DISPLACEMENT MONITORING AT THE MICRON LEVEL USING DIGITAL PHOTOGRAMMETRY

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Abstract: This paper describes a low-cost photogrammetric system comprised by two off-the-shelf CCD cameras to monitor the deformations of concrete elements. The basic design of the system and its implementation is presented. Emphasis is given on the calibration procedure that is necessary to achieve accuracy in the order of 10ths of microns. The calibration plate consists of a high definition grid, with known cell dimensions at ±2 microns accuracy. The displacement monitoring is carried out fully automatically in a sequence of image pairs, acquired at specific epochs during the experiment. The obtained results demonstrate that high accuracies can be achieved for distances of about 30cm from the object's surface.

1. Introduction

Displacement monitoring at the micron level accuracy is a critical issue in several civil engineering research activities. The most common issue is the verification of theories and mechanical models by appropriate load experiments on test objects and structures. During these load tests, parameters such as load, strain, stress, displacement, deformation, cracks and other defects have to be monitored [11]. From the aforementioned parameters, displacement and deformation are typically measured using resistive strain gages, extensometers and inductive displacement transducers. These conventional measurement tools provide single measurements of strains and displacements at selected locations, in real time and with high precision. However, there are significant issues associated with their use in engineering material tests: 1) specimen preparation is necessary (e.g. strain gages bonding), 2) extensometers should be removed from the specimen prior to failure to avoid damage, 3) instruments must be placed in contact to the test object, 4) single point information is acquired and, 5) measurements are restricted to a small number of points.

To overcome the limitations of conventional measurement tools, optical methods such as digital photogrammetry may be used instead. Photogrammetric methods are based on distantly obtained images that represent an instantaneous record of a situation that may change in time. Photogrammetric methods are suitable for monitoring displacements in load experiments since they allow automatic measurements for a large number of points in 2D and 3D space. Usually the entire specimen body is represented by a number of properly distributed discrete points. The deformation on these points under different load conditions is recorded by one or more CCD cameras and evaluated using digital photogrammetric techniques. The acquisition time ranges from short to instantaneous thus allowing the capture of even high frequency displacements.

The main advantage of photogrammetric methods is the possibility to monitor hundreds of detail points simultaneously and with no additional cost. The accuracy of the methods is high under a controlled environment and is comparable to that of conventional techniques [17, 3]. However, photogrammetric methods require specialised equipment, software and hardware that are expensive and not widely available. It is also questionable whether off-the-shelf CCD cameras can be used for 3D measurements at the micron level accuracy. In this work, the possibility of using conventional CCD cameras for displacement monitoring is evaluated. Section 2 gives the background theory on photogrammetric techniques as implemented in deformation monitoring applications. Emphasis is given on the calibration procedure that is essential to achieve high accuracy results, in the order of 10ths of microns. Section 3 describes the load experiment that was performed on FRP reinforced concrete elements. The displacement monitoring is carried out fully automatically in a sequence of image pairs, acquired at specific epochs during the experiment. The basic design of the system and the calibration strategy is discussed. The first results from the implementation of the system are also presented. The paper concludes in section 4 with remarks presented on the described application.

2. Photogrammetric procedure for displacement monitoring

The aim of displacement monitoring is to determine the magnitude and direction of motion for a number of discrete points at the object’s surface, in each deformation state. Using photogrammetric approaches, the object coordinates are accurately calculated in 3D space from data acquired by two high resolution CCD cameras. The two cameras should be positioned at front of the specimen in such a way to ensure that the discrete points on the object’s surface are captured simultaneously by both of them. The system must have the capability of tracking detail points with high accuracy and in a fully automatic way, in all subsequent images. Using photogrammetric principles, the 3D coordinates of these points, which are related to the specimen’s surface at each stage of load, are precisely calculated. The accuracy obtained depends on the internal system accuracy and the distance from the object’s surface.

