PROTOTYPE OF THE VISION SYSTEM FOR DEFLECTION MEASUREMENTS

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Summary

The vision-based method of civil engineering construction's in-plane deflection measurements was developed. Displacement field of the analyzed structure resulting from load was computed by means of digital image correlation coefficient. The application of homography mapping enabled the deflection curve to be computed from two images of the construction acquired from two distinct points in space. The shape filter and rectangular marker detector were implemented to provide higher level of automation of the method. There are discussed developed methodology, created architecture of software tool as well as experimental results obtained from tests made on lab set-ups.

Keywords: digital image correlation, image registration, vision systems, deflection measurement.

PROTOTYP SYSTEMU WIZYJNEGO DO POMIARÓW UGIĘĆ

Streszczenie

W pracy przedstawiono opracowany prototyp systemu wizyjnego do pomiarów dwuwymiarowych deformacji konstrukcji. Pole przemieszczeń analizowanego obiektu, powstałe pod wpływem działających obciążeń, wyznaczono przy pomocy znormalizowanego współczynnika korelacji. Zastosowanie przekształcenia homograficznego umożliwiło wykonanie pomiarów ugięcia konstrukcji na podstawie jej dwóch obrazów zarejestrowanych z dwóch różnych punktów przestrzeni. Zaimplementowany filtr kształtów oraz detektor znaczników referencyjnych umożliwił zwiększenie automatyzacji procesu pomiarowego. W artykule przedstawiono opracowaną metodykę, architekturę stworzonego oprogramowania oraz wyniki testów eksperymentalnych systemu na stanowisku laboratoryjnym.

Słowa kluczowe: korelacja obrazów, nakładanie obrazów, systemy wizyjne, pomiary ugięcia.

1. INTRODUCTION

Structural Health Monitoring methods can be divided into two main categories: local methods and global methods. The latter are applied if a global change in the geometry or motion of a structure under the loads can be observed. On the other hand, local methods make use of the physical phenomena acting locally within a small area of the construction. Vision-based techniques belong to the group of contactless global SHM methods which enable global measurements of static deformations as well as dynamic processes to be carried out. They allow damage detection to be performed by means of a change in the geometry of a structure analysis, such as deflection curve or mode shapes of vibrations. In diagnostics of civil engineering structures, displacements' measurements are the major aspect of constructions' static states and dynamic characteristics evaluation. In this area, the analysis of deflection shapes of structures has become more significant and accurate than other methods of the analysis [1-6].

Nowadays, the increase of availability of vision systems for the measurement of motion and three-dimensional geometry of objects is noticed on the world markets. However their number is still small in the field of measurement of deformations and low-frequency vibration of structures.

In this paper, the developed prototype of vision based system, for in-plane measurement of civil engineering structures displacement fields' is presented. The system provides monitoring of static states of civil engineering constructions such as displacements, deflections and deformations. The system consists of one or more high resolution digital cameras mounted on a head or on portable tripods, the software embedded in MS-Windows operating system, lighting system and the set of special markers placed on the construction. Calibration patterns which enable computation of the scale coefficient and lens distortions are also parts of the system.

Deflection curve is obtained from two images of the construction: reference one and the one acquired after application of a load. The principle of the method is calculation of object's points displacement by means of normalized cross correlation coefficient. Image registration techniques were introduced in order to increase flexibility and accuracy of the method. Perspective distortions of the construction's image are removed by means of homography mapping, which allows two photographs of the object to be taken from two distinct points in space. In order to calculate correspondences between matching features on both images, new technique of markers detection and shape filtering, as well as sub-pixel corner detection are introduced.

2. VISION MEASUREMENT SYSTEMS CURRENTLY AVAILABLE ON THE MARKET

Nowadays, there are a lot of optical systems for three-dimensional structure and motion measurements. These systems allow for considerable shortening of a time needed for carrying out phenomena analysis, as well as getting three-dimensional structures of inspected objects. In this paper, optical measuring systems available on the market were listed, their most important features were described and they were divided into groups on account of the principle based on which they operate. The most important companies offering vision measurement systems existing at present on the market are: Correlated Solution, GOM, LIMESS Messtechnik & Software, Dantec Dynamics, Metris (Krypton 9000) [7-24].

