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THE POTENTIAL OF PHOTOGRAMMETRIC METHOD OF MEASUREMENT DYNAMIC DISPLACEMENTS OF FLEXIBLE BRIDGES[1]

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Steel-ground structures are more susceptible than other bridges to the forces associated with their operation. Among the most difficult forces to measure and interpret are those which cause the occurrence of rapid movements. Electronic sensors are normally used for the evaluation of such movements, such as accelerators, distance meters, LVGT etc. Classical surveying methods make it possible to carry out precise displacement surveys using a "tracking" mode, several times per second, and these can therefore be used to study movements at a frequency of 1 Hz for a range of displacements of at least 1 mm. A higher frequency of registration, while simultaneously increasing the number of measured points, is possible using a photogrammetric method.

In the classical sense, photogrammetry is a technique for determining specific geometric features based on measurements of points on images of an object and their mathematical processing. Currently, images are made using widely available high-resolution digital cameras, allowing images to be captured at the desired distance, with good image stabilization and short exposure time.

In this paper, we present investigations using a method of measuring these rapid movements with one or more cameras and a variable number of lighting targets. This method includes the installation of lighting for the object, stabilization of the cameras, image capturing and automatic processing. Each measurement is performed using image-matching algorithms and refers to several (at least two) fixed points in the object space. This method was tested on following real objects: (1) a railway bridge during the passage of a number of trains at different speeds; and (2) a rotating footbridge. Objects were photographed using a PointGrey Black Fly camera from a distance of less than 50 m and with a frequency of 50 Hz. The results are presented in the form of two-dimensional displacement vectors of four points with a precision of ±0.5 mm. The course of the measurement and the evaluation of the results indicate the high potential of the method in studying the dynamics of flexible structures. In conclusion, it was stated that the described solution is a concept and is to serve as an inspiration for particular applications. It is now the subject of further development.

Key words: Dynamic displacement; Photogrammetric survey; Image matching

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1. INTRODUCTION

Metal-soil structures are defined as being flexible, since they are subjected to considerable strain, during both their construction and operation, resulting from a dynamic relationship between aggravating factors. They are mostly exposed to dangerous strain while being buried. They are therefore subjected to continuous monitoring during backfilling, at least by measurements of the horizontal and/or vertical movement of the crown. The measurement techniques used (and the appropriate organization of the construction) enable these to be performed in static mode. After the buried and fortified structure is complete, it becomes more stable and can be safely operated, however, heavy road or rail traffic impact the exhaustion of the construction and slowly lead to the development of threats. This is especially dangerous in relation to the unstable subsoil. Problems arising from a range of dynamic operating loads also occur in different types of bridges, which vary in their vulnerability to them.

Measurements of structures subjected to the operation of fast-changing forces are burdensome for both users and survey teams, and also require the use of equipment which operates automatically. There are several known examples of these types of measurements using electronic sensors, such as LVGT, accelerometers, distance-meters, tilt-meters and feeler gauges (Beben, 2011; Bęben and Mańko, 2005; Flener and Karoumi, 2009; Hou et al., 2005; Marques et al., 2016). Descriptions in the literature show that studies of the structures are carried out individually (one or a limited series of measurements are performed on the selected object), mostly for research rather than to ensure safety.

Today, it is becoming increasingly popular to think about building or construction in the context of its life cycle, from planning, through its design, construction, operation, demolition, and even the ultimate recycling of the materials from which it was made. Greater importance is now placed on taking care of the structure's "health". From a geometric point of view, a need arises to periodically or continuously monitor the shape of the object, and this is known as structural health monitoring (SHM).

In the case of flexible structures, SHM takes the form of cyclic measurements not only of the deflections, but also of factors affecting this "health"; these include atmospheric conditions, operating loads and the relationship with the surrounding objects. This in turn requires the consideration of future measurements at the design stage, involving decisions on the selection of sensors, their location on the object, procedures and timetables for their development, communication systems and methods of supervision of their operation. In the case of metal-soil constructions, the sensors could fulfil their task during the construction works, including earthworks as a factor which can affect the shape and stability of metal coating.