The internal accuracy of the system mainly depends on the geometric reliability of the camera equipment and the feasibility to perform accurate coordinate measurements on digital images. For precise measurement applications, off-the-shelf CCD cameras require proper calibration to determine their internal characteristics which are essential to carry out photogrammetric activities. The aim of the calibration procedure is the estimation of a variety of unknown parameters, collectively known as the interior orientation parameters. These are usually the coordinates of the principal point, camera constant and image coordinate corrections that compensate for various deformations from the image perspective model [8]. In order to establish a reliable correspondence between object coordinates and their projection on the image plane, the interior orientation parameters should be known with the maximum possible accuracy. Otherwise, the derived measurements in the object space will be affected by systematic errors and therefore will be degraded in accuracy.

A number of calibration methods exist for commercially available CCD cameras [6]. The majority require external control information which is usually acquired from an appropriate calibration field. A calibration field consists of distinct and specifically marked target points that are established and precisely measured in a nominated coordinate system. The accuracy of the calibration procedure depends directly on the characteristics of the calibration field; accurate calibration can only be achieved if the target coordinates are accurately known and the target points are regularly distributed on the entire volume of the measurement space [18]. When 3D measurements are required at the micron level, the dominant problem is the availability of such a control field that provides accuracy in the order of few microns (1-2 μm). The acquisition of the appropriate control field in 3D space is quite difficult and costly, but this problem can be partially avoided if all target points lay on the same plane. The calibration of a camera using planar control points is a particular case of the calibration problem that is usually solved by acquiring few images of the calibration plate with different orientations. Such type of images provides the system with adequate information to calculate the unknown interior orientation parameters [13].

Whatever the calibration method is, the coordinates of the control points have to be observed on the images with the maximum possible accuracy. Depending on the target shape, different methods may be employed to calculate the target coordinates in image space with sub-pixel accuracy. Although a variety of target shapes (circular, square, cross or ring) may be used, it has been shown that circular white targets in a dark background provide significant advantages, since they can be easily identified in different image scales and orientations [5]. The estimation of the circular target coordinates is usually accomplished by calculating the center of gravity of the target or by fitting a rotated ellipse at the edges of the white pixels. The accuracy of these methods may reach the 1/100 of a pixel [16]. If a planar calibration field has to be used, the control points may be located at the intersections of a grid that is formed by parallel and perpendicular lines. In this case two different approaches may be employed: a) template matching of a cross pattern on the line intersections [2], or b) identification of the grid lines with sub-pixel accuracy and calculation of target coordinates at the intersection of the grid lines [10]. In both cases the obtained accuracies are comparable to those achieved using circular targets.

When the internal geometry of the two cameras is known, accurate measurements of the detail points on the specimen surface can be carried out. For this purpose, the orientation of the two cameras relative to the object reference system has to be estimated. This includes the determination of three rotational and three translational parameters for each camera, commonly known as the exterior orientation parameters. Depending on the mathematical models used, the exterior orientation parameters may be estimated during camera calibration or separately by implementing a photogragmmetric space resection [1]. The space resection requires a minimum of three control points in space, which are usually acquired from the calibration field. This results to the calculation of the exterior orientation parameters with respect to the calibration field reference system.

At the final stage, some detail points have to be defined on the object’s surface. These points will be identified on the images captured by both cameras and be tracked in all image frames acquired at different deformation states. Such discrete points may be positioned at distinct texture variations or artificially created on the object’s surface. In the second case, circular targets may be attached or appropriate patterns may be projected on the object’s surface [17]. In order to calculate the 3D coordinates of a detail point in the object space, its image coordinates have to be observed in the two images. Typically, detail points are initially defined on the left image and then their correspondences are identified on the right. The procedure is commonly known as stereo matching or stereo correspondence. Various approaches may be employed to deal with stereo correspondence problems. The most common implementations are based either on cross correlation or on least squares matching (LSM) algorithms [9].