There are following systems for the measurement of three dimensional motion available: PONTOS/TRITOP (GOM), Vic 2D/Vic 3D (Correlated Solution/LIMESS). Accuracies of these systems vary in the range from 1/50 to 1/100 pixels, whereas sizes of measured object depend on the configuration of the system: from a few mm up to 10 m. Available frequencies of images acquisition are in the range from a few to a few hundred thousand frames per second, depending on the used resolution and the field of view. For example in the PONTOS system, carrying out measurements requires placing special markers on examined structures. An acquisition of vibration of the structures with the help of the pair of high-frequency cameras is the next step of the measurement. A course of the displacement of particular points of the object is the analysis result.

The systems PONTOS ARAMIS/ (GOM), Vic 2 D/Vic 3 D (Correlated Solution/LIMESS) or Q- 400 - II (Dantec Dynamics) can be applied to measurements of displacements, deformations and stresses of the structure. ARAMIS (GOM) is an example of systems of this type, which enable analysis of the deformation and stresses of objects with complicated geometry, deformed under the load. The system uses the method of three-dimensional correlation and high resolution digital cameras. A stochastic or regular pattern is placed on the inspected structure. The object under the load is observed by one or more digital cameras. The visualization of three-dimensional deformations of the structure is obtained as a result of the analysis.

Systems ATOS, TRITOP (GOM), and 3 D-Cam (Correlated Solution/LIMESS) are used in the reverse engineering for the measurement of the three-dimensional shape of objects. ATOS is the active vision system, which means that a shape of the light pattern projected onto the examined surface is analyzed. The scanner works on the principle of a triangulation, two cameras are observing courses of stripes on the measured detail which enables three-dimensional coordinates of all points of interest to be determined. Measurements requires placing round markers with a known diameter on the analyzed structure. In the next step, the prepared object is registered by a photogrammetric camera from a few different points of view. The software allows for finding coordinates of all markers.

Three-dimensional measurements of geometry using three cameras are carried out by the following devices: Krypton of K series (Metris) and OPTIGO (Cognitens). Krypton system uses 3 linear cameras, additionally it has a possibility of tracking the markers put on the structure, whereas OPTIGO uses 3 matrix cameras for the measurement of a geometry. Active interferential techniques are offered by systems: ESPI SD-30 / SD-10S systems (GOM); Shearwin NT (Correlated Solution /LIMESS), or Q-810 (Dantec Dynamics) can be applied for the measurement of the deformation. Measurement methods are based on phenomena of interference and they concern little objects [7 - 24].

3. MEASUREMENT METHOD

The method of non-contact measurement of civil engineering constructions' in-plane deflection consists of three major steps [1-4]. In the first step, a rectification [25],[26] of images acquired from distinct points of view, not coincident with the reference one which can be chosen by an user, is performed by means of homography matrix **H**. In the following step, the deflection of a construction is calculated using the normalized cross correlation coefficient (NCC). Sub-pixel feature detection techniques were introduced in order to increase the accuracy of the measurement. In the final step, the scale coefficient is computed with the help of a circular intensity pattern with a known diameter. The developed algorithm is presented on figure 1.

Image registration [30] is a method of stitching two or more images taken at different times, from distinct points of view or by using different imaging devices. In this work, homography mapping was introduced to align two images acquired from distinct points of view.

Image rectification [1-4],[25],[26] is a process of projective distortions reduction by means of homography transformation. Four pairs of coplanar corresponding points are sufficient for the computation of matrix **H** if none three of them are collinear.

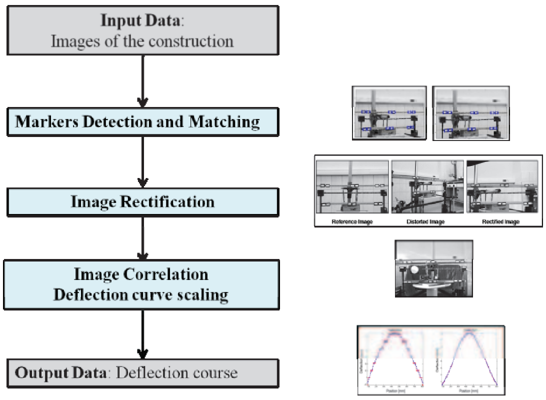

Fig. 1. Developed algorithm of the in-plane deflection measurement

The set of corresponding points used for the homography computation consist of vertices of rectangular markers, which are placed on the structure. Markers must be coplanar with the plane of the construction and can't change their position as it deforms [1-4]. Coordinates of the corresponding points on both images are calculated by automatic corner detector. In the first step, rectangles are detected on images by means of contour processing and shape filtering methods. Exact positions of each of markers' vertices are determined by the sub-pixel improvement of the detector. Vertices' positions are expressed in polar coordinates in the coordinate frame with the origin at the center of mass of markers' set. Markers are sorted by comparison of their corners' polar angles and distances from the origin. As the alternative for the aforementioned method of feature matching, image patch correspondence matching based on binary codes recognition has been developed. When the homography mapping between two images of a construction is calculated, projective distortions of the particular plane of the object are removed from the image.