In this paper we focus on one of the methods for measuring displacements, which may, according to the authors, effectively compete with other geodetic and non-geodetic techniques. This is a *photogrammetric method*, which is a way of measuring selected geometric features based on images of the object. It has at least two indisputable advantages: 1) the uniform measurement of a large number of points; and 2) archival value. These offer the opportunity to analyse old photographs, for example in order to observe the behaviour of other, unmeasured earlier points on the object, in order to obtain new data for previously unpredictable conclusions. This work presents a photogrammetric approach for testing susceptible bridge structures, including the base geometry and organization of the proposed solutions and the results of test measurements at exemplary selected bridge structures. The results confirm the existence of these advantages, which distinguish the proposed method from other measurement techniques.

2. PHOTOGRAMMETRIC SURVEYS OF BRIDGES

2.1. Expected displacement vectors and methods of measurement

Spatial objects can change their shape or location in 3D; however, sometimes only the main components are of interest, such as the horizontal, vertical or diagonal components. According to the logic of the design, construction and diagnostics of bridges, displacements are essential for construction to take place in the vertical plane. Vertical vectors constitute the most important component, and the design and the assessment of the load-bearing capacity of bridges and their susceptibility to load are based on these. Numerous scientific studies and expert opinions confirm this principle (Jinga et al., 2008; Lacis, 2016). Similar characteristics are shown by metal-soil structures of an ovoid shape, for which the displacement vectors are in the normal direction to the shell at the location of a certain section. Characteristic locations of the section are the crown and the walls at the point of the largest span, where the key size is defined in the vertical or horizontal direction.

When planning measurements for this type of construction, a technique is required that allows reliable results to be obtained in these directions, perpendicular to the steel coating. Relative and absolute surveys can be considered here. The *relative displacement* of the crown (its horizontal or vertical shift) can be set in relation to the base (one or two points). These are very important, as they illustrate the distribution of strains at a selected point. Relative observations may cover the entire structure in a homogeneous way, if they are related to the common reference points.

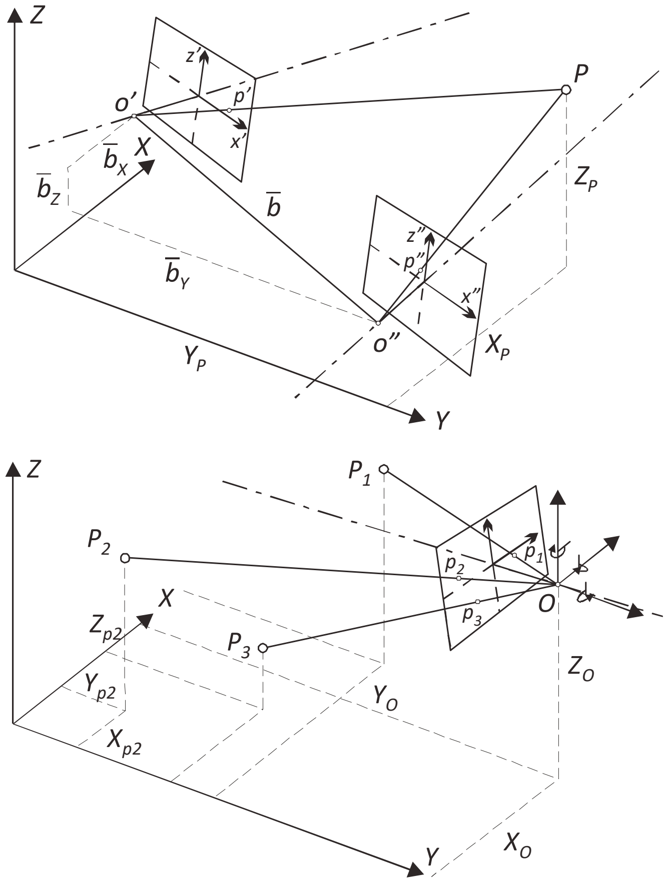
However, as a reference for measurements it is intuitively understood that the base or network of fixed points is independent of the object. Using fixed points of reference located outside the object, the *absolute displacement* of the structure (as an independent object) can be assessed. Academic debate is ongoing regarding which approach is more accurate, but engineering practice shows that more importance is given to absolute measurements. These may be solved in various ways: traditionally, using a multiple-point (at least three-point) reference network, or with reference to a single point (with external control of its stability). In exceptional cases, the position of the instrument can be taken as a reference.