Figure 1: Calibration plate

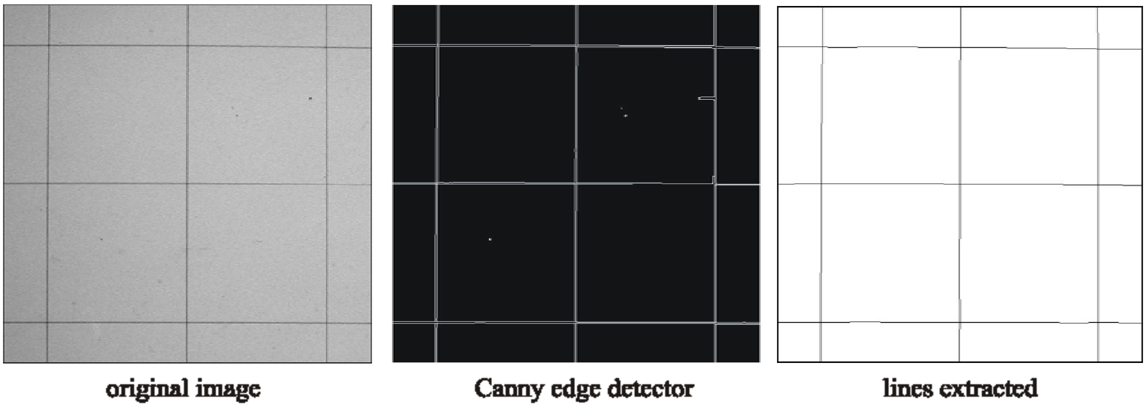


Figure 2: Identification of the grid lines

In both cases unique correlation areas, usually 5-20 pixel squares, are defined on each measured detail point. These image patches are tracked in each successive image with sub-pixel accuracy, up to one hundredth of a pixel. The object coordinates at the center of each correlation patch are then calculated by photogrammetric space intersection (triangulation) [1].

The object coordinates of every detail point are measured in each deformation state. The coordinates acquired from the first image set, when forces are not applied to the specimen yet, are considered as the reference state. The displacement is estimated from the coordinate differences in X, Y, Z direction between the reference state and the upcoming deformation states. The results may include 3D contours of the specimen surface, deformation vectors as well as the plane strain tensor. The expected accuracy mainly depends on the distance among the camera station and the object surface. It is accepted that the minimum sensitivity of the photogrammetric methods is 1:30000 of the field of view. That means that with a 3 cm field of view, the sensitivity is 1 micron, and with a 30 cm field of view, the sensitivity is 10 microns [17].

3. Implementation

In order to evaluate the use of photogrammetric methods for displacement monitoring in engineering research, several load experiments were carried out. The main purpose of this work was to investigate if commercially available CCD cameras are adequate for accurate measurements in the order of 10^{th} of microns. Two Nicon 5700 cameras at 5MB resolution were used in the experiments.

	Left Camera		Right Camera	
Parameter	**value**	**error**	**value**	**error**
focal length c (pixels)	2684.87	0.493	2688.15	0.309
principal point xo (pixels)	1227.97	0.323	1243.91	0.492
principal point yo (pixels)	1021.19	0.276	981.42	0.595
radial distortion k1	-0.211483	0.000413	-0.207168	0.000657
radial distortion k2	0.213276	0.001368	0.208302	0.002262
decentering distortion p1	0.001241	0.000024	0.000284	0.000041
decentering distortion p2	-0.000942	0.000027	-0.001378	0.000047

Table 1: Interior orientation parameters

The two cameras were calibrated separately by the use of a planar calibration field available by Zeiss Inc. It consists of a high definition grid engraved on a plate of glass. The intersections are 22.5 mm apart and accurately calibrated to a tolerance of 0.002 mm. The dimensions of the plate are 23×23 and a total of 121 control points can be of use. The calibration method that was adopted is fully described in [19]. Several photographs of the calibration field were acquired with different orientations and rotation angles (fig. 1). The coordinates of the control points in the image space were calculated at the intersections of the grid lines. For this purpose vertical and horizontal lines were automatically extracted from the images with sub-pixel accuracy.

To identify the linear features on the images, the Canny edge detector is employed [4]. The result of this operation is a binary image whereby the left and right edges of linear features are represented by white pixels. Straight lines are identified on the binary images using Hough Transform [12]. Connectivity between straight lines is then established and the extreme edge points along each line are recognized. Extracted edge points are then used to define the search space for the intermediate points along the line. Image profiles along the outline edge points are inspected to determine the location of the intermediate points with sub-pixel accuracy, by means of a moment based edge operator (fig. 2) [7]. The extracted grid lines are classified as vertical or horizontal and the coordinates of the control points are measured at the line intersections.