The normalized cross correlation coefficient [25,26] (NCC) is applied for the computation of the in-plane displacement field. In the developed method, the reference image of unloaded construction is divided into intensity patterns whose position are computed by means of the NCC coefficient. The displacement vector for each of the measurement points is computed as a difference between positions of the pattern on two images of the construction: taken before and after application of a load. [1-4].

In order to express a deflection curve in metric units, calibration of the system is necessary. It is performed by a circular intensity pattern with a known diameter. Optionally, full camera calibration is performed in order to obtain intrinsic parameters, which are necessary for reduction of radial and tangential lens distortions [1-4].

4. FEATURE POINT DETECTION AND MATCHING

The higher level of automation was provided by development of novel markers' detection and matching algorithm. Two sets of rectangles are detected on two images by means of binary image processing, contour detection and shape filtering. The set of corresponding points positions necessary for homography computation, consisting of vertices of rectangles, are calculated by Harris corner detector with a sub-pixel improvement of the accuracy. Markers are expressed in polar coordinates and sorted with respect to marker set's center of the mass.

The binary image I of resolution M by N is the image which consist of two kind of pixel areas: A – the foreground and B – the background where A and B are two sets of pixels defined as [27-29]:

$$A = \{(x, y) : 0 \le x \le M, 0 \le y \le N \ \ and \ \ I(x, y) = 1\}$$
$$B = \{(x, y) : 0 \le x \le M, 0 \le y \le N \ \ and \ \ I(x, y) = 1\} \quad (1)$$

Let D_8 be the 8-neighbourhood [27-29] of a pixel p_i = (x,y). A closed contour (or a boundary) of a foreground region A on a binary image is a set of pixels defined as follows:

$$cc = \{p_{i=1,2,...,n} \in A : (\forall p_i \exists p \in (B \cap D_g(p_i)) \ \ and \ p_i = p_N)\} \quad (2)$$

The first step of the algorithm is binarization of a grayscale image. The threshold value is obtained by analysis of an intensity histogram of an image. In the next step, contours enclosing all foreground object are detected [27-29] on both of images. Contours are transformed to the chain polygon representation in which only endpoints of the line elements approximating the contour are stored. In the case of the implementation of the method in described software, the set of points consist of vertices of rectangular markers. Contours are filtered by the shape filter whose response is the strongest for convex, rectangular contours with user defined ranges of: area enclosed by the boundary, width to height ratio and angle between sides of the quadrilateral. Obtained vertices positions are refined by Harris corner detection algorithm with the sub-pixel accuracy improvement. The example of application of the method is illustrated on figure 2.

It is assumed that there is no rotation about the optical axis of the camera coordinate frame from which the reference image was obtained. In the first step, the center of mass of set of markers' vertices is computed. The calculated point becomes the origin of the new coordinate frame. All of the points have to be expressed in this new coordinate frame in the polar representation. Next, the sorting of points is performed. Points' polar angles and radial distances from the origin are input to the comparison function passed to the sorting algorithm. The sorting is carried out on sets of markers on both images of the construction.

Fig. 2. Example of the application of rectangle detection algorithm

In the second method, the position and orientation of the camera is not constrained by the requirement of no rotation described above. The image patches which are matched on two images are coded markers. The marker consists of N rows and N columns of small squares arranged in chessboard-like pattern. Each of the squares can be black which represents logic 1 or white which represent logic 0. The innermost 2x2 pattern of the marker is the same for all markers and resemble letter ‘L’ (see figure 3). The outer part of the chessboard pattern is different for each marker and encodes the number. The position of each square marker on the image is detected by means of algorithm described previously. Next, the homography mapping is applied to remove the perspective distortions from the image of the marker. Image patch is rectified using data from marker model which is specified by the user. The marker orientation is decoded from the innermost ‘L’ shaped pattern of the marker. In the last step, the image patch is encoded as N x N array of logical values. In the pattern matching step, actual images of markers are not compared with each other, but instead their code representations are. The process is much faster than image pattern matching methods.

