

High Accuracy Deformation Monitoring of a Concrete Beam using Automatic Photogrammetric Techniques

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Key words: Deformation monitoring, Automation, Loading test, Image matching, Non contact method, Low cost

SUMMARY

Deformation monitoring of construction objects, like beams, in laboratory conditions are very useful for the theoretical design of material behaviour modelling. It is typically undertaken using contact methods, which can achieve accuracies better than 0.5mm, but measurements of displacements can be done point-wise and in one dimension only. In order to enable the use of non contact methods comparably high accuracies must be ensured; data can be collected during a dynamically developed phenomenon; displacements in three dimensions can be provided; the data processing and result extraction will not be time consuming. In this paper an application of an automatic photogrammetric process is proposed, which satisfies all previously mentioned prerequisites for monitoring the dynamic behaviour of concrete beams when exposed to mechanical strain during a loading test. Accurate geodetic measurements for the determination of 3D coordinates of control points and acquisition of image stereo-pairs by a system of two calibrated and synchronised digital cameras mounted on a stable basis are required. Images are taken in load free state and in every loading epoch until the beam reaches its breaking curve. When all data is collected, the exterior orientation of the first stereo-pair is calculated by a photogrammetric resection solution. In every epoch an automatic target localisation algorithm, based on a combination of normalized cross correlation and least squares matching, is applied in order to measure image point coordinates pre-signed points on the beam. Afterwards, 3D point coordinates are calculated by a photogrammetric intersection solution using the results of the template matching as well as the stable exterior orientations. Point displacements from the beginning of the loading test to the total beam breakage are computed. The experimental results show that the attained accuracy is 0.5-1mm in object space.

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1. INTRODUCTION

Among the most common engineering applications is the deformation monitoring of structures or structural components under loading conditions. There are two main approaches of observing the structural behaviour: contact and non contact methods. According to the contact methods, high accuracy instruments, such as dial gauges, extensometers, LVDTs (Linear Variable Differential Transformers) and fibre optics are used to measure displacements on the surface of the object with very high accuracy ($10\text{-}1000\mu\text{m}$). Their greatest disadvantage is their ability to measure point-wise and in one dimension only. In most cases, due to the strain imposed to the object, it is likely to be damaged as those devices are really fragile and require a considerable amount of attention. Also, these are expensive devices and are not applicable to some parts of the structure, due to practical reasons, whose detection of behaviour is significant for the test though.

Non contact methods provide the opportunity to measure a large number of points distributed over the whole object, in three dimensions with respectable results related to the required accuracy. Various techniques have been proposed and applied, either low cost or by using special and expensive instruments, on several cases with great success and with very accurate results. Such techniques for indoor-laboratory applications are:

- Geodetic techniques implement spatial intersection for the determination of the 3D coordinates of specific points, by acquisition of high accuracy angle measurements. Automation of procedures with the use of robotic total stations (RTS) (Gikas, 2008) has increased the range of applications of this method. However it is still impossible to monitor dynamic deformations because the measuring procedure is time consuming (Tsakiri et al., 2004).
- Close range photogrammetric techniques with the use of automated procedures (automatic localisation, image correlation, automatic recognition and measurements) and use of one, two or more synchronized digital cameras. They can be applied in order to acquire 3D points with increased accuracy and reduced on-site time (Fraser & Riedel, 2000; Psaltis & Ioannidis, 2006; Fryer et al, 2007). These techniques can be fast and cost effective applying various techniques, such as rectification, stereo-restitution or photo-triangulation (Luhmann et al, 2006).
- Terrestrial Laser Scanners (TLS), time-of-flight or phase shift, are able to collect dense 3D point data over the entire object and establish a permanent visual record, without the requirement of targets. However, the cost of those devices is high and their perceived poor precision (worse than 2mm) has precluded their use (Gordon et al, 2003).
- Structured light 3D scanners are used for measuring the three dimensional shape of an object using projected light patterns and a system with one or two cameras and a LCD projector. Nonetheless, designing such a system is of high cost and as with all optical

methods, it raises difficulties regarding reflective, semi-transparent and transparent surfaces (Fechteler & Eisert, 2008).

- Videometric methods offer high precision detection and continuous 3D data but once again, it is expensive to use high definition synchronized camcorders.
- Microwave (RADAR) interferometry for very high accuracy (at the order of microns) but less robustness, and application possibilities on objects of limited dimensions (e.g., 3D ESPI System Q-300®, etc).

In this paper a low cost method based on optical techniques and automate image correlation is developed and applied, for the achievement of high accuracy results for monitoring in three dimensions of pre-signed points on the surface of a loaded concrete beam. Geodetic measurements before the beginning of the loading test and acquisition of image stereo-pairs during the loading phase are made, using a system of two calibrated and synchronized digital cameras. The measuring process is automated and the achieved accuracy is better than 1mm. At first, the proposed procedure is described, being followed by conducted loading test, the data collection and data processing. Thereafter, the results and conclusions exported are mentioned.