A number of 17 images, acquired at 2560×1920 pixel resolution, were used for camera calibration. The calibration software was supplied with a total of 1400 control points that were automatically identified on the images.

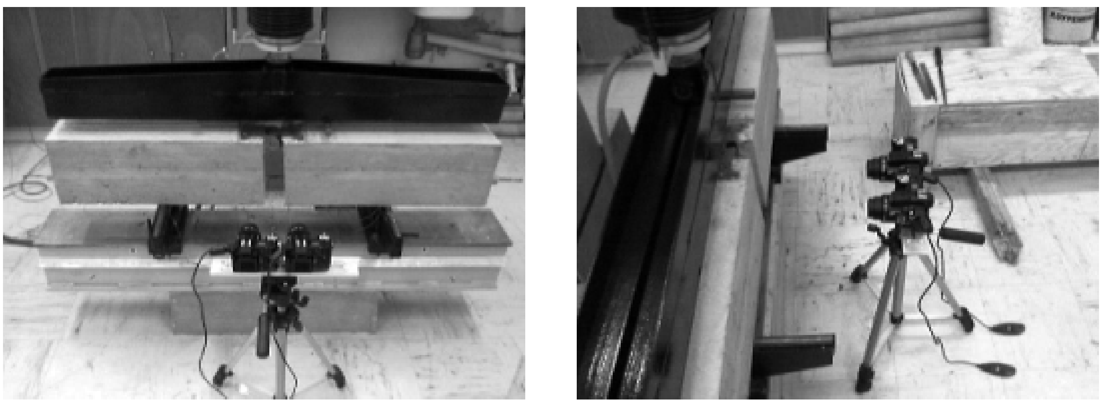


Figure 3: Experiment configuration

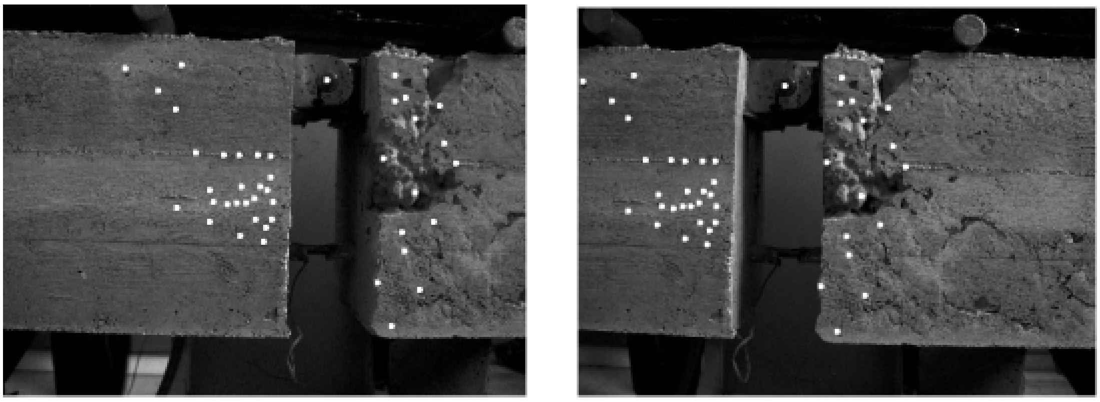
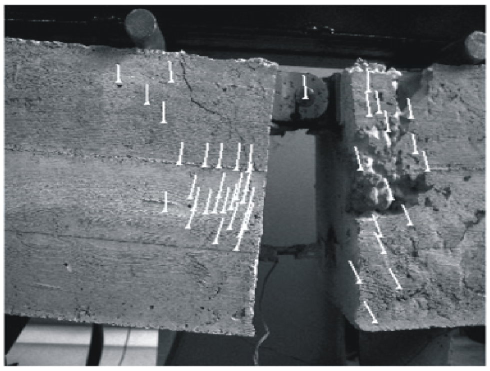