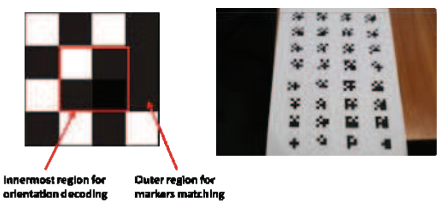

Fig. 3. Example of marker used for pattern matching and set of markers on real photograph

The matching of markers by means of their code representations’ comparison can be applied in problems like image rectification, image registration method (image stitching, mosaicing) as well as in 3D structure and motion reconstruction techniques based on epipolar geometry [25,26] and fundamental matrix (corresponding set of points needed for F matrix computation can be encoded as the chessboard pattern markers).

5. DEVELOPED SOFTWARE

The main purpose of the software is construction’s continuous monitoring and diagnostics. As a standalone system (operating in on-line mode) can immediately evaluate changes of static states of structure and send them to a diagnostic center.

Application provides advanced operations on camera devices like live preview mode or remote modification of camera parameters. System's IO Handler module allows multiple picture acquisition devices to operate in the real-time. Application supports popular SLR cameras with available driver libraries used for device management from system.

Calibration module (figure 4) allows calculating calibration data based on images of a planar chessboard pattern with a known geometry (odd row and even column count). Calibration process results contains intrinsic and extrinsic camera parameters. Calibration data is necessary for identification of camera's position and orientation with respect to the examined object. The intrinsic camera parameters can be used for reduction of radial and tangential distortions from acquired images.

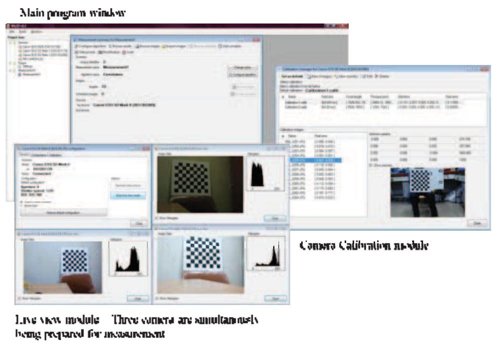

Fig. 4. Software modules: main window, live preview, camera parameter setting module and camera calibration module

Camera configuration is accessed and modified from configuration window. Common modifiable camera parameters consists of shutter speed, aperture value and ISO speed. Configuration window provides also specific camera parameters: live view zoom and information about battery level. Enabling live view mode allows quick check on how modified parameters affect camera’s work. It’s possible to store camera configuration. Such stored configuration can be loaded into camera manually or automatically after connection (depending on settings).

The developed software tool provides a high level of measurement process automation, accomplished by automated operations like image acquisition, image preprocessing and algorithm calculation (Figures 4,5). Although the system is suitable for online work using data acquisition devices, it's also possible to perform offline measurements using existing images.

Correlation algorithm provided with software tool is fully customizable: user can modify start/end point for measured line on calculated images, search window size and window count. During configuration it's possible to test algorithm on measurement images in order to fine-tune algorithm parameters. User can make algorithm work automatically whenever new image has been added to measurement. This feature combined with possibility of creating scheduled sequences of picture taking makes it possible for software to automatically execute data acquisition and calculation.

Rectification algorithm provides functionality on generating perspective transformation for images based on image markers' location on image. In rectification window user can modify rectification parameters and see preview images: original image, original image with drawn image markers' locations, transformed image and reference image. Rectification parameters are stored in the measurement configuration.

Scale algorithm is used for converting pixel values into real length unit. In order to calculate scale coefficient user has to load image containing circular marker and provide information about its size. After scale coefficient has been calculated, analyzed images results will be shown in millimetres instead of pixels.

The system warns the user when a critical level of measurement estimates has been exceeded. A message is sent by e-mail or text message. It's possible to send data to external monitoring and diagnostics systems using TCP/IP. Data generated by the application can be exported to external data sheets in popular formats e.g. Excel spreadsheet, PDF and HTML

The software architecture is shown in figure 6. The drivers (DRV) are the modules that provide data acquisition from cameras: configuration, remote picture taking and downloading. Drivers are coordinated by an IO Handler (IO HDLR) responsible for device data transfer synchronization to ensure no conflicts in the driver's work. The data processor (DATA PROC) performs all image calculations such as vision algorithms and preprocessing methods. The database server (DBS) is used for storing various project data – downloaded images, algorithm results and configuration. The limit checked module (ALM) checks if measurement estimates are within allowed limits. The messenger (MSGR) is responsible for sending messages when the estimate crosses limit values. The configuration server (CFGS) is a separate storage module used for storing system configuration. The watchdog (WDG) controls a system's performance.

