The automation of deflection measurements of engineering objects using a physical pendulum and mono photogrammetry

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SUMMARY

Engineering objects, e.g., dams, chimneys, etc., are subject to static and dynamic loads caused by the influence of external factors such as sunlight, wind, rain, daily or annual temperature changes, hydrological and geotechnical conditions, and - in the case of dams - also the level of water impoundment in the reservoir. Such loads invoke the occurrence of elastic or permanent deformations and displacements of civil structures. In the case of tall facilities, all that results in occurring deflections from the plumb line. Such deflections are primarily measured using physical pendulums ranked as the fundamental methods of surveying high-rise structures. Usually, they are utilized in mechanical measuring sets consisting of suspended wires equipped with a weight immersed in a tank filled with a liquid that dampens potential vibrations. As a result, the trace shifts of the suspension point relative to the reading tables located on the subsequent observation object platforms are measured. The achievements of precision mechanics and optoelectronics allow the construction of measuring devices supporting geodetic supervision at the stages of diagnosing and forecasting deformations on the tested objects. Contemporary surveying engineering and digital photogrammetry are closely linked with automated measurement technologies aimed at real-time observations. The article presents a developed device allowing for automatic registration of the vertical deflections without any accuracy losses along measured subsequent sections. The work demonstrates an experimental verification of the proposed solution, allowing for automatically registering changes in the object verticality. The main working principle relies on an electronic camera recording an image of the reference signals projected onto target plates attached to the instrument's structure. Each particular platform reflects the object's behavior. The main principle of the results' assessment is that image processing enables multiple inclination angles relative to the adopted reference plane using the known (and widely used in photogrammetry) principles of projective geometry. The results are related to the external Cartesian coordinate system XYZ.

1. INTRODUCTION

A mechanical plumbing device is used to determine deflection changes or examine the linearity of building fragments in the vertical plane. Such a method has been utilized in precise engineering measurements for many years. Mainly, it is applied in high-rise buildings or water dams. A comprehensive presentation of methods for determining the verticality of slender objects is given in an online publication [1]. It describes four main strategies: plumb-bob technique, installing spirit levels, working with theodolites, and optical plummets. Detailed descriptions of typically geodetic (surveying) methods are given in [2,3]. The problems of ensuring the straightness of erected objects are of particular importance in endangered, hazardous areas [4,5]. In addition to the mentioned cases regarding landslides or seismic regions, mining [6] or industrial terrains [7] are also noteworthy. Modern civil engineering indeed employs structural solutions to reduce the impact of adverse factors [8], adopting modern solutions and innovations [9] in the process of training specialist staff [10]. However, reliable and precisely performed measurements are essential in each of these circumstances. As presented in the publication [11], the best accurate solutions are obtained by combining various measurement technologies – in the case of deformation monitoring – metrological and physical data capturing methods.

Regarding classical approaches, utilizing instrumental solutions known in land surveying, the problem of their proper calibration becomes extremely vibrant [12]. Another operating philosophy concerns devices with the measuring principle based on optoelectronic methods [13] or image analysis and recognition [14]. Due to their versatility and susceptibility to automation, while assuring the highest accuracy, the presented methods are becoming increasingly popular. The authors' general motivation was to develop a device designed to measure even very long measuring sections along the plumb line while simultaneously recording the relevant images with an electronic camera. The image of the object's vertical changes is recorded against the reference shield's background located on the main frame. The evaluation of the results is based on the image processing with any possible angle of inclination relative to the reference plane using the principles of projective geometry commonly known in photogrammetry. The results are expressed in relation to the external Cartesian coordinate system XYZ, thus providing the relative deflection measurement of an examined object.

2. SYSTEM ASSUMPTIONS

The central element of the mechanical plumb is a string made of, e.g., stainless steel equipped with a weight adapted to its length and placed in a container filled with liquid. The measurement relays on determining the average position of the wire and defining its distance from the observed point. Observations of the wire positions expressed in the X and Y directions are carried out using reading microscopes placed on unique supports perpendicular to each other or using co coordimeters differing in design and measurement technique. Figure 1 shows the construction of a classical mechanical plumb and the principle of determining tilt changes in the vertical plane XH.