Having thus defined the problem, the most attractive of the survey methods appears to be the trigonometric method, which is based on measurements of horizontal and vertical angles and distance, and allows a determination of the triaxial components of the Cartesian coordinate system. Depending on the specific behaviour of the object, stress can be calculated in terms of its components (Δx, Δy), (Δx, Δz) (Δy, Δz) or (Δx, Δy, Δz). A certain difficulty of interpretation with respect to trigonometric measurements is that the individual values are measured with different accuracies, depending on the precision of the instrument used and the impact of various external factors. Certain advantages in this respect are offered by *photogrammetry*; this has an inner precision which is nominally uniform over the entire surface of the picture. Among the possible approaches to photogrammetric development, better results can be expected at the base of *planar elaborations*, that is, parallel to the plane of images, than from spatial ones. The *spatial case* (3D vectors) requires pictures taken from various directions, and requires the object to be stable at the time of registration (with a single camera), or the simultaneous use of several cameras.

2.2. The basic rules of photogrammetry

The essence of photogrammetry involves taking pictures of the measured object in such a way that the values of the geometrical features of interest can be determined on the basis of their development. To use this in movement surveys, it is necessary to capture images periodically and to measure them using the change in position of selected points, in order to calculate the size of the displacement vectors. The selection of cameras, their location, operating parameters and the method used in signalling points depend on the ground conditions, the shape of the object and the expected characteristics of the vector displacement field. This in turn affects the form of the mathematical model used to develop the pictures.

Regardless of the specifics of the survey, the photogrammetric technique is based on a typical calculation scheme, including internal and external elements of the camera, and collections of known and measured points in the object space. The relationships between points in the image and in the space are solved based on the condition of *coplanarity* (Fig. 1a) or *collinearity* (Fig. 1b) of the homologous linear elements (rays). The distortion of the beam passing through the camera lens is also taken into account (Brown, 1971; Fu et al., 1987). This way both planar (2D) and spatial (3D) coordinates can be measured. In the case of *displacement surveys*, the result of planar elaboration is a set of vectors parallel to the plane of the image. Consequently, the result of spatial elaborations are 3D vectors.



a)

b)

Fig. 1. Two rules of 3D photogrammetric computations: a) based on coplanarity rule, where point P, its images p′, p″ and centres of projection O′, O″ lie in the same plane; b) resection based on the collinearity condition, where each terrain point P, its image p and centre of projection O are in the same line.

2.2.1. The planar case

The picture (photograph) is a *central projection* of the object space to the plane. In modern cameras, there is a mounted plate of photosensitive elements in this plane, which collects and counts the photoelectric charges transferred by the rays of light passing through the lens using a CCD or CMOS technique. The amount of energy detected corresponds to the brightness of the subject in a given place. The position of the point can be specified using the planar coordinates (x, y) or (x, z) defined by the edges of the CCD/CMOS plate (sensor) and its principal point (the position of the centre of projection).

If the object (or a part of it) is displaced, then its individual points are recorded in other locations by the sensor, and their new positions can be measured in the image coordinate system. The differences in the coordinates constitute the displacement vector of the point at the object space projected onto the imaging plane. When the camera is directed perpendicularly to the main plane of the object, then the conversion of the vector is limited to its rescaling, and in the case of oblique photographs, its rotation around the respective axes.

