Vision based condition assessment of structures

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Abstract: In this paper, a vision-based method for measuring a civil engineering construction’s in-plane deflection curves is presented. The displacement field of the analyzed object which results from loads was computed by means of a digital image correlation coefficient. Image registration techniques were introduced to increase the flexibility of the method. The application of homography mapping enabled the deflection field to be computed from two images of the structure, acquired from two different points in space. An automatic shape filter and a corner detector were implemented to calculate the homography mapping between the two views. The developed methodology, created architecture and the capabilities of software tools, as well as experimental results obtained from tests made on a lab set-up and civil engineering constructions, are discussed.

1. 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]. Damages in SHM can be defined as changes in the material properties or the geometry of a structure which can affect its overall performance. SHM 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 can be observed. On the other hand, local methods make use of the physical phenomena acting locally within a small area of the construction.

A damage developed in the structure decreases its rigidity and alters the dynamic and static properties to certain extent. The data for damage detection can be either dynamic, vibration-based properties or static deformation profiles. It is usually more preferable to obtain dynamic types of data because they contain more information regarding a given structure [2,3]. Unfortunately, obtaining dynamic data usually requires devices which are expensive to set up, maintain and automate. Otherwise, usually only low frequency or low-order vibration mode shapes of the structure can be obtained. Moreover, it can be very difficult or even impossible to excite a large structure, such as a bridge to vibrate. The static deformation profile requires much less effort, and therefore using the static deflection for damage detection has become more attractive.
The damage detection methods can be divided into two groups, the first one regarding vibration based data and the second one concerning analysis of the deflection course curve. In the dynamic properties analysis, the vibration mode shapes, changes of natural frequency and the curvature of the mode shapes can be employed for damage detection, localization and assessment [2,3,4,5]. On the other hand a lot of methods applicable for damage detection based on the static deflection course have been developed. Jang [6] presented a strain damage locating vector (DLV) method, i.e. a method combining DLV and static strain measurements. Guo Hui-yong et al [7] applied a strain energy and evidence theory for damage detection. The evidence theory method was proposed to identify structural damage locations. Then, structural modal strain energy was utilized to quantify structural damage extents. Chen Xiao-Zhen et al [8] developed a method of damage identification using limited test static displacement based on the grey system theory. In his work, the grey relation coefficient of deflection curvature was defined and used to locate a damage in the structure. Staszewski and Patsias [9] presented an application of the wavelet transform for damage detection based on optical measurements. Gokdagi [10] developed a wavelet-based damage detection method for beam-like structures. The continuous wavelet transform (CWT) coefficients of both the damaged mode and the approximation function were computed, and thus a reliable damage index could be obtained by taking their difference. On the other hand, Hui Li et al [11] proposed a new damage identification method based on Fractal theory and wavelet packet transform. The location of damage in the beam was determined by the dramatic fluctuation appearing on contour of estimated FD and the extent of the damage was estimated by FD-based damage index. Rahmatalla and Eun [12] presented a method of damage detection based on the distribution of flexural curvatures and constraint forces along a structural beam-member.

In most of these method, the smooth deflection curve obtained from many measurement points is necessary for the correct damage detection and localization. As the structure becomes more complex, more sensors are needed and the cost increase may be significant. Sometimes, it is extremely challenging to attach sensors to a structure because of the environmental conditions or the geometrical constraint. Non-contact experimental techniques have been developed as alternatives. For example, Jing Shia [13] at al presented an example of use of the computer vision technology to capture the static deformation profile of a structure, and then employ profile analysis methods to detect the locations of the damages. Vision-based techniques belong to the group of non-contact global SHM methods which enable dense global measurements of static deformations, as well as dynamic processes, to be carried out. Their main advantages are high measurement density, low cost and universality.