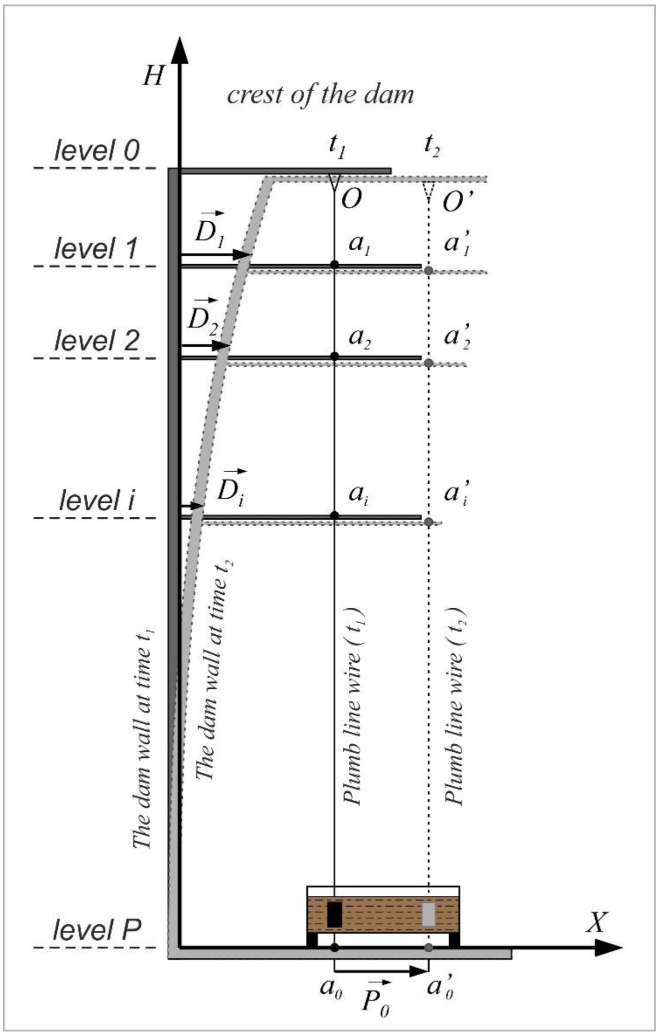


Fig 1. A schematic diagram of a weighted plumb line installation. Horizontal displacements at the subsequent survey levels

Assignments:

a_0, a_1, a_2, a_i - vertical wire position readings over time t_1,

a'_0, a'_1, a'_2, a'_i - vertical wire position readings over time t_2,

O, O' - position of the vertical suspension point in the subsequent measurement period,

$\overrightarrow{P_0}$ - plumb displacement $\overrightarrow{P_0}$ at the level of the bottom of the shaft in the time interval $\Delta t = t_2 - t_1$,

$\overrightarrow{D_1}, \overrightarrow{D_2}, \overrightarrow{D_i}$ - displacement vectors of the dam shaft's wall at subsequent observation levels in a given time interval.

The principle of determining the deflection of the dam wall over time t_i at the individual observation levels in the XH plane is demonstrated in Figure 1. The plumb is fixed at the O-hanging point, and the measuring tables are attached to the dam wall structure at the levels: 1, 2,… i. The points O and O' denote the successive positions of the vertical suspension point in time t_1 and t_2. To determine the displacement at any observation level, knowledge of the current vertical displacement $\overrightarrow{P_0}$ at the bottom level of the shaft is required. Current displacement value $\overrightarrow{D_\iota}$ on an i-level can be determined regarding the formula (1):

$$\overrightarrow{D_\iota} = \overrightarrow{P_0} - (a_i' - a_i) = (a_0' - a_0) - (a_i' - a_i) \tag{1}$$