Planar photogrammetry has practical applications in many cases, and due to its advantages seems to be particularly useful in measuring the displacement of bridges. One modification, or extension, is the measurement of the object in several planes parallel to each other; then, to get results, different scale coefficients are required which are dependent on distance. In this case, the camera should be oriented so that the line of sight is perpendicular to the direction of movement of the observed points.

2.2.2. The spatial case

In this arrangement, images can be taken from any place and in any direction. In order to fit these into a uniform spatial system, it is necessary to select several *tie points*, which allow the calculation of a resection in order to determine the parameters of *external orientation* (EO) of the camera. In particular, this function can be assigned to other points visible in several pictures. In order to establish the scale, it is necessary to know the external coordinates of at least two points located in the object space. The coordinates (or their changes) are determined on the basis of the condition of collinearity or coplanarity of homologous rays.

2.2.3. Automation of measurements and calculations

The main limitation of the possibility to accelerate photogrammetric process is the time-consuming selection of suitable points in consecutive images. Streamlining this process requires two actions: (1) efficient selection of points; (2) automatic tracking of the changes in their positions. Generally, the first operation is performed either manually or using an appropriate signalling with intelligent search algorithms. A coded target or a specific way of lighting is typically introduced. The second step can be performed using one of the many proven image correlation algorithms (Gruen, 2012; Sutton et al., 2009).

With automatically determined points, their position is measured in the subsequent images and the calculation is carried out according to the predetermined procedure, assuming that the previously-determined coordinates are used as input for the calculation of changes in their positions. If any of the points is determined incorrectly, this procedure may be used to detect outliers and to either skip an observation or to repeat the point search and apply it in the next iteration.

2.3. The solutions used in practical applications

The applications of photogrammetry in bridge deflection surveys have been implemented for decades. Images made using special, film-based cameras were elaborated on the basis of optical observations; this was time-consuming and unreliable work. Along with the rapid development of digital photography, new opportunities for photogrammetry arose and a number of studies started to appear. These have also been applied to bridges, and a brief review of these applications was completed by Jinga et al. (2008). These authors summarized their survey in a table listing the major aspects of bridge measurement applications between the years 1985 to 2003. In Table 1, several applications are shown with their authors. The headings include types of measurement, cameras, targets, network control and software.

Table 1. Applications for bridge deformation surveys (selected from Jinga et al., 2008)

Researcher	**Test object**	**Type of measurement**	**Target and type of photography**	**Camera used**	**Network control**	**Software used**
Bales (1985)	Reinforced concrete deck	Crack length and width	Diffuse targets, non-flash photography	Zeiss UMK 10/1318, metric film camera (100 mm lens)	Control point survey	Stereoscopic comparator
Bales and Hilton (1985)	Steel I – beam	Vertical deflection	as above	as above	as above	as above
Kim (1989)	Highway bridge	Long-term deformation monitoring	Diffuse targets, non-flash photography	Metric film camera (150 mm lens)	Control point survey	Self-developed
Cooper and Robson (1990)	Steel bridge	Deformation	Retro-reflective targets, flash photography	Zeiss UMK 10/1318 metric film camera (100 mm lens)	Control points	Intermap analytical comparator
Forno et al. (1991)	Arch bridge	Deformation	Retro-reflective targets, flash photography	Zeiss UMK-10 N metric camera (2.1 m lens)	Control points	Microscope
Albert et al. (2002)	Reinforced concrete beam	Vertical deflection	Diffuse targets, non-flash photography	Kodak DCS660 digital camera, machine vision camera (24 mm lens)	Distance measurement between targets	Ellipse operator
Leitch (2002) Jauregui et al. (2003)	Steel beam	Vertical deflection	Diffuse targets, non-flash photography	Kodak DCS660 digital camera (28 mm lens)	Control point survey	FotoG

Among other authors, Abdel-Sayed et al. (1990) suggested the use of a camera for the deformation monitoring of soil-steel bridges. Their aim was to determine the cross-sectional shape of the metal conduit at certain locations and to assess deformations through periodic monitoring. Camera stations were located inside the construction, and 6 mm diameter retro-reflective circles and two scale rods (horizontal and vertical) were used as targets. The evaluated accuracy of the method was 2–7 mm for a structure with a span of 4 m.