2. PROPOSED PROCEDURE

Three main parameters have been taken into consideration for the selection of the proposed procedure taken into account:

- 3D monitoring of a great number of points with accuracies up to 1mm or better
- simplicity of the technique and use of low-cost instruments; even a non expert could perform the measurements and apply the proposed procedure
- on line or almost on line calculation of the results.

The method includes (a) measurements and data acquisition at the laboratory and (b) data processing and compilation of deformation diagrams in three dimensions. The steps of each one of the above two stages are described and the flow chart of the procedure is given below (Figure 1).

(a) Data acquisition in the test field:

- Placement of a pair of calibrated and synchronized digital cameras in stable positions, so that the geometry of the two optical bundles and the pixel size in object space will allow the achievement of high accurate results.
- Reflective targets, which are appropriate for the achievement of the most accurate geodetic distance measurements, are placed as control points (necessary measurements for the scaling of the photogrammetric stereo-model system); and, placement of targets, which are special for automatic image recognition, on the points to be monitored on the beam.
- Geodetic measurements (angles and distances) of the control points, with a total station of high accuracy qualifications.
- Acquisition of an image stereo-pair at load-free state (0 epoch), using a stable system of two synchronized and calibrated cameras or video camcorders.
- Acquisition of the image stereo-pairs at each epoch during the test, by using remote control so that no intervention will be made on the cameras' position and orientation; as an

alternative video recording may be used by two synchronized video camcorders.

- For the accuracy and quality control of the results, repetition of (i) the acquisition of the stereo-pair of the last epoch and (ii) the geodetic measurements of the control points (for those that have been placed in stable locations independent of the movement of the beam).

(b) Data processing:

- Recording of the synchronised image frames, derived from the two cameras, for each epoch (including 0-epoch).
- Image processing (if required) in order to facilitate later automatic procedures for image matching.
- Calculation of the object coordinates of the control points, using the geodetic measurements before or/and after the end of the loading test. Selection of an object coordinate system the axes of which should have a physical meaning for the determination of the displacements (e.g., x-axis parallel to the basic displacement direction and so on).
- Manual measurement of the image coordinates of control points at the stereo-pair of the 0-epoch (reflective geodetic targets are not appropriate for automatic localization and measurement on the images).
- Photogrammetric resection for the calculation of the parameters of the exterior orientation of each image of the stereo-pair at the load-free state (0-epoch). In case geodetic measurements of (at least 4) control points have been made after the end of the loading test, a photogrammetric resection adjustment for the images of the last epoch follows;

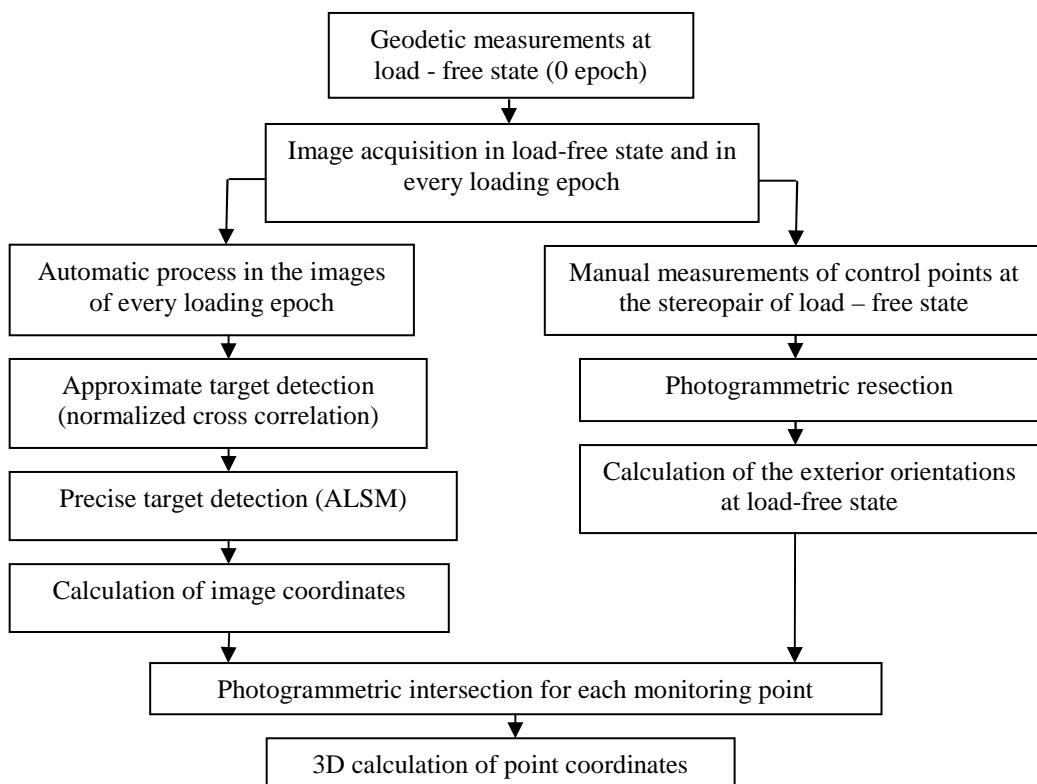


Figure 1: Flow chart of the proposed procedure

comparison of the two sets of exterior orientation parameters of each camera in order to ensure the precondition that cameras have remained stable in terms of location and orientation during the whole duration of the loading test.