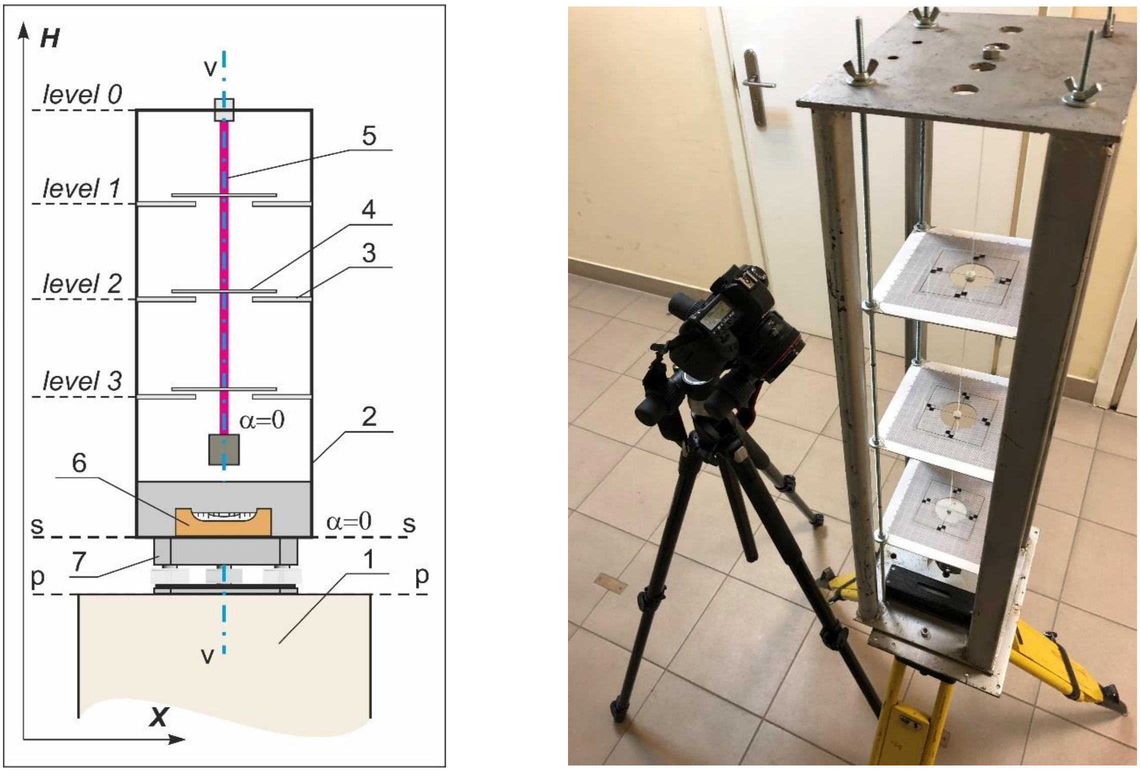
where:

a_0, a_i are the magnitudes of the initial readings,

a_0', a_i' are the magnitudes of current readings.

Readings of the initial and current position of the vertical wire at individual observation levels are made with a telescope coupled with a micrometric division.

The solution presented in Figure 2 illustrates the idea of building a model of a measuring shaft and the device built on which experimental parks were carried out.



(2.1) (2.2)

Fig. 2 Scheme of the developed measuring shaft and its prototype
(2.1 - schematic diagram, 2.2 – the prototype with a camera recording subsequent images at observation levels)

Assignments:

1. Test pillar
2. Model of the measuring shaft
3. Reference plate (reading table)
4. Control table (moving, attached to the vertical)
5. Mechanic plumb (strain)
6. Observation tabular level
7. Tribrach

α – given inclination angle

The solution presented in Fig. 2 illustrates the idea of building a model exemplifying a measuring shaft with the device attached. A Canon 5D Mark II camera [15] with a fixed focal length lens f = 50 mm was used to record images of the target plates at subsequent observation levels. Selected technical parameters of the camera are presented in Table 1.

Table 1. Summary of selected technical parameters of the camera Canon 5D Mark-II [15]

Camera type	DSLR
Matrix	
Maximum resolution	5616 x 3744 pixels
Effective pixel number	circa 21 Mpix
Matrix size	Full frame (around 36 mm x 24 mm)
Matrix type	CMOS
Connection	
USB 2.0: connects the camera to a personal computer	
Can be connected to a wireless data transmitter WFT-E4 II WiFi	
Electronic cable release	
Lens mount	Canon EF

The inclination measurement with the developed device is based on registering the reference shield using an electronic camera located at a given observation level and the controlled tray, suspended on the vertical wire near the reference shield. The reference consists of a millimeter grid, while the controlled dial has 4 symmetrically distributed measurement signals in the form of a black and white chessboard. The utilized shield forms made it possible to measure using visual readings taken on the recorded images.

