Monitoring of Civil Engineering Structures Supported by Vision System

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ABSTRACT

In the paper the optical-based method of civil engineering construction's in-plane deflection measurements and state monitoring was presented. 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. This new approach was feasible by employing homography transformation in order to remove perspective effects. The implemented image pre-processing and analysis methods make possible to develop fully automatic system. In the paper there were also discussed the damage detection and localization issues based on the irregularity detection by means of the analysis of the deflection's curve wavelet transform coefficients. The results of the model based Probability of Detection for the measurement method was presented. The developed methodology, vision-based measurement system as well as experimental results obtained from tests made on lab set-ups and civil engineering constructions were investigated.

INTRODUCTION

Structural Health Monitoring of civil engineering constructions involves integrating sensors, data transmission and computational power in order to detect, localize and assess damages within a structure which can lead to its failure at the present time or in the future [1]. Any damage developed in the structure decreases its rigidity and changes its dynamic and static properties.

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The assestment of the constructions' state is usually carried out using data associated with dynamic processes because this type of data contain more information [2,3,4,5]. Unfortunately, due to requirements of the expensive set up, maintainance and automation, usually only low frequency or low-order vibration mode shapes of the structure can be obtained. Moreover, it is very difficult to excite a large structure to vibrate. On the other hand, the static data, such as deflection curve, requires much less effort. Therefore, the application of the static deflection for damage detection has become more sufficient. Many methods of damage detection based on change the analysis of deflection curve's shape has been developed. Gokdagi [6] developed a wavelet-based damage detection method for beam-like structures. CWT coefficients of both the damaged mode and the reference case have been computed, and thus a reliable damage index could be obtained. On the other hand, Hui Li et al [7] proposed a new crack identification method based on fractal theory and wavelet packet transform. The location of damage in the beam was determined by fluctuations on the contour of estimated FD and the extent of the damage was estimated by FD-based damage index. Rahmatalla and Eun [8] presented a method of damage detection based on the distribution of flexural curvatures and constraint forces along a structural beam-member. Guo Hui-yong et al [9] used a strain energy and evidence theory for damage detection. The evidence theory method was applied to identify structural damage location and structural modal strain energy was utilized to quantify the damage extent.

In most of these method, the smooth deflection curve obtained by the measurement of the deflection in many points is necessary for the correct damage detection and localization. Non-contact experimental techniques have been developed as alternatives. The vision systems can be applied in this field due to their high measurement density, low cost and universality. For example, Jing Shia [10] at al presented an example of use of the computer vision system to capture the static deformation profile of a structure, and then employ profile analysis methods to detect the locations of the damages. Rucka [11] developed method of crack localization in beam-like structures and extended the use of the method to plates [12]. In all of the methods, the image analysis based on the edge detection or region processing were employed for the deflection curve computation. In this paper, the authors present the application the digital image correlation (DIC) to obtain the displacements of the construction's points. Optical measurements using DIC were introduced to experimental mechanics in the paper [13], where authors described measurement method of the test specimen's deformation by means of correlation coefficient. DIC measurement techniques have found broad scientific and industrial applications [14],[15],[16], for example: structural analysis of welded joints [17], measurement methods developed for nano- and micro-scale deformation processes induced by mechanical [18] and thermal [19] factors, testing of specimens during fracture process [20], [21], [22]. Yoneyama et al. [23] presented application of digital image correlation to the load testing of the bridge construction, proving the correctness of the method with results of measurements using displacement transducers.

In this paper the developed vision system dedicated for an in-plane measurement of civil engineering structures displacement fields' is presented. The paper introduces the applied mathematical apparatus as well as the developed software tool for deflections' monitoring. The proposed algorithm of crack detection in the beam-like components based on CWT has been presented and the probability of detection of the method for a given structure has been shown. The accuracy of the system has been tested in the laboratory by comparing the results obtained by the system with the tactile measurement using Leica LaserTracker. The paper presents the results of the field test on the tram viaduct deflected under the weight of passing vehicles and the comparison with the data acquired by the radar interferometer.

VISION IN-PLANE DEFLECTION MEASUREMENT METHOD

In the developed system to carry out the measurements [24-27], a reference image and one or more images of the construction under the load are acquired. The successive photographs can be taken from distinct points in space. The mapping **H** [28] is applied to transform all images and removes the projective distortions from the image of a plane of interest of the structure. Therefore, photographs acquired from different points in space can be spatially overlaid with the reference image.The mapping **H** is computed using set of markers coplanar with the plane of construction which are detected and matched automatically by developed contour processing and shape filtering techniques [24-27]. Next, the image of the construction’s plane is divided into intensity patterns. The set of corresponding patterns are identified on the reference image and tracked on the images of the structure under the load by means of normalized cross correlation coefficient (NCC) [29]. The deflection curve is computed as a difference between positions of the corresponding image patches on two images. In the last step, the scale coefficient computed from pattern of known geometrical dimensions [24-27] is applied to rescale the beam’s deflection curve to metric units. The method is schematically shown on the figure 1a.