Valença et al. (2008) describe the use of photogrammetry in the on-site monitoring of a pedestrian bridge during load-tests. The proposed methodology was validated by comparing the obtained results to values measured with LVDT. It was concluded that photogrammetry can be used in structural monitoring without losing accuracy, and that it exhibits additional advantages in relation to traditional methods.

Özgür et al. (2014) undertook work to implement photogrammetric techniques for monitoring the bridge over the Bosphorus in Istanbul. Points signalled by LED lamps were photographed with three digital cameras located on one bank of the Straits. The authors used cameras with a 1/4" CCD matrix and a pixel size of 7 μm. Points spaced up to 150 m from the shore were obtained with accuracies of $RMS_y = \pm 20$ mm and $RMS_x = \pm 14$ mm. These results appear to be insufficiently accurate.

Jiang and Jauregui (2010) proposed a photogrammetric bridge deflection surveying system which consists of a Kodak CCD or CMOS high-end digital camera, retro-reflective targets, an RDC network control method, and camera placement options from two elevations on one side of a bridge, or from one elevation but from both sides of the bridge. Based on the laboratory and field results, using comparisons with a dial gauge and differential level measurements, it was shown that the system yielded differences from the other methods of between 1 and 2 mm.

Marques et al. (2014) monitored a 100-metre, three-span steel rail bridge using strain gauges installed over the pillars. A camera was used to measure deflections of spans; image capturing was triggered via a button on the rail, which was activated by oncoming trains.

The laser optical system PSM 200 and (independently) a motion-sensitive camera were used by Lacis (2016) in the structural monitoring of a timber-concrete experimental bridge. A laser installed perpendicularly to the bridge was oriented in a longitudinal direction towards the middle of the timber beam. The authors point out the advantages of the high precision (resolution 0.01 mm) and high frequency (up to 500 Hz) of the system. The drawbacks include the observation of only a single point and a lack of stability control. In contrast, a camera can measure more points, in addition to the control points. The captured images can be sent wirelessly, although this requires a more sophisticated development.

Similar work has been carried out in relation to other objects such as dams (Fryer and Bartlett, 1989; Kersten and Maas, 1995) and tunnels. Studies concerning dams were based on 3D photogrammetry; the problem involves covering this large object with images. Scaioni et al. (2014) discussed an image-based approach called ‘photogrammetric levelling’ as applied to the measurement of deflections of the tunnel. This was based on the metric rectification of each single image, depicting a couple of special rods to be hung on levelling benchmarks.

Green (2012) investigated the important problem of the automatic selection of points in pictures and matching them with consecutive shots. His work takes the form of a review and highlights the possibilities in this field.

In conclusion, it should be noted that since the establishment of digital photography, investigations have been carried out by many authors to apply this to the measurement of bridge deflections. The examples illustrate the high hopes which exist for the widespread use of photogrammetric studies in this area. An open field of activities is still the quasi-continuous monitoring of bridges subjected to dynamic loads. This issue is the topic of research of this work.