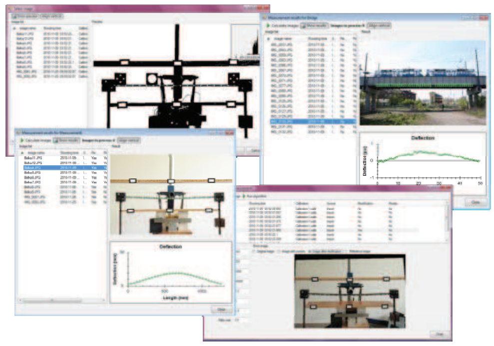

Fig. 5. Software modules: Measurement module, rectification module, image correlation module and result browsing module

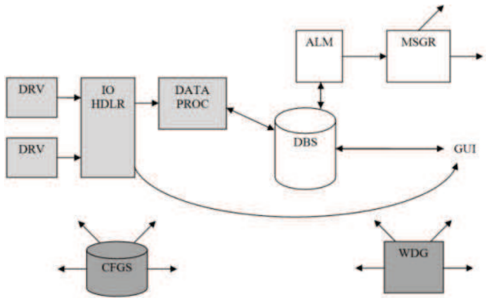

Fig.6. Software Tool Architecture

6. LAB TESTS OF THE DEVELOPED SOFTWARE

In the first examination, the system performance was tested on the lab-setup consisting of steel frame fixed at one end, loaded by the single weight (Figure 7,8). The point of application of the force could be moved along the length of the vertical part of the frame which provided variable loading conditions. Two digital SLR cameras Canon EOS 5D Mark II with a lens with Canon 24-70mm f/2,8L zoom lens with 50 mm focal length adjustment were placed in two points on the scene. The first one was positioned in such a way that its optical axis was perpendicular to the construction's plane. The second one was placed at the same distance from the construction as the first one, but its orientation was changed – the angle between its optical axis and the direction perpendicular to the frame's plane was 50 degrees. During the investigation, the load was moved along the length of the vertical part of the frame. The set of its positions (d [mm]) has been presented in table 1. For each of the load positions, 30 images were captured by both cameras. The mean value of the measured maximum deflection (in free endpoint of the beam) and its standard deviation were computed for deflection curves obtained by both cameras, for each of the positions of the load. The difference between the corresponding values of statistical parameters (mean value of maximum deflection) calculated from the data captured by the first camera and the second one was a measure of the error introduced to the system by the rectification algorithm. Additionally, the noise of the method resulting from the lighting conditions as well as inaccuracy of correlation algorithm were investigated. The scale coefficient value in the examination was 0.174 mm/pixel.

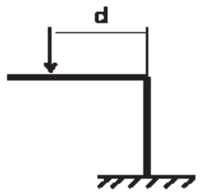

Fig. 7. The lab set-up

Fig. 8. The photograph of the first lab set-up

In next experiment, the developed software was tested by performing the continuous vision monitoring of the structure under the load. The wooden beam of the length of 180 cm supported at two ends was inspected construction (figure 9). The beam was loaded by a point force acting in the middle of its length. There was no artificial speckle pattern on the plane of the structure, natural texture of the material was used as an intensity pattern in correlation method. The measurement was verified with the help of the laser distance sensor Disto D5. The conducted experiment was divided into continuous measurement sessions of 30 photographs, separated by 10 minutes breaks. The continuous change of the deflection in the point of maximum deflection during investigation was observed (figure 13). It was confirmed on the basis of the measurement with the laser distance sensor.

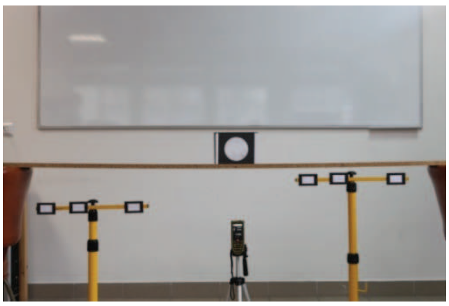

Fig. 9. The photograph of the second lab set-up

The position of the camera with respect to the construction as well as its orientation were changed during the investigation. The measurement of the noise of the method was carried out to examine the influence of the lighting conditions on the method. The digital SLR camera Canon EOS 5D Mark II with Canon 24-70mm f/2,8L zoom lens with 45mm focal length adjustment was used. There were no artificial lights present on the scene. The measurement points from which images were acquired are shown on figure 10.

