, the images are scaled using control baselines established in the survey area (Fig. 1). This is accomplished by measuring the lengths of the baselines in the images. For the baselines defined by Eqs. (1), the following values were obtained:

$$s_X = 0.329 \text{ m}, s_Y = 0.405 \text{ m}. \tag{4}$$

The image scale factors for the X and Y-axes are calculated using the following equations:

$$m_X = \frac{s_X}{S_X}, m_Y = \frac{s_X}{S_X}. \tag{5}$$

The overall image scale is calculated as the arithmetic mean of the scale factors determined for the X- and Y-axes. For the considered case, the resulting image scale is:

$$m = \frac{1}{50.06}.$$

The calculated scale factor is then used to convert the tilt values obtained in image units into absolute (real-world) units.

The geometric parameters of the upper part of the chimney are determined by vectorizing its outline in the Digitals software package. First, the Create Linear Object tool is selected from the Capture menu. The outer contour of the chimney top is then digitized by sequentially marking characteristic points along its perimeter. To improve the accuracy of the approximation of the curved surface, the Insert Arc function is applied, which smooths the individual linear segments and generates a geometrically consistent contour.

In the final stage, the positions of the control points are refined to conform to the shape of the contour, thereby minimizing digitization errors and producing an accurate model of the chimney's upper cross-section. The resulting contour is then used to determine the coordinates of the cross-sectional center, construct the geometric axis of the structure, and calculate its tilt (Fig. 3).

Figure 3. Result of generating the geometrically refined contour of the chimney's upper cross-section after adjustment of the control points.

The geometric parameters of the lower cross-section of the chimney are determined in the same manner. Since part of the contour is obscured by structural elements of the chimney, only the visible points along the perimeter are digitized. Based on the digitized points, the Digitals software package automatically determines the center and diameter of the circle, enabling reconstruction of the missing portion of the lower ring and generation of the complete cross-sectional contour. The reconstructed contour is subsequently used to determine the geometric axis of the structure and calculate its tilt (Figs. 4–5).