2.1 Experimental work on the model

Multiple measurements of the shaft model inclinations were carried out in the stable instrument positions controlled by a precise spiritual level to verify the design assumptions and determine the visual accuracy of the surveys performed. A tubular level with a relative resolution of 0.05mm/m was used in the experimental works. The test procedure is demonstrated in Fig. 3.

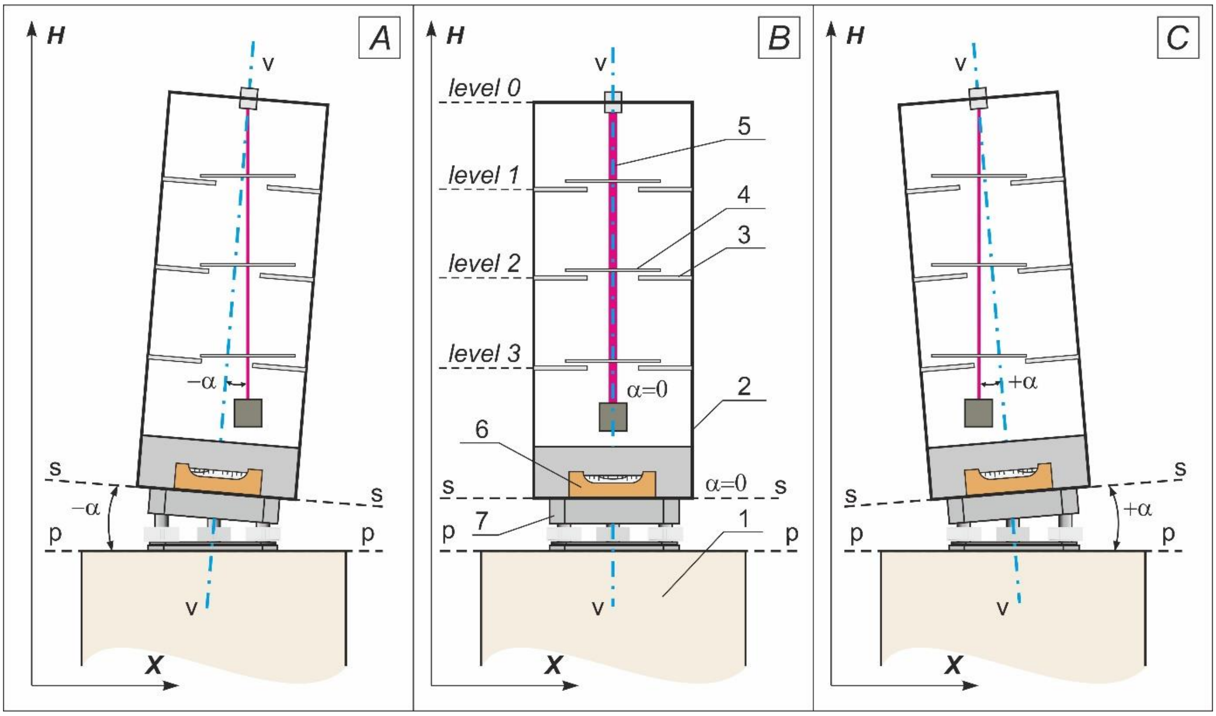


Fig. 3 Position variants of the measuring shaft model (A - at negative inclination angle (α<0); B - starting position (α=0); C - at positive angle inclination (α>0); the other assignments like in Fig. 2)

The experiments were carried out in a total of 13 fixed measurement positions. In the starting position (Fig. 3B), the axis of the shaft model was in a vertical position, and the tilt angle of the α model was 0. Subsequently, six inclinations of the shaft model were set up at a given negative angle of inclination (α<0) (Fig. 3A). Then, another six inclinations of the shaft model were fixed at the positive tilt angle (α>0) (Fig. 3C). Images for the first, second, and third observational levels were recorded at each inclination position. On the recorded images, measurements were made by visual observation of the status of two extreme signals controlled relative to the reference grid. All measurements were carried out twice. The results of the experimental work are presented in Table 2.