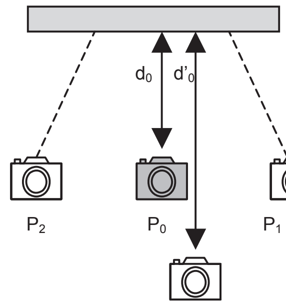

Fig. 10. The points of space from which images were acquired

7. RESULTS OF THE EXAMINATION

In the first examination, the mean value of the noise of the method for the natural lighting conditions was 0.002 mm (0.015%). For the images captured from one point in space, the standard deviation of calculated displacement value in the point of maximum deflection (repeatability of the method) was not affected by the change of position of the load and had value about 0.004 mm. Introduction of the rectification algorithm increased the error of the method. The maximum value of the difference between displacement calculated from the reference point and from the second position was about 0.15 mm. The relative error induced by the rectification calculated as the ratio between difference Δx (table 1) and the displacement computed from the reference image was in a range between 0.001% to 0.2%. The results of the examination are shown in the table 1. The examples of curves of deflection for different positions of load are presented on figure 10.

In the second experiment, when there was no artificial speckle pattern on the object because of that value of the measurement noise (its standard deviation obtained from a series of 30 images) of the method induced by variable illumination condition turned out to be 0.04 mm (Fig. 11). The standard deviation of the measured value of the deflection in the point of maximum deflection was 0.03 mm for the case of the images acquired from the same point in space, however the standard deviation of the measurement after application of rectification reached value of 0.19 mm.

Table 1. The results of examination. The first column – position of a load with respect to the fixed end of the frame (Figure 10). The columns 2 - 5 – results (mean value from 30 images and standard deviation) of deflection computation in point of maximum deflection for camera 1 and 2. The column 6 – difference between results obtained from two cameras, in mm, column 7 – the relative difference with respect to the first camera, in percents.

	Camera 1		Camera 2			
d[mm]	mean	std	mean	std	Δx	Δx%
-	0.002	0.003	0.012	0.092	0.119	-
550	18.306	0.003	18.147	0.105	0.159	0.008
360	10.794	0.005	10.686	0.089	0.108	0.01
200	4.114	0.004	4.138	0.093	0.020	0.005
600	20.937	0.004	20.907	0.129	0.030	0.001
-	0.002	0.005	0.011	0.093	0.109	-

Results of measurement are shown on figure 12. In figure 13, an increase of the average value of beam's displacement in the maximum point of deflection resulting from the increasing deformation can be noticed. In figure 14, the change of the standard deviation resulting from application of the rectification algorithm was shown.

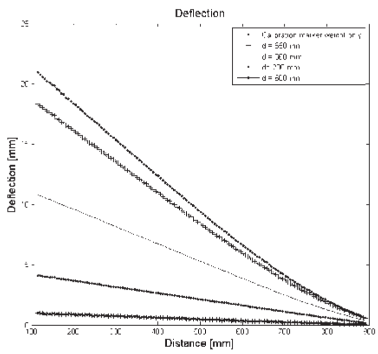

Fig. 10. Deflection courses for different cases of the loading (table 1). Results obtained from the reference camera

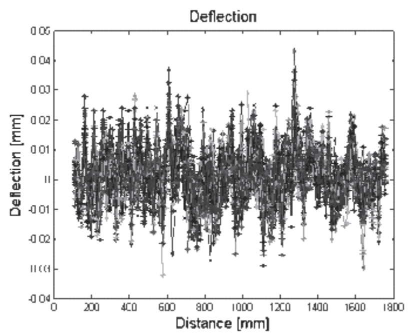

Fig. 11.The noise of the method in the case of object without artificial speckle intensity pattern

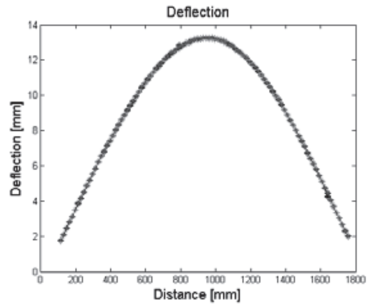

Fig. 12. Deflection curve family (from 30 images) calculated from images acquired from the Point P_0

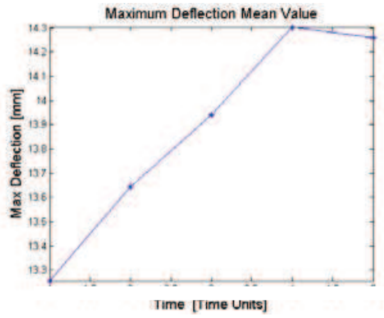

Fig. 13. Increase of the mean value of the displacement in the point of maximum deflection. Time interval between each point is 10 minutes.