In this paper, the developed vision-based method dedicated for in-plane measurement of a civil engineering structure's displacement fields is presented. The deflection curve is obtained from two images of the construction: the reference one and the one acquired after application of the load. The principle of the method is calculation of the object’s points displacement by means of a normalized cross correlation coefficient. The analysis of the deflection course of the beam under the load make it possible to apply the various damage detection, localization and assessment methods based on the strain energy or the deflection’s shape curvature. Image registration techniques were introduced in order to increase the 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 [14-18]. In order to calculate correspondences between matching features on both images, new techniques of marker detection and shape filtering, generation of identifying codes, as well as sub-pixel corner detection are introduced. The developed software tool provides a high level of measurement process automatization, accomplished by operations like image acquisition, image preprocessing and analysis. This can become an essential part of a vision-based monitoring system suitable for online work using data acquisition devices, such as high resolution SLR cameras. The system monitors the state of the construction and informs the user when the critical level of measurement estimates has been crossed and a message can be sent by e-mail. It is also possible to send the necessary data to external
monitoring and diagnostics systems using a TCP/IP protocol. All data generated by the application can be exported to external data sheets in popular formats e.g. Excel spreadsheet, PDF and HTML.

2. Overview of the in-plane deflection measurement method.
The proposed in-plane deflection measurement method consists of three major steps. First, the rectification \([19,20]\) of the image taken from a point of view different than the reference point is performed by means of the homography matrix \(H\). In the next step, deflection of the construction is calculated using a normalized cross correlation coefficient. Sub-pixel techniques were introduced in order to increase the accuracy of the measurement. In the last step, the scale coefficient: \(W\) [mm/pix] is computed with the help of a circular intensity pattern by means of image processing and area analysis techniques \([14-18]\). The developed algorithm is presented on Figure 1.

2.1. Markers detection and matching
The set of corresponding points consists of vertices of rectangular markers which are placed on the structure. Markers must be coplanar with the construction’s plane and can’t change their position as it deforms \([14-18]\). The positions of the corresponding points on both images are calculated by an automatic corner detector. Firstly, rectangles are detected on the images by means of contour processing and shape filtering techniques. The markers are sorted and matched by means of comparing their corners’ expressed in the polar coordinate system. As an alternative to the aforementioned method of feature matching, image patch correspondence matching based on code recognition is proposed.

2.2. Image registration.
Image registration \([21]\) is a method of aligning two or more images taken at different times, from different viewpoints or by using different imaging devices, after application of the geometric transformations. In this work, homography mapping has been introduced for the reduction of perspective distortions on the image, which enabled a deflection’s course to be measured from two images of a construction taken from distinct points of view.

![Figure 1. The developed algorithm of the in-plane construction’s deflection measurement.](image-url)
2.2.1. Image rectification by means of homography mapping

Image rectification [19,20] is a process of projective distortion reduction by means of homography transformation. The homography mapping which transforms a set of coplanar points on the distorted image into a corresponding set of points on the reference one is given by (1).

\[ x' = Hx \]  

Four pairs of coplanar corresponding points are sufficient for computation of the matrix \( H \) if no three of them are co-linear. In this paper, a set of markers which are coplanar with the analyzed part of a construction’s plane and can’t change their positions as a structure deforms are used for computation of the homography matrix [14-18]. If all points of the analyzed image are transformed through the mapping (1), projective distortions of the particular plane are removed from the image.

2.2.2. Deflection measurement by means of a correlation coefficient

In this paper, a normalized cross correlation coefficient [20,22] (NCC) is applied for the computation of the in-plane displacement field. In the developed method, the reference image of the unloaded construction is divided into intensity patterns whose positions are computed by means of NCC. The displacement vector for each of the measurement points is computed as the difference between positions of the pattern on two images of the construction: taken after and before deformation [14-18].

2.2.3. Calibration of the system

Calibration is performed by a circular intensity pattern with a known diameter, \( D_{\text{mm}} \). In addition, full camera calibration is performed to obtain intrinsic camera parameters, which are necessary for the reduction of radial and tangential lens distortions from the image of the construction [14-18].

3. Automatic detection and matching of markers for homography computation.

In order to make the measurement method more automatic, two marker detection and matching algorithms were developed. In the first one, a set of rectangles is detected on two images by means of binary image processing, contour detection and filtering. The corresponding points, vertices of the rectangles, are calculated by a Harris corner detector with improved sub-pixel accuracy. In the second method, the set of markers consists of coded patterns of black and white squares (Figure 2). The rectangles enclosing markers on the image are detected by the aforementioned method and their matching is performed by comparison of numerical codes.