3. THE APPLIED SOLUTION

3.1. Camera, lenses and computer programs

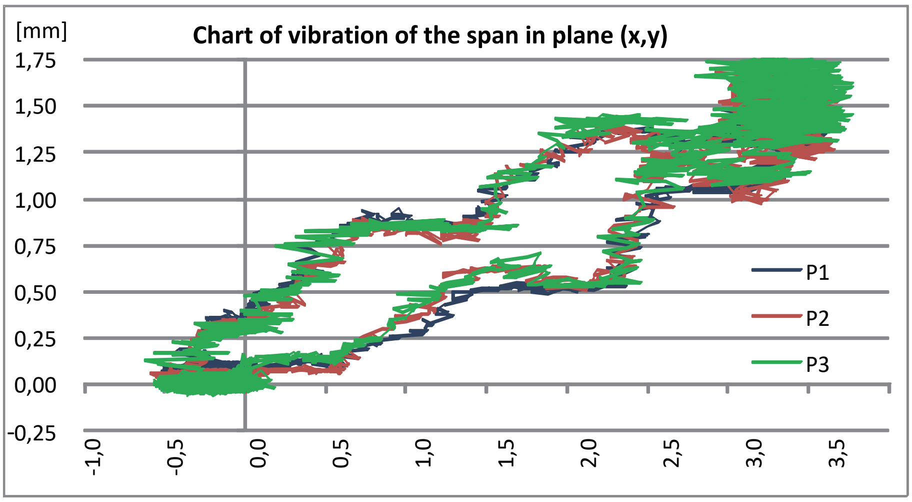
For the purposes of measuring a bridge, a procedure was developed involving the selection of a camera and lens, a method of signalling points, the manner of recording, and the method of calculation. Due to the novelty of this work, it has been limited here to a single-camera scheme and the measurement of 2D displacements in planes parallel to the imaging plane. A PointGrey Black Fly camera was selected; this has a CMOS 2480×2048 matrix and a pixel size of 5.5 microns. The camera has a central shutter and an image stabilizer, and any lens with a one-inch C mount can be attached to it. The focal length of the lens depends on the dimensions of the object, lighting and shutter speed.

The camera has a USB port to be connected to a laptop or modem. An existing control program was used which allows the user to view the shooting space and to limit this to a smaller area, to set the parameters of the image (focal length, focus, aperture, shutter speed, white balance and ISO rating) and to determine the frequency of shooting. It can start and stop recording at a given moment, sending the acquired images to the computer's memory. Another program searches the points in the initial image and then selects the same points from consecutive images with sub-pixel accuracy. The scale of the development is calculated based on the set of external coordinates and the displacement of each point is converted into the object space based on the local scale. The results of calculation are visualized in the chart and transferred to a spreadsheet for further analysis.

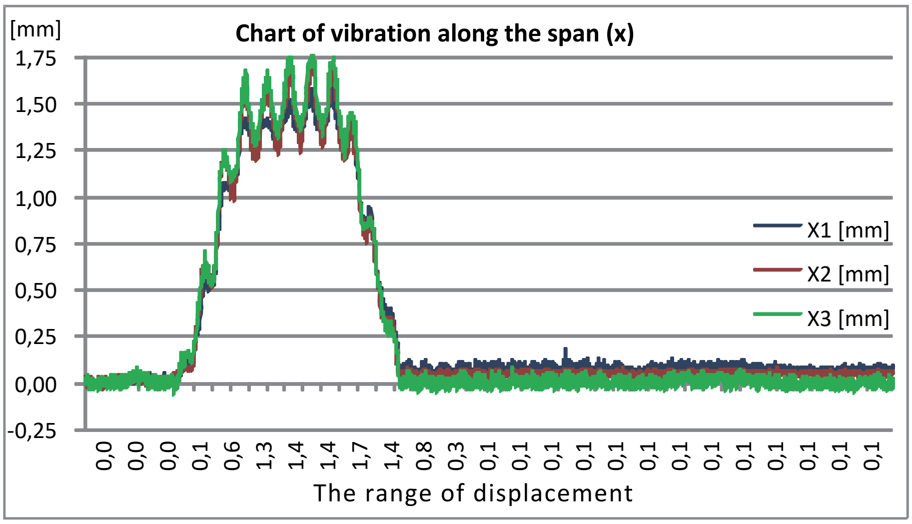
A method of signalling points using LED lamps is applied. Lamps are mounted on the structure using magnets or by gluing. At this stage, lamps are switched manually, but in the future these could be started using commands from a computer. The starting location of the lamps is measured by total station.