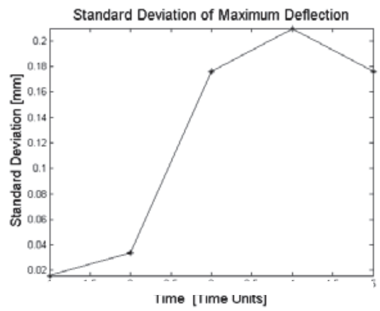

Fig. 14. Increase of the standard deviation of the displacement values calculated from the series of 30 images after application of rectification. Time interval between each point is 10 minutes

8. CONCLUSIONS

SHM vision-based measurement system enables structure static and quasi-static states assessments during inspections and on-line continuous state monitoring to be performed by means of analysis of changes in the geometric properties of the structure, such as a shape of the deflection curve. The introduction of image registration techniques has improved the flexibility, universality and accuracy of this method. The technique of in-plane deflection measurement, with application of image registration methods, presented in this article enables images of the construction to be taken from different points of view during examination. The lab tests revealed that the influence of the lighting on the performance of the method was negligible (measurement noise value 0.03%). The standard deviation of the deflection computation, in the case of images obtained from the same point in space amounted to 0.004 mm. When the rectification algorithm was applied, the standard deviation of maximum deflection was located in the range between 0.03 mm to 0.15 mm for specimens with artificial speckle pattern and up to 0.2 mm for the objects without special texture. The developed techniques of marker detection and matching make it possible to create an application with fully automatic vision structure's on-line monitoring systems in which the construction can be examined during its everyday use. On the other hand, the developed methods can be applied in an user-friendly software which can help one to quickly assess the state of the construction during inspection. The system has employed easily available digital SLR camera as the measuring sensor for the measurement of static or quasi-static states of structures. It can be applied to the structures with an artificial texture in the form of the optical noise, natural texture of materials and when special geometric markers are available. The system has provided high measurement density without use of active optical methods. It can be employed to various civil engineering structures like bridges, footbridges, chimneys, viaducts, girders, ceilings, halls, masts, wind turbines, buildings, machines and devices.

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BIBLIOGRAPHY

[1] Kohut P., Holak K., Uhl T.: *Application of image correlation for SHM of steel structures*, Structural Health Monitoring 2008: proceedings of the fourth European workshop, Cracow, Poland, , July 2-4 2008, pp. 1257–1264

[2] Uhl T.: *SHM of civil structures – methods, tools and applications*, Proceedings of the international conference on Experimental Vibration Analysis for Civil Engineering Structures EVACES'09, Dolnośląskie Wydawnictwo Edukacyjne, Wrocław 2009

[3] Uhl T., Kohut P., Holak K.: *Construction deflection examination by means of correlation coefficient*, Proceedings of the 13th School of Modal Analysis,Cracow, Poland 2009,

[4] Uhl T., Kohut.P, Szwedo M., Holak K.: *Static and dynamic optical measurement in SHM of civil structures*, Proceeding of the 7th international workshop on Structural Health Monitoring, DESTech publications, Lancaster 2009

[5] Kohut P., Kurowski P.: *The integration of vision based measurement system and modal analysis for detection and localization of damage*, Engineering achievements across the global village, The International Journal of INGENIUM, Cracow , 2005, pp.391-398

[6] Kohut P., Kurowski P.: *The integration of vision system and modal analysis for SHM applications,* Proc. Of the IMAC-XXIV a conference and exposition on structural dynamics, January 30-February 02 St. Louis, 2006, pp. 1-8

[7] Lee, M., Precht, M., Tyson, J., Schmidt, T.: *Application of 3D Measurement System with CCD Camera in Microelectronics, Advanced Packaging*, November 2003.

[8] Schmidt, T., Tyson, J., Galanulis, K.: *Full-Field Dynamic Displacement and Strain Measurement Using Advanced 3D Image Correlation Photogrammetry*, Experimental Techniques, Vol.27, No.3, pp.41-44, May/June 2003.

[9] Johnson, E., Woodard, N.: *Low-Cost Electrical Resistance Spot Welding Technique for Micro-Optical Component Mounting with Sub-Micron Tolerance*, Proceedings of Photonics Packaging Symposium, San Francisco, CA, Aug. 2003.