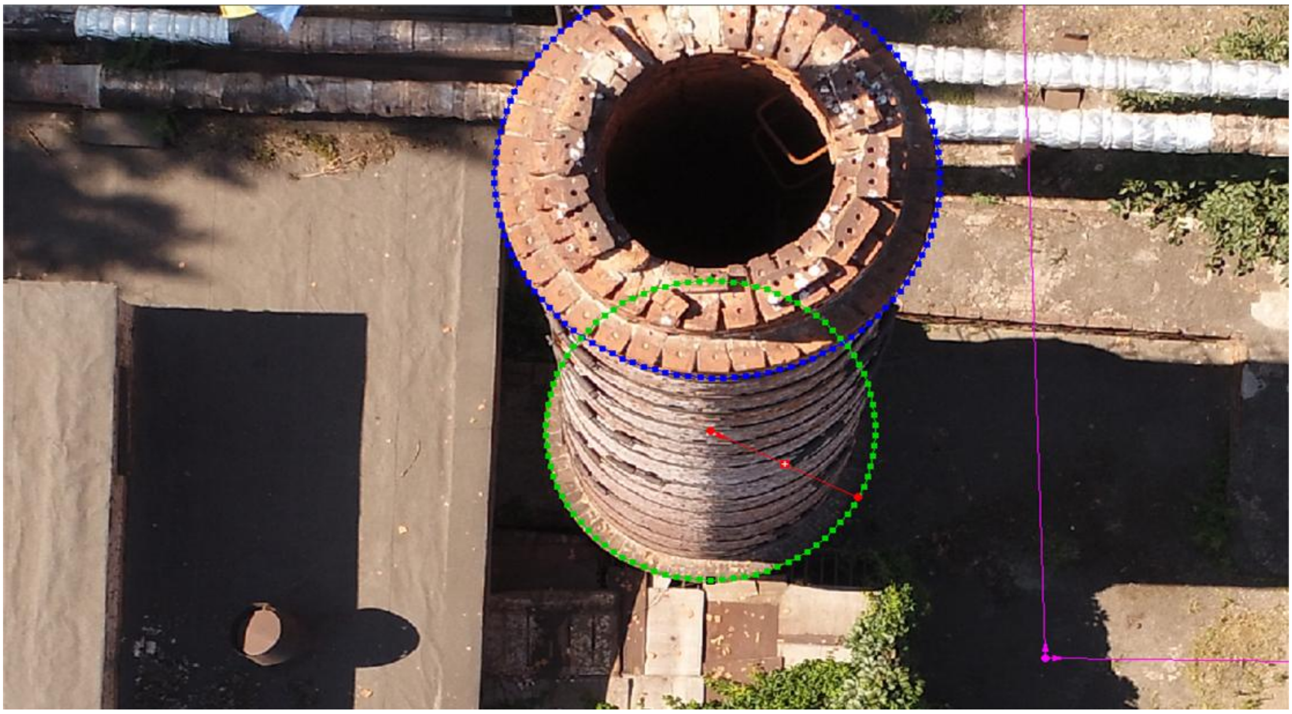


Figure 4. Determination of the center and diameter of the lower cross-section after reconstruction of the missing portion of the chimney ring.

Fig. 5 illustrates the procedure for determining the perimeter of the lower cross-sectional contour of the chimney using the Digitals software package. For the chimney considered in this study, the perimeter was determined to be:

$$P = 11.221 \text{ m.}$$

The diameter of the chimney is calculated from the measured perimeter according to the well-known equation:

$$D = \frac{P}{\pi}, \quad (6)$$

and is equal to:

$$D = 3.57 \text{ m.}$$

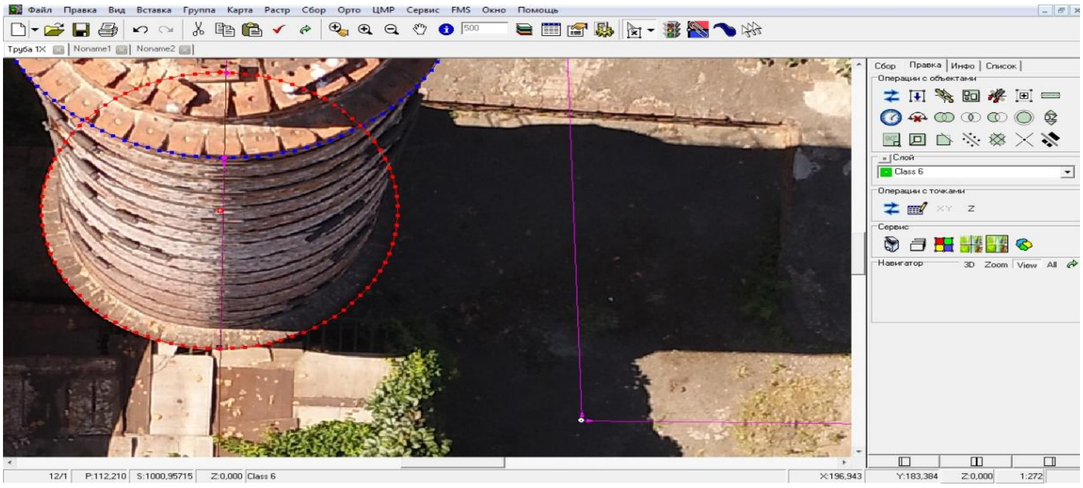


Figure 5. Determination of the perimeter of the lower cross-sectional contour of the chimney using the Digitals software package.

For the subsequent calculations, the centerline of the chimney is constructed by connecting the centers of the upper and lower circles, as shown in Fig. 6. This procedure is carried out using the Digitals software package.

The upper and lower cross-sections correspond to the horizontal cross-sections of the chimney at the levels of its top and base, respectively, while the vertical distance between their geometric centers was assumed to be equal to the total height of the investigated structure, i.e., 35 m. The displacement of the center of the upper cross-section relative to the center of the lower cross-section characterizes the magnitude of the chimney tilt.