3.2. First attempts in the application of this method

The first bridge measured using the proposed method was a bridge on the high-speed railway route. Photogrammetric survey was performed in conjunction with other techniques. The station of the camera was located under the bridge, and the points were signalled using four LED lamps facing downwards at a distance of 8.1–9.0 m from the camera. Their location was measured by Leica TCRP1201+ total station. Due to the camera's orientation, there were no points of reference.



a)



b)

Fig. 2. Selected graphs showing photogrammetrically registered vibrations of a steel bridge: (a) in the plane; and (b) along the bridge

A lens of focus length75 mm, aperture 8 and time exposure 1:1000 were used, so that the image of the object was very obscured (underexposed) and the LEDs could be clearly seen. During the passage of a train, the bridge was photographed at a frequency of 50 Hz.

In the first image, the positions of the lamps were localized, numbers were assigned to them and the distances from tacheometric survey were calculated. In successive images, the program localized the lights and their image coordinates were calculated. Displacements were calculated from the coordinate differences, which were converted into field values. Next, graphs of the displacements over time were prepared. Figure 2 illustrates a graph of the 2D horizontal movement of three points located in the middle of the bridge span (left) and their components along the span (right). The similarity of these three graphs indicates the high repeatability of the results.

The second test object was a rotatable footbridge. The camera was installed on the axis of the rotation mechanism, filming the end of the footbridge. One pair of lamps was installed at the end of the bridge (the hooks of the last shrouds) and the second pair in the coupling of further shrouds. Figure 3 shows the raw image of the LEDs mounted on the footbridge (Fig. 3a), and one of the charts of the vibration of the footbridge that occurred during its movement (Fig. 3b). It is possible to draw conclusions about the behaviour of the footbridge based on the graph, rather than on the basis of static measurements.

a)

b)

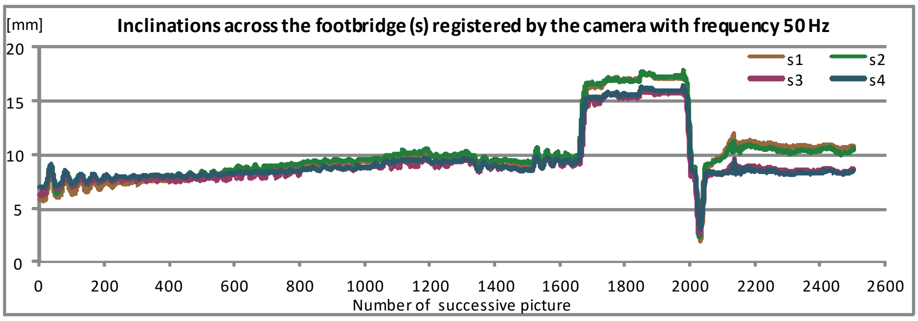


Fig. 3. Graph of inclinations across the footbridge during partial rotation: a) the original image with locations of LED lights; b) the example of the illustration of measured displacements of points s1–s4

3. FINAL REMARKS AND FUTURE WORKS

The aim of the study described here was to present the solution that can be effectively used in measuring the flexible structures under load. The solution is so versatile that it was used in other measuring tasks. In this work, its proven and potential opportunities were indicated and adaptation for measuring flexible structures were proposed.

The examples of applications discussed here, both in the literature and developed by the authors, provide information about the enduring vitality of this technology in surveys; they also show its potential opportunities. The paper discusses the idea of photogrammetric method for measuring displacements of flexible structures. Geometric bases for development of image coordinates were indicated and a solution based on dynamic registration of points marked by LED lighting were proposed. The run and results of two preliminary test measurements were briefly presented, which are the basis for further development. Descriptions of research and the results presented in the article are only confirmed illustration of the possibilities of the proposed solution.

The technical studies described above form the basis of a preliminary stage, which in the future should result in further automation of the process. There is also an ongoing work on increasing the efficiency and reliability of pre-sented technique, with particular emphasis on the uncertainties of measurement. A research project concerning those investigations have been submited. Its aim is to automatically elaborate images from several cameras operating synchronously, including automatic tracking of points in the pictures, the calculation of displacements and remote signaling of potential dangers.

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