Table 2. Shaft model tilt values in 13 fixed positions

No.	Level	0	1	2	3	P	0	1	2	3	P	1	2	3
	Distance [m]	0.895	0.698	0.497	0.303	0.000	0.895	0.698	0.497	0.303	0.000	0.698	0.497	0.303
	Preset angular inclination with a machine level α=0.05 mm/m	Theoretical deflection value of the shaft model from the vertical at the set inclinations [mm]					The deflection value of the shaft model from the vertical at the set inclinations [mm]					Differences in deflection values [mm]		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-6·α	0.269	0.209	0.149	0.091	0.000	0.269	0.210	0.159	0.083	0.000	0.001	0.010	-0.007
2	-5·α	0.224	0.175	0.124	0.076	0.000	0.224	0.174	0.132	0.077	0.000	-0.001	0.008	0.001
3	-4·α	0.179	0.140	0.099	0.061	0.000	0.179	0.133	0.102	0.068	0.000	-0.007	0.003	0.008
4	-3·α	0.134	0.105	0.075	0.045	0.000	0.134	0.100	0.086	0.038	0.000	-0.004	0.012	-0.007
5	-2·α	0.090	0.070	0.050	0.030	0.000	0.090	0.061	0.060	0.018	0.000	-0.009	0.010	-0.012
6	-1·α	0.045	0.035	0.025	0.015	0.000	0.045	0.028	0.031	0.014	0.000	-0.007	0.006	-0.001
7	0	0.000	0.000	0.000	0.000	0.000	0.000	0.004	-0.010	-0.004	0.000	0.004	-0.010	-0.004
8	1·α	-0.045	-0.035	-0.025	-0.015	0.000	-0.045	-0.032	-0.035	-0.024	0.000	0.002	-0.010	-0.009
9	2·α	-0.090	-0.070	-0.050	-0.030	0.000	-0.090	-0.072	-0.057	-0.039	0.000	-0.003	-0.007	-0.009
10	3·α	-0.134	-0.105	-0.075	-0.045	0.000	-0.134	-0.116	-0.069	-0.044	0.000	-0.011	0.006	0.001
11	4·α	-0.179	-0.140	-0.099	-0.061	0.000	-0.179	-0.151	-0.100	-0.058	0.000	-0.011	-0.001	0.002
12	5·α	-0.224	-0.175	-0.124	-0.076	0.000	-0.224	-0.182	-0.128	-0.068	0.000	-0.007	-0.004	0.008
13	6·α	-0.269	-0.209	-0.149	-0.091	0.000	-0.269	-0.209	-0.155	-0.077	0.000	0.000	-0.006	0.014
Mean value												-0,004	0,001	-0,001
Standard deviation												±0.007		

Table 2 shows:

- in columns 3 to 7, the theoretical value of the shaft model tilt from the vertical,
- in columns 8 to 12 experimentally determined values of shaft deflection from the vertical,
- in columns 13 to 15, the differences between the measured and theoretical deflection values at individual observation levels with 13 inclinations of the shaft model set.

Based on the repeated observations at three levels and for 13 given inclinations of the shaft model, the average measuring error of the model deflection was determined ($\delta = \pm 0.007$ mm). A graphical representation of the obtained results is shown in Fig. 4.