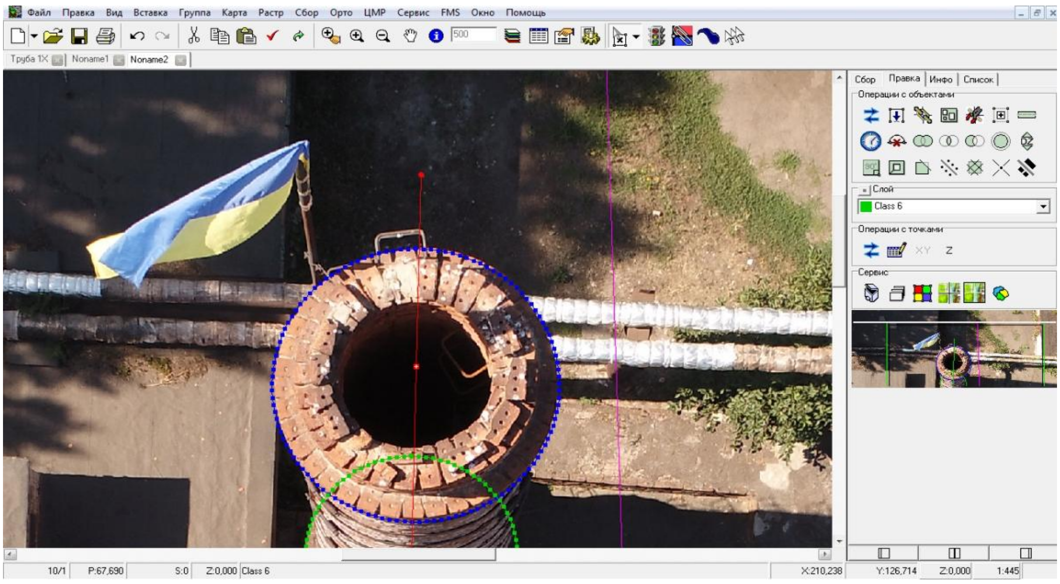


Figure 6. Centerline constructed through the centers of the upper and lower circles of the chimney.

Using this centerline, the values of $a_{i,}$ b_i are measured. For the images acquired along the X, Y, the measured values are presented in Table 1.

Table 1. Calculation of the tilt of the chimney at the Central City District Heating Plant (Kryvyi Rih) based on two measurement cycles.

Quantity	Value	Quantity	Value
a_1^X (mm, image units)	4.93	a_2^X (mm, image units)	7.43
b_1^X (mm, image units)	3.68	b_2^X (mm, image units)	6.18
a_1^Y (mm, image units)	5.05	a_2^Y (mm, image units)	7.52
b_1^Y (mm, image units)	3.84	b_2^Y (mm, image units)	6.33
a_1^X (mm)	246.7	a_2^X (mm)	371.8
b_1^X (mm)	184.4	b_2^X (mm)	309.6
a_1^Y (mm)	252.6	a_2^Y (mm)	376.5
b_1^Y (mm)	192.3	b_2^Y (mm)	317.1
Δx_1 (mm)	62.3	Δx_2 (mm)	62.2
Δy_1 (mm)	60.3	Δy_2 (mm)	59.4
ΔL_1 (mm)	86.7	ΔL_2 (mm)	86.0
Mean tilt $\Delta\bar{L}$ (mm)	86.4	Relative error (%)	1

In Table 1, the quantities a_i^X, b_i^X, and a_i^Y, b_i^Y are presented as measurement results obtained from the digital image using the Digitals software package. The values are expressed in millimeters within the image coordinate system. To convert these values into the corresponding real-world linear dimensions, they should be divided by the scale factor:

$$Z = \frac{z}{m}, \tag{7}$$

where z is any of the quantities a_i^X, b_i^X, or a_i^Y, b_i^Y measured in image units, m is the image scale factor, and Z is the corresponding value expressed in real-world units.

The use of two independent image sets improves the reliability of determining the spatial position of the centerline of the structure and minimizes the influence of photogrammetric processing errors. Based on the obtained values, the absolute tilt of the chimney along the X- and Y-axes is calculated using Eqs. (2-3).

For additional verification of the reliability of the obtained results, a control comparison was performed with the results of the total station-based determination of the chimney tilt. The reference tilt value was taken as 85.6 mm. The mean value obtained from two UAV survey cycles was 86.35 mm. The absolute difference between the results was 0.75 mm, while the relative discrepancy was 0.87%, indicating a high level of agreement between the results and confirming the applicability of the proposed method for determining the tilt of tower-type engineering structures.