The developed software (Fig. 1b) enables constructions’ deflection measurement using digital SLR cameras for remote image acquisition and provides image processing algorithms to calculate the deflection curve. Two modes of operation are available: the on-line and the off-line mode. In the first case, an user specifies the date and number of measurements and then the system works fully automatically carrying out the image acquisition and the deflection measurement. The off-line mode provides analysis of the images registered by other devices or in previous sessions. The software has embedded tools for image rectification, camera calibration and the scale coefficient calculation from special calibration patterns. The result browser module carries out the visualization of calculated curves of deflection, storing of the data and automatic reporting. The additional feature of the software is detection of exceeding of an threshold level of maximum deflection and sending alerts to a client by an e-mail.

a) b)

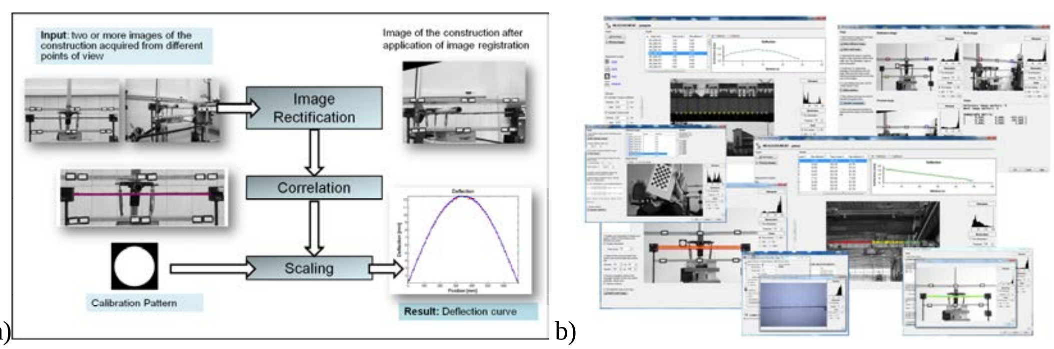
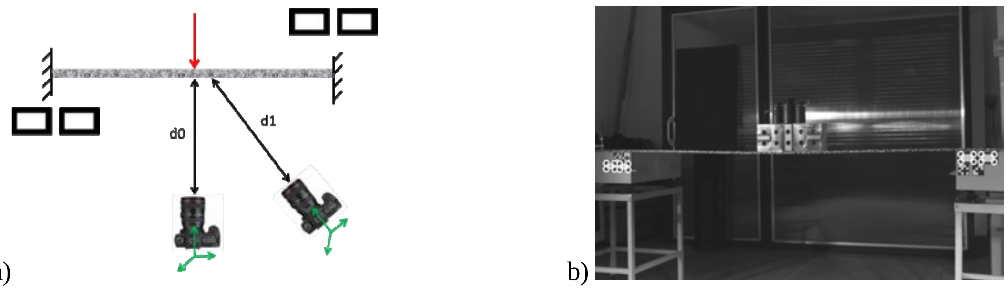


Figure 1. a) Main steps of the developed algorithm. b) developed software tool.

EXPERIMENTAL INVESTIGATION OF THE METHOD IN THE LAB.

The lab setup consisted of aluminum beam of length 1.8 m and cross section 50x10 mm (figure 2) fixed at both ends. The beam was loaded by a point weight acting at the middle of its length. The set of rectangular markers necessary for homography matrix computation was placed coplanar with the beam's plane. Photographs of the construction were acquired by a system of two digital Canon 5D Mark II cameras with 21.1 MPix image resolution and lens Canon 24-70mm f/2.8L with focal length f ~= 50 mm adjusted. The camera used for acquisition of the reference had its optical axis perpendicular to the plane of the construction. The second camera was translated and rotated with respect to the first one and it was used for calculation of the deflection field from the images after application of rectification.



a) b)

Figure 2. a) The lab setup shown schematically. b) the image of the setup captured by one of the camera.

In order to evaluate the performance of the described vision system, the results of the deflection measurements have been compared to the data obtained with the use of Leica LaserTracker model LTD 860. Tactile measurements were performed on the beam without a load and then on the loaded one. As a result of the measurement of a single point, its coordinates x, y, z were obtained. Differences in coordinates of corresponding points before and after deformation gave the value of a deflection.