3.1. Rectangle detection algorithm

The binary image \( I \) of resolution \( M \times N \) is an image which consists of two kinds of pixel areas: \( A \) – foreground and \( B \) – background where \( A \) and \( B \) are defined as:

\[ A = \{(x, y): 0 \leq x \leq M, 0 \leq y \leq N \text{ and } I(x, y) = 1\} \]

(2)

\[ B = \{(x, y): 0 \leq x \leq M, 0 \leq y \leq N \text{ and } I(x, y) = 0\} \]

(3)

Let \( D_8 \) be the 8-neighborhood [23-26] of the pixel \( p_i = (x,y) \). The closed contour (or boundary) of the foreground region \( A \) on the binary image is a set of pixels defined as follows:

\[ \text{contour} = \{p_{i=1,2,...N} \in A: (\forall p_j \exists p \in (B \text{ and } D_8(p_i))) \text{ and } p_i = p_N\} \]

(4)

The first step of the algorithm is binarization of the gray-scale image. The threshold value is obtained by analysis of the image's intensity histogram. In the next step, the contours enclosing all the foreground object are detected [23-26] and transformed to the chain polygon representation in which only endpoints of the line elements approximating the contour are stored. The set of points consists of vertices of rectangular markers. All detected boundaries are filtered by a 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 the angle between the sides of the quadrilateral. The obtained vertices’ positions are refined by the Harris corner detection algorithm with a sub-pixel improvement. The method is illustrated in Figure (3).

![Figure 2. Example of a marker used for pattern matching and a set of markers on a real photograph.](image)

3.2. Sorting of points in a polar coordinate representation

It is assumed that there is no rotation around the optical axis of the camera with respect to the camera coordinate frame from which the reference image was captured. In the first step, the center of the mass of the set of markers’ vertices is computed. The calculated point becomes the origin of the new polar coordinate frame. All of the points have to be expressed in this coordinate frame. Next, the sorting of points is performed. The 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.

3.3. Sorting of markers using the code representation of coded image patches.

In the next method, the position and orientation of the camera is not constrained by the requirement of no rotation described in Sub-Chapter 3.2. The image patches which are matched on two images are coded markers. Each marker consists of N rows and N columns of small squares arranged in a chessboard-like pattern (Figure 2). Each of the squares can be black, which represents logic 1, or white, which represents logic 0. The innermost 2x2 pattern of the marker is the same for all markers and resembles the letter ‘L’. 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 the algorithm described in Sub-Chapter 3.1. The marker orientation is computed from the innermost ‘L’ shape pattern of the marker. In the last step, the image patch is encoded as an NxN 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.

![Figure 3. Rectangle detection algorithm carried out on the lab set-up image.](image)
4. Software for construction deflection measurement.

The main purpose of the developed software tool is construction monitoring and diagnostics with the use of vision signals. Measurement is the main data structure in the software. Measurement consists of images, algorithms with their configuration, and results generated by each of the algorithms. The application provides operations on devices such as live preview mode or remote modification of camera parameters. The system's IO Handler module allows multiple picture acquisition devices to operate in real-time. The application supports popular SLR cameras with available driver libraries used for device management from the system.

The calibration module (Figure 4a) added to the system allows calibration data based on calibration images to be calculated. Calibration data consists of intrinsic and extrinsic camera parameters. Calibration images are the images containing a calibration chessboard with odd row and even column count. Calibration data is necessary for identification of the camera's position and orientation needed for calculation in stereo-vision algorithms and obtaining the lens distortions coefficients.

![Figure 4a](image1.png) ![Figure 4b](image2.png)

**Figure 4.** Software modules: a) Camera IO Handler module, Calibration module, b) Measurement module, Rectification module, Image correlation module and the Result browsing module

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

4.1. Experimental evaluation of the software

In the first examination, the lab set-up (Figure 5a), consisted of a steel frame loaded by a point force acting in the middle of the beam and a set of markers coplanar with the frame surface. Image were acquired by Canon EOS 450D digital camera. The in-plane deflection curve was obtained by analysis of two images of the construction, acquired before and after application of the load. The image of the loaded construction was taken from different positions in space.