[10] Schmidt, T., Tyson, J., Galanulis, K.: *Dynamic Strain Measurement Using Advanced 3D Photogrammetry*, Proceedings of IMAC XXI, Orlando, FL, Feb. 2003

[11] Tyson, J., Schmidt, T., Shahinpoor, M., Galanulis, K.: *Biomechanics Deformation and Strain Measurements with 3D Image Correlation*, Experimental Techniques, Vol.26, No.5, pp.39-42, Sept./Oct. 2002

[12] Tyson, J., Schmidt, T., Galanulis, K.: *Advanced Photogrammetry for Robust Deformation and Strain Measurement, Proceedings of SEM*. 2002 Annual Conference, Milwaukee, WI, June 2002

[13] Hotz, W., Hänggi, P., *Determination of Forming Limit Curves*, 2001. Bergmann, D., Ritter, R., 3D Deformation Measurement in small Areas based on Grating Method and Photogrammetry, 1998

[14] Alpers, B., Bergmann, D., Galanulis, K., Winter, D.: *Advanced Deformation Measurement in Sheet Metal Forming*, 1999

[15] Steinchen, W. & Yang, L.: *Digital Shearography, Theory and Application of Digital Speckle Pattern Shearing Interferometry*, SPIE Press, 2003

[16] Schmidt, T., Tyson, J.: *Pulsed Laser Systems for Wide Field Vibration Analysis*, ASNT Fall Conference, Oct. 2000

[17] Tyson, J.: *Non-Contact Full-field Strain Measurement with 3D ESPI*, Sensors, Vol. 17 No. 5, pp. 62 - 70, May 2000

[18] Tyson, J.: *Dynamic Deformation Analysis with Pulsed ESPI,* Society of Experimental Mechanics Conference, June 1999
[19] Tyson, J.: *Full-field Vibration and Strain Measurement with 3D ESPI*, Sensors, Vol 16 No. 6, pp. 16 - 22, June 1999
[20] Tyson, J.: *Advanced Brake Squeal Analysis and Vibration Measurement*, 4th International Brake Colloquium, Gramado, Brazil, April 15, 1999
[21]Tyson, John: *Portable Interferometry Systems for Rapid NDI*, USAF Aircraft Structural Integrity Conference, Dec. 1998
[22] Tyson, John: *Practical Composite Repair Evaluation*, Proceedings of 41st Int'l SAMPE Symposium, Vol. 41, Book 1, pp. 609-614, March 1996.
[23] Tyson, John: *Shearography NDE of Rocket Motor Components*, Joint Army-Navy-NASA-Air Force Nondestructive Evaluation Subcommittee Meeting, July 14-16, 1992
[24] Chu T. C., Ranson W. F., Sutton M. A., Peters W. H.: *Application of digital-image correlation techniques to experimental mechanics*. Exp Mech. 25, September 1985, pp.232–24
[25] Hartley R., Zisserman A.: *Multiple View Geometry in Computer Vision*, Cambridge University Press, 2004
[26] Ma Y., Soatto S., Kosetska J., Sastry S.: *An Invitation to 3D Computer Vision*, Springer-Verlag, New York 2004
[27] Gonzales R., Woods R.: *Digital Image Processing*, Prentice Hall 2002
[28] Russ J.: *Image Processing Handbook*, CRC Press 1998
[29] Shapiro L., *Computer Vision*, Prentice Hall, 2000
[30] Zitova B., Flusser J.: *Image registration methods: A survey*, Image and Vision Computing 21, Elsevier, 2003
[31] Holak K, Kohut P., Cieślik J.: *Application of three-dimensional vision techniques in mechanical vibrations measurement (in polish)*, Proceedings of the 8th Workshop of Mechatronics Design, 2008, pp. 63-70
[32] Uhl T., Kohut P., Holak K.: *Image correlation techniques in structures deflection measurement*, Proceedings of the international conference on Experimental Vibration Analysis for Civil Engineering Structures EVACES'09, Dolnośląskie Wydawnictwo Edukacyjne, Wrocław 2009
[33] Bradsky G., Kaebler A.: *Learning OpenCV*, O'Reilly 2008

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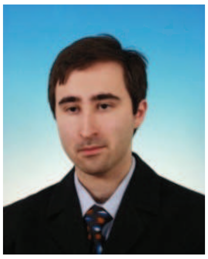

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