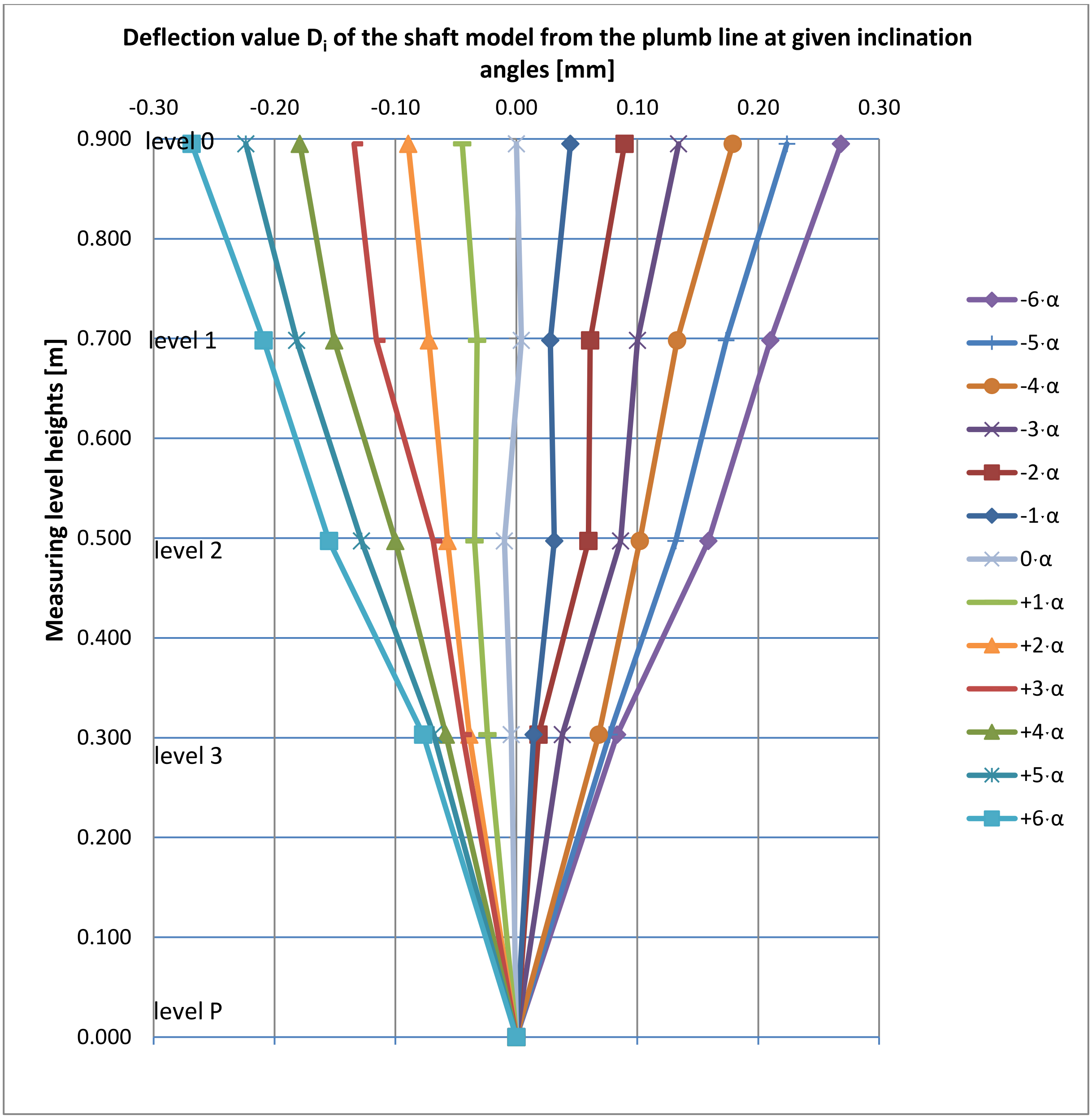


Fig. 4 Diagram of the model deflections from the plumb line at given inclination levels

3. CONCLUSIONS

The developed measuring device can be used to study the verticality of various engineering objects – for example, dams or high-rise buildings. Due to its relatively simple design and high offered accuracy, it can be widely used wherever there is a need for automated monitoring of structures in the low-cost version. In future studies, the authors plan to use reference and controlled shields equipped with coded signals in the measurements to fully automate the determination of their mutual position and determine the amount of shaft deflection at specific observational levels. It is also planned to use Leica NIVEL precise inclinometer to benchmark the results of angular measurements of shaft model tilts in two mutually perpendicular directions. Obtained readings will pose the reference values to determine and validate the proposed method's measurement accuracy.

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BIOGRAPHICAL NOTES

Piotr Gołuch is employed as a university professor at the Department of Photogrammetry and Remote Sensing, Wrocław University of Environmental and Life Sciences. Vice Faculty Dean (Environmental Engineering and Geodesy) for Civil Engineering and Geodesy & Cartography studies. He specializes in photogrammetry and its applications in surveying engineering. Author or co-author of over 80 scientific publications and conference papers. His achievements include many patents, mainly in the field of geodetic instrumentation.

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