Figure 4: Measured detail points (left and right image)

The calibration results, i.e. the parameters of the interior orientation and the respective standard deviations, are presented in table 1. To asses the quality of the calibration method, the control points were projected to the image plane using the estimated interior orientation parameters. The standard deviation of the residuals between measured image coordinates and the projected control points was calculated for each image. The overall standard deviations for all images were $\sigma_x = 0.18$, $\sigma_y = 0.15$ and $\sigma_x = 0.20$, $\sigma_y = 0.24$ (in pixels) for the left and right camera respectively.

The two cameras were mounted on a stable base and placed in front of a concrete beam, at a distance of 30 cm. The beam is consisted by two rectangular blocks of concrete. A steel ball joint at the top joints the blocks and allows the rotation by the axis of the join. At the bottom a glass fiber reinforcing polymer (GFRP) bar joints the two blocks (fig. 3). To estimate the exterior orientation parameters of the camera stations, the calibration plate was captured by both cameras. Then a typical photogrammetric resection was implemented twice. To evaluate the accuracy of the coordinate measurements in the object space, the coordinates of the control points were calculated by photogrammetric intersection and compared to the actual ones. From the observed residuals it was shown that accuracies better than of 100 microns can be only achieved in the area around the center of the image. The dimension of this area in the object space is about 11×9 cm. The root mean square error (RMSE) of about 30 control points was estimated at $\sigma_x = 19.6$ µm, $\sigma_y = 19.3$ µm, $\sigma_z = 36.7$ µm. Outside this area, the observed errors are gradually increased due to the large distortions of the lenses that cannot be compensated by the calibration model.

The measurements were carried out for five deformation states. About 100 detail points were selected to be measured on the surface of the concrete element. These points were automatically identified in textured areas with high intensity by the use of a Harris operator [15]. They were identified on the left image of the first deformation state and then transferred to the right image. A least squares matching approach was used in order to find point correspondences with sub-pixel accuracy [9]. The measurement points were tracked on the subsequent images using optical flow techniques. For this purpose, the Lucas-Kanade iterative method was implemented [14]. From the 100 detail points initially selected, 42 were successfully tracked in all subsequent images (fig. 4). The object coordinates of these detail points were calculated at each deformation state by photogrammetric intersection. Displacement vectors as well as deformation diagrams in X, Y, Z direction were finally created for each measured point (fig. 5).



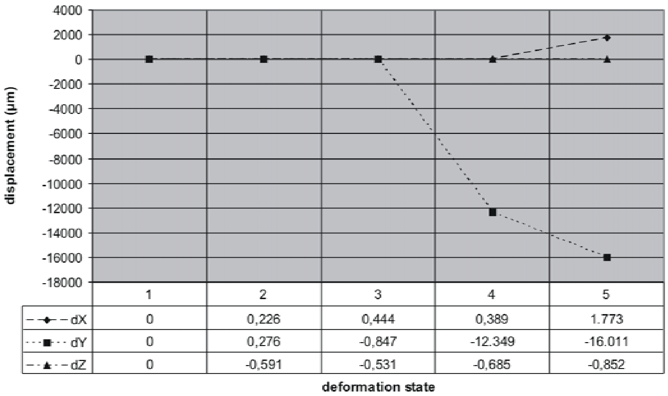


Figure 5: Deformation vectors and displacements

4. Concluding remarks

Although photogrammetric methods offer great advantages compared to conventional monitoring methods used in engineering experiments, it is still questionable whether the accuracy requirements can be achieved under different circumstances. In this work, the potential of using commercial CCD cameras for displacement monitoring at the micron level accuracy was investigated.

From the implementation results it was demonstrated that accuracies in the order of 10ths of microns can be expected, for a distance of about 30 cm from the object’s surface. The accuracy is mainly affected by the distortion of the lenses that are usually enlarged in conventional CCD cameras. However, proper calibration may compensate these sources errors and offer acceptable results near the centre of the image.