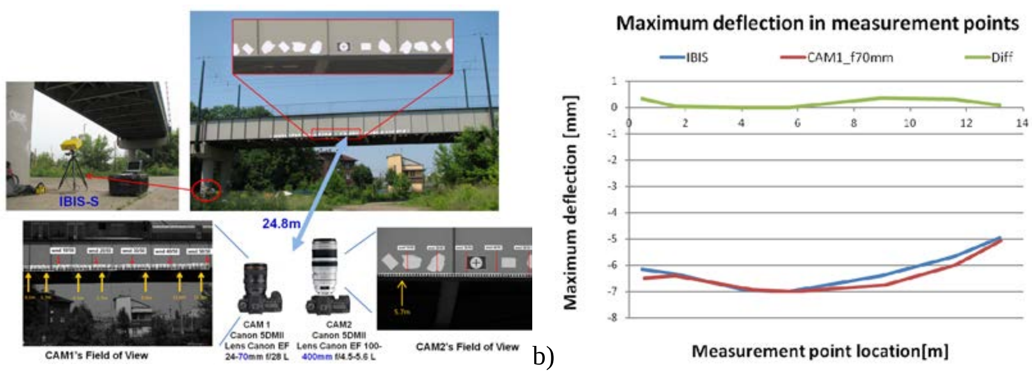
Displacements of the beam's 18 points under the load measured by Leica LaserTtracker were compared with the displacements obtained by the vision system. Two sets of displacement curves were analyzed: the fist computed from the images captured by the reference camera and the second set calculated from images after application of the rectification. In the case of reference images, the experimental investigation revealed that the maximum difference between optical system and Leica LaserTracker was 0.174 mm, the minimum difference amounted to 0.010 mm while the mean difference was 0.063 mm. Results for the second camera (for images after application of the rectification) were similar. The maximum difference between optical system and Leica LaserTracker in this configuration equaled to 0.149 mm, the minimum had value 0.002 mm while the mean difference amounted to 0.064 mm.

THE EVALUATION OF THE VISION SYSTEM ON THE CIVIL ENGINEERING CONSTRUCTION

28 meter long viaduct segment deflected under the load of passin trams was investigated construction (figure 3a). Measurements have been performed using two Canon EOS 5D Mark II SLR cameras. Cameras have been situated in the distance of 24.6 from the object. The first camera was equipped with Canon EF 24-70mm f/28 L lens set to work with 70 mm of focal length. The field of view for this camera spanned

13.5 meters. The second camera was equipped with a telephoto lens (Canon EF 100-400mm f/4.5-5.6 L) set to 400mm focal length. The camera was used for monitoring smaller fragment of the construction of length 2.32 m. In addition, the continuous deflection measurement was performed using interference radar IBIS-S [25].

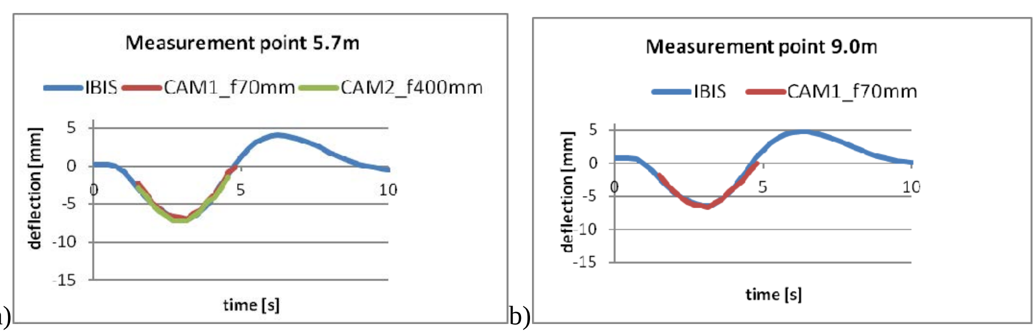
Displacements were analyzed at 7 points of the span, located in the central part of the structure. Measurements were performed by both systems during a tram passings [30]. The maximum values of deflection for each point were compared. Observations were collected for 8 tram passages. The minimum difference between two techniques amounted to 0.08 mm, while the maximum difference reached 0.93 mm.



a) b)

Figure 3. a) The measurement set up to monitor the deflection of the viaduct segment under the load of riding tram vehicles. b) The shape of the viaduct in the moment of the maximum deflection during a sample tram passing. The graphs presents results obtained by two methods as well as the difference between them.

Figure 3b shows the shape of the viaduct in the moment of the maximum deflection during a sample tram passing. The graphs presents results obtained by two methods as well as the difference between them. In Fig. 4 the deflection of two chosen points on the span during the same tram passing is presented in the time domain.