Table 2 – Control comparison with the results of total station-based tilt determination

Method / Cycle	**Tilt, mm**	**Difference from the Reference Value, mm**	**Discrepancy, %**
UAV, Cycle 1	86.7	1.1	1.29
UAV, Cycle 2	86.0	0.4	0.47
Mean UAV Value	86.35	0.75	0.87
Reference Total Station Value	85.6	0	0

To assess the accuracy of the tilt determination, an uncertainty budget was established that accounts for the main components of the photogrammetric process, including digital image scaling, contour vectorization, determination of the geometric center of the cross-section, ground sampling distance (GSD), and the repeatability of the results obtained from two independent observation cycles. The combined standard uncertainty was determined by combining the individual uncertainty components, while the expanded uncertainty at a confidence level of approximately 95% was calculated using a coverage factor of k=2.

Table 3 – Uncertainty Budget

Source of Uncertainty	**Standard Uncertainty, mm**
Image scaling	0.80
Contour vectorization	0.70
Determination of the cross-section center	0.90
Effect of GSD and image discretization	0.55
Repeatability of the two cycles	0.35
Combined standard uncertainty ((u_c))	**1.54**
Expanded uncertainty ((U_{95})), (k = 2)	**3.08**

Based on the uncertainty assessment, the tilt of the investigated chimney can be expressed as K= (86.35±3.08) mm at a confidence level of approximately 95%. The corresponding confidence interval ranges from 83.27 to 89.43 mm. This interval represents the range of possible tilt values, taking into account the main sources of uncertainty associated with the photogrammetric determination, and confirms the repeatability of the results obtained from the two observation cycles.

The total tilt of the chimney is then calculated as follows:

$$\Delta L = \sqrt{\Delta x^2 + \Delta y^2}, \tag{8}$$

Since the investigated structure is an industrial chimney, the application of the provisions of the international regulatory document CICIND (Model Code for Steel Chimneys) is justified and consistent with its scope. Using the chimney height determined from UAV-based aerial survey data, the limiting deviation of the chimney from the vertical can be calculated in accordance with the provisions of Section 11.7 of the CICIND Model Code for Steel Chimneys using the following formula: [17, p. 22]::

$$\Delta_{\text{доп}} = \max(0{,}025, \frac{H}{0{,}6}). \tag{9}$$

where H is the height of the chimney (m). For the chimney considered in this study, the height is 35 m. Therefore, the allowable tilt is:

$$\Delta_{Limit} = 0.058 \text{ m}.$$

The calculations showed that the tilt of the investigated chimney is 0.086 m (Table 1), which exceeds the calculated limiting value of 0.058 m. The identified exceedance indicates the need for an urgent comprehensive technical inspection of the structure by a specialized organization to assess its actual technical condition and make a well-founded decision regarding the conditions for its further operation.

The proposed method is not limited to determining the overall tilt of the structure. To provide more comprehensive information about the structural condition, it is advisable to determine the centers of intermediate horizontal cross-sections of the chimney at different elevations. Constructing circles that represent the geometry of the masonry at each cross-section makes it possible to determine the local deviations of the centerline from its position at the base and to analyze the spatial deformation of the structure over its entire height.

The coordinates of the centers determined at multiple elevation levels make it possible to construct a three-dimensional digital model of the chimney using the Digitals software package, AutoCAD, or other specialized software. Such a model enables visualization of the spatial position of the centerline, determination of the direction of the tilt with respect to the cardinal directions, and analysis of the influence of external factors, including wind loads, thermal deformations, and differential foundation settlement.

An additional advantage of using an unmanned aerial vehicle (UAV) is the ability to perform a detailed visual inspection of the external surface of the structure. High-resolution aerial images make it possible to identify cracks, localized damage, masonry defects, deterioration of the protective coating, and other signs of structural degradation. Combining photogrammetric measurements with the results of the visual inspection provides a comprehensive assessment of the technical condition of the chimney, establishes an information basis for predicting the progression of deformation processes, and supports informed decision-making regarding the continued operation, maintenance, repair, or rehabilitation of the structure.