Future work will concentrate on the use of two high resolution video cameras that will be both synchronized to monitor high frequency displacements. Furthermore, emphasis will be given on the calibration procedures to optimise the estimation of lens distortions parameters, which will improve the obtained accuracies.

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References:

[1] ASPRS,: Manual of Photogrammetry. Fifth Edition, 2004.

[2] Baltsavias, E.P., Waegli, B.,: Quality Analysis and Calibration of DTP Scanners. Paper presented at the 18th ISPRS Congress in Vienna. In 'International Archives of Photogrammetry and Remote Sensing', Vol. XXXI/B1, pp. 13-19, 1996.

[3] Bradshaw, G.,: Non-Contact Surface Geometry Measurement Techniques. Dept. of Computer Science, Trinity College Dublin, Ireland, 1999.

[4] Canny, J. F.,: A computational approach to edge detection. Transactions on Pattern Analysis and Machine Intelligence, vol. PAMI-8, pp. 679-698, November 1986.

[5] Clarke, T.A, : An analysis of the prospects for digital close-range photogrammetry, Photogrammetry. (Invited paper). ISPRS Journal of Photogrammetry and Remote Sensing, 50(3): pp. 4-7, 1995.

[6] Clarke, T.A., Fryer, J.F., : The development of lens calibration methods and models. Photogrammetric Record, 16(91): pp 51-66, 1998.

[7] Cosandier, D., Chapman, M.A,: High Precision Target Location for Industrial Metrology. SPIE Vol.1820, Videometrics, pp.111-122, 1992.

[8] Fraser, C. S.,: Digital camera self-calibration. ISPRS Journal of Photogrammetry and Remote Sensing, 52(4), pp. 149-159, 1997.

[9] Gruen, A.,: Adaptive least squares correlation: a powerful image matching technique. South African Journal of Photogrammetry, Remote Sensing and Cartography, 14(3), pp. 175-187, 1985.

[10] Habib, A., Lee, Y., Morgan, M., 2002. Bundle Adjustment with Self-Calibration using Straight Lines. Photogrammetric Record Journal, 17(100):635-650, October 2002.

[11] Hampel, U.; Maas, H.-G.: Application of digital photogrammetry for measuring deformation and cracks during load tests in civil engineering material testing. 6th Conference on Optical 3-D Measurement Techniques. Prof. A. Grün, Institute of Geodesy and Photogrammetry, Swiss Federal Institute of Technology, Zürich, Vol. II, pp. 80-88, 2003.

[12] Kamat V., Ganesan S.,: A robust Houghtransform technique for description of multiple line segments in an image, in: Proceedings of International Conference on Image Processing (ICIP'98), pp. 216–220, 1998.

[13] Lopez-Anido, R., El-Chiti, F.W., Muszyński, L., Dagher, H.J., Thompson, L., and Hess, P.E.,: Composite Material Testing Using a 3-D Digital Image Correlation System. Composites 2004, American Composites Manufacturers Association, 7 pp., Oct. 6-8, Tampa, FL, 2004.

[14] Lucas, B., Kanade, T., An iterative image registration technique with an application to stereo vision. Proc. DARPA Im-age Understanding Workshop, 1981.

[15] Schmid C., Mohr R., Bauckhage C.. Evaluation of interest point detectors. International Journal of Computer Vision, 37(2):151–172, June 2000.

[16] Shortis, M.R., Clarke, T.A., Short, T.,: A comparison of some techniques for the subpixel location of discrete target images, Videometrics III. Boston. SPIE Vol. 2350. pp. 239-250, 1994.

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

[18] Willneff J., Maas H.-G,: Design and calibration of a four-headed camera system for use in microgravity research. International Archives of Photogrammetry and Remote Sensing, XIXth ISPRS Congress Amsterdam 2000Volume XXXIII, Part B5/2, Comission V, pp 894-899, 16-23 July 2000, Amsterdam, The Netherlands, 2000.

[19] Zhang, Z.,: Flexible camera calibration by viewing a plane from unknown orientations, Proceedings of the Fifth International Conference on Computer Vision (Proc. ICCV'99), Vol.I: 666-673, 1999.