Displacement of the beam at the point of maximum deflection was acquired using by the laser OMRON Z4M-S100 sensor with a resolution of 0.008 mm. The average difference between the result obtained by the vision system and a laser based measurement was less than 0.5% (the relative value).
The deflection curve calculated with sub-pixel accuracy improvement is presented in Figure 7a. Performed tests showed influence of rectification algorithm on the accuracy of the deflection’s measurement [14-16,18]. The error at the point of maximum deflection induced by image rectification of images acquired from a different point of view reached values ranging from 0.03 % (a typical case, for a slight difference in positions of the camera) to 1.5 % (the extreme case, when displacement and change of orientation of the camera between two positions was the largest) [14-16,18]. The results of the rectification algorithm are presented on the Figure 6.

In the next examination, the system performance was tested on the lab-setup consisting of steel frame fixed at one end, loaded by a single weight (Figure 5b). 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 focal length \( f = 50 \text{ mm} \) 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. 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 mean 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.
Figure 7. The in-plane deflection curves obtained by the vision based measurement method. The results obtained by measurement on the first (a) and the second (b) lab set-up respectively.

The mean value of the noise of the method for the natural lighting conditions amounted to 0.002 mm. For the images captured from one point in space, the standard deviation of calculated displacement value in the point of maximum deflection was not affected by the change of position of the load and reached value 0.004 mm.

Introduction of the rectification algorithm increased the error of the method. The relative error induced by the rectification calculated as the ratio between difference $\Delta x$ (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 7b.

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 and 3 – results (mean value from 30 images and standard deviation) of deflection computation in point of maximum deflection for camera 1 and 2. The column 4 – difference between results obtained from two cameras, in mm, column 5 – the relative difference with respect to the first camera, in percents.

| Camera 1 | Camera 2 |
|----------|----------|
|          |          |
| $d$ [mm] | mean std | mean std | $\Delta x$ | $\Delta x\%$ |
| 550      | 18.306 0.003 | 18.147 0.0105 | 0.159 | 0.008 |
| 360      | 10.794 0.005 | 10.686 0.0089 | 0.108 | 0.01 |
| 200      | 4.114 0.004 | 4.138 0.0093 | 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 | 1.09 |

5. Conclusions and future work
Vision-based measurement techniques enable damage detection to be performed using analysis of the changes in the geometric properties of the structure, such as shape of the deflection curve. The measurements are carried out without making any contact with the structure. Moreover, they allow dense measurement of the displacement field to be carried out. Because of that, the analysis of the deflection course of the beam under the load make it possible to apply different damage detection, localization and assessment methods based on the strain energy and the deflection’s shape curvature
without the necessity of the deflection’s curve approximation. The introduction of image registration techniques has improved the flexibility, universality and accuracy of this method. The technique of in-plane deflection measurement presented in this article enables images of the construction to be taken from different points of view during examination. Simplification of the measurement procedure is possible because the complicated, expensive and time-consuming step of camera positioning is not necessary. The developed techniques of marker detection and matching make it possible to create an application which can be used in automatic vision condition diagnostics systems in which the construction can be monitored during its everyday use. On the other hand, the developed methods can be applied in user-friendly software which can help one to quickly assess the state of the construction during inspection.

In the next stage, curvature analysis methods of the damage detection, localization and assessment will be implemented in the software for diagnostics of the structures based on their static deflection curve shape. The developed techniques have been extended to 3D measurement of static and dynamic states of the structures. Three-dimensional vibration courses of a structure's points of interest can be reconstructed by means of epipolar geometry existing between two views of the stereo-camera system. If both cameras are calibrated, reconstruction of the structure at the particular instant of time (positions of points in 3D space) can be estimated from each pair of frames of the video sequences. The three-dimensional deformation of the structure and velocity of its points can be computed. The application of epipolar geometry for the computation of 3D courses of vibrations in selected points of the construction makes it possible to measure the dynamic processes of the structures using a binocular system. The calculated displacements of the selected points can be used to obtain mode shapes. On the basis of the estimated mode shape, damage detection and localization by energetic methods can be employed.

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