Thus, the proposed method integrates UAV photogrammetry, digital modeling, and geodetic analysis, enabling the tilt of tower-type engineering structures to be determined rapidly, non-contactly, and with sufficient accuracy, while also providing a comprehensive assessment of their technical condition.

Conclusions

As a result of this study, a method was developed and validated for determining the tilt of tower-type engineering structures using unmanned aerial vehicles and digital photogrammetric processing of aerial imagery. The proposed approach is based on determining the geometric parameters of the upper and lower cross-sections of the structure from digital images acquired from opposite viewing directions, followed by calculation of the spatial position of the centerline and the magnitude of the tilt.

Experimental studies confirmed the feasibility of using a DJI Phantom 4 Pro UAV in combination with the Digitals software package for the geodetic monitoring of tower-type structures. The obtained results showed that the determined tilt of the chimney (0.086 m) exceeds the calculated limiting value (0.058 m). This exceedance substantiates the need for an urgent comprehensive technical inspection of the structure using instrumental monitoring methods to assess its actual technical condition and determine the appropriate conditions for its further operation.

The proposed method provides a comprehensive assessment of the technical condition of engineering structures. In addition to determining the magnitude of the tilt, it enables the construction of a three-dimensional spatial model of the structure, determination of the position of its centerline at different elevation levels, analysis of deformation patterns, and detailed visual inspection of the external surface. The use of high-resolution aerial imagery also enables the timely detection of cracks, masonry damage, localized defects, and other signs of structural deterioration.

The obtained results confirm the applicability of UAV-based aerial surveying and digital photogrammetry for determining geometric parameters and assessing the tilt of tower-type engineering structures. In this study, the spatial referencing of the photogrammetric model was performed without the use of RTK positioning, while the camera's internal parameters were determined through automatic self-calibration during photogrammetric processing. The resulting spatial model provided sufficient quality to accomplish the objectives of the study and to determine the tilt of the investigated structure.

A promising direction for future research is the automation of tilt determination using computer vision algorithms, the integration of aerial photogrammetric data with terrestrial laser scanning and GNSS measurements, and the development of an automated real-time monitoring system for the technical condition of tower-type engineering structures. The implementation of such an approach would improve the efficiency of geodetic monitoring, facilitate the timely detection of hazardous deformations, and contribute to the safe operation of tall engineering structures.

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РОЗРОБКА МЕТОДУ ВИЗНАЧЕННЯ КРЕНУ ІНЖЕНЕРНИХ СПОРУД БАШТОВОГО ТИПУ

Анотація. *У статті досліджено сучасні підходи до визначення крену інженерних споруд баштового типу із застосуванням безпілотних літальних апаратів та методів цифрової фотограмметрії. Актуальність дослідження* *обумовлена необхідністю підвищення точності, оперативності та безпеки геодезичного контролю технічного стану висотних споруд, які в процесі експлуатації зазнають впливу природних і техногенних факторів. Запропоновано методику визначення крену димових труб, що базується на виконанні аерофотознімання квадрокоптером із подальшою фотограмметричною обробкою отриманих цифрових зображень у програмному комплексі Digitals. Детально розглянуто основні етапи польових робіт, планування маршрутів польоту, отримання фотоматеріалів, побудову просторової моделі об'єкта, визначення координат характерних точок конструкції та розрахунок величини крену. За результатами експериментальних досліджень підтверджено високу ефективність запропонованої методики, яка забезпечує отримання достовірних геометричних параметрів споруди та дозволяє виконувати оцінку її просторового положення з необхідною точністю. Встановлено, що використання безпілотних літальних апаратів істотно скорочує тривалість польових вимірювань, зменшує трудомісткість геодезичних робіт, мінімізує ризики для персоналу під час обстеження важкодоступних об'єктів та знижує економічні витрати порівняно з традиційними методами інструментального контролю. Практична цінність дослідження полягає у розробленні універсальної методики геодезичного визначення крену баштових споруд, придатної для виконання експлуатаційного контролю, технічного обстеження, моніторингу деформацій та своєчасного виявлення небезпечних змін просторового положення висотних інженерних конструкцій.*

Ключові слова: *безпілотний літальний апарат (БПЛА); квадрокоптер; аерофотознімання; фотограмметрія; крен споруди; димова труба; геодезичний моніторинг.*