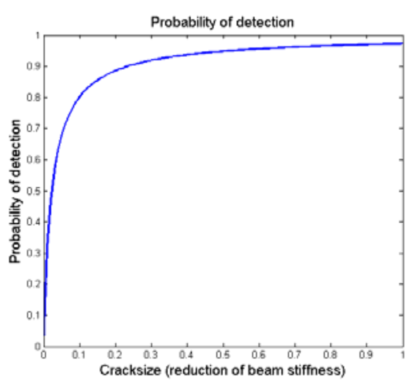


a) b)

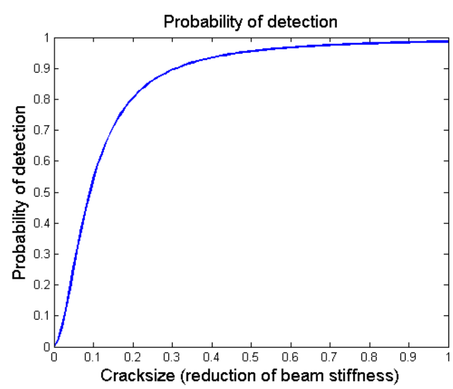
Figure 4. The displacement of two chosen points on the span during the same tram passing is presented in the time domain. A), the deflection of the point at the distance 5.7 m from the start point on the span measured by three methods, b) the deflection of the point at the distance 9.0 m from the start point of the span.

DAMAGE DETECTION AND PROBABILITY OF DAMAGE DETECTION AND LOCALIZATION

The deflection curve consists of densely measured displacements of points and can be used for the damage detection and localization. In this paper, the transform method based on continous wavelet transform (CWT) coefficients analysis has been applied to damage detection and localization. The Continous Wavelet Transform ~~given~~ makes it possible to detect and localize the crack of the beam-like structure directly by finding the scale and shift values of the transform corresponding to the maximum of CWT coefficients. The analysis of the CWT transform of the deflection curves for reference and crack beams, with gradually increasing level of the damage has been carried out. It was assumed that the damage has been correctly detected and localized if the error of the localization was less or equal to 5 mm . The wavelet ‘gaus4’ has been used as the basis function in the CWT computation. In the numerical investigation, the simply supported Euler-Bernoulli MES model of the beam has been developed. The material and geometrical parameters of the beam were as following: the length 1000 mm, cross sectional area 500 mm^2, Young modulus $2.1*10^5$ MPa. The crack of the beam was modeled as local reduction of the beam’s stiffness. The image formation has been simulated as pin-hole projection of the camera with known internal and external parameters. The Gaussian noise has been added to computed images of the deflection to model the errors induced by image correlation function. The investigation for increasing level of the noise and increasing damage extend has been carried out. The probability of detection (mPOD) curves [31] has been calculated based on the numerical data. Hit or Miss method of probability detection has been used. The results of the damage detection for a given level of the noise and the increasing extend of the crack has been employed for the probability of the detection and localization curves computation. Curves has been computed for standard deviation of the noise equal to 0.005 and 0.05 pixels. The mPOD curves were presented on the figure 5. The investigation has shown that the system detects and localizes correctly (with ±5 mm neighborhood of the real crack’s position) the damage greater than 10% and 20% of the beam’s stiffness for the standard deviation of noise equal to 0.005 and 0.05 pixels respectively with a probability greater then 80%.



a)



b)

Figure 5.Computed mPOD curves for two standard deviations of the noise a) 0.005 pixels, b) 0.05 pixels.

CONLUSIONS

Tests carried out on the lab set-up has proved that deflection course obtained by the developed vision system was comparable to results measured by tactile metrological device with high accuracy. Examintions revelaed that the measured deflections after an application of the rectification resulted in the data which have been very close to the results obtained from the case of the reference camera. In the case of the the reference images, the mean difference in deflections between optical system and Leica LaserTracker was 0.063 mm, while the measurement with an application of the rectification resulted in the mean difference equal to 0.064 mm.

The developed damage detection method based on deflection course curve calculated by means of digital image correlation and CWT made it possible to detect and localize the position of the crack for beam-like structures. The main advantage of CWT method is direct calculation of the damage position on the span of the beam for which CWT coefficients reach the maximum value. The experimental test proved that, for the applied standard deviation of the noise, the system can localize the position of the damage which correspond to 10% and 20% reduction of the beam's stiffness for the standard deviation of the noise equal to 0.005 pixels and 0.05 pixels respectively.

The field tests allowed to determine the applicability of proposed vision-based technique for measuring the deflection of civil engineering constructions. The vision system measurement resulted in the data which matched the points' displacement registered by interferometric radar. The minimum difference between the vision technique and the radar amounted to 0.08 mm, while the maximum difference achieves equaled 0.93 mm. Its main advantages are simplicity of the measurement, the possibility of obtaining dense field of a deflection, an application of commonly available digital camera, the easy image acquisition process which can be performed from different points in space as well as easy interpretation of measurement results.

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