- Automatic localisation by matching techniques and automatic measurements of image coordinates of the monitoring points at the stereo-pairs of every loading epoch. Matching procedure is made in two stages: approximate positions of possible templates of all targets are located using normalized 2D cross correlation; final position of the template is defined through Least Squares Matching.
- Photogrammetric intersection for the calculation of the object coordinates of each one of the points (targets) to be monitored in all epochs.
- Calculation of the displacements of each point in three dimensions. Diagrams were constructed which show the horizontal and vertical displacements of points through the loading epochs.

2.1 Automatic detection

Automatic detection of the targets on the images can be achieved using various matching techniques. Since photogrammetric targets with a distinctive pattern, known shape and size are used for the test, template matching is a proper choice. The detection of the targets in each image is conducted in two stages. The first stage is the approximate detection of the targets, in which the approximate positions of possible templates are located. These are used as initial values for the next stage, the precise detection, where the final position of the template is defined with sub-pixel accuracy.

The approximate positions are acquired using normalized 2D cross correlation. In normalized cross correlation, the template lays on every possible position on the image and then the value of the coefficient ρ (Equation 1) is calculated for every position. The final position of the template is that where ρ has the maximum value.

$$\rho(u, v) = \frac{\sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [g(i, j) - \bar{g}_{uv}] [t(i-u, j-v) - \bar{t}]}{\sqrt{\sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [g(i, j) - \bar{g}_{uv}]^2 \sum_{i=u}^{u+R} \sum_{j=v}^{v+C} [t(i-u, j-v) - \bar{t}]^2}} \quad (1)$$

where: g = image function of the reference

t = image function of the template

R = rows of the template

C = columns of the template.

This can be done easier and quicker if the localisation is restricted to specific parts of the image (i.e. blobs). This is achieved by image histogram thresholding, according to which a statistical criterion is calculated. At first, the image is transformed into a binary raster and then the criterion is calculated repetitively until the minimum value is acquired. The minimum value represents the most appropriate threshold value. For every blob as well as the template, the tone mean is calculated with regards to the criterion. Afterwards, the normalized

correlation factor is recalculated for both the template and the image, while the approximate image coordinates are defined.

The precise detection of the targets is achieved through Least Squares Matching (LSM), based on adaptive least squares correlation (Grün, 1985). The method is tagged as "adaptive", because it can be executed in a self-tuning mode, meaning that the parameter set to be estimated can be automatically corrected in order to obtain a most appropriate estimation model set-up, with respect to the specific signal content of the patches to be matched.

The function of the method requires the import of specific parameters, which are: template size, maximum shift, maximum rotation and maximum number of iterations, color correction (optional), template image, image for the adjustment, center image coordinates on the template, approximate values (as acquired by the previous stage). The procedure is iterative. Every time the template is detected on the research window the execution is interrupted. Since the shape of the template is defined repetitively as well, it is highly likely that the calculated values of grey level are no longer integral, so the image is resampled using bilinear interpolation.

In some cases the solution vector converges very slowly, that it oscillates, or it even converges to a false solution. These cases indicate severe correlation problems and require further attention (Grün, 1985). The problem of weak or impossible correlation stems from that the data sets do not have sufficient signal content to allow for a reasonably accurate correlation. Although such a situation is signalized by an inflation of the standard deviations of one or both shift parameters values, the size of those standard deviations do not always represent a suitable quantitative measure for the amount of insecurity of the correlation. False correlation threatens if the data of the picture window allows for multiple solutions and if the first approximations for the least squares process are not close enough. The least squares estimator might then converge to a side-minimum.

3. LOADING TEST

The loading test was conducted in the Laboratory for Earthquake Engineering of the School of Civil Engineering of the National Technical University of Athens, Greece. The reinforced concrete beam is of a rotated T shape; a graphical representation of the beam and its dimensions are shown in Figure 2a. The vertical leg of the beam is pegged out using a hinge. The force during the loading test is executed on the upper part of the vertical leg of the beam. The area of the beam under study, in which cracks are expected to happen, is the intersection area of the horizontal and vertical legs of the T-shaped beam. The weakest areas are those around the two right angles of the intersection.

Thirty four black and white square targets (0.9 cm x 0.9cm), which constitute the points to be monitored, were placed close to the horizontal and vertical edges of the beam and on the whole surface under study. Distances between the targets were about every 10 cm, with increased density in the areas around the two corners of the beam (Figure 4). During the loading test seven more targets were attached to the beam's surface in places where shear cracks were formed, in an attempt to be measured (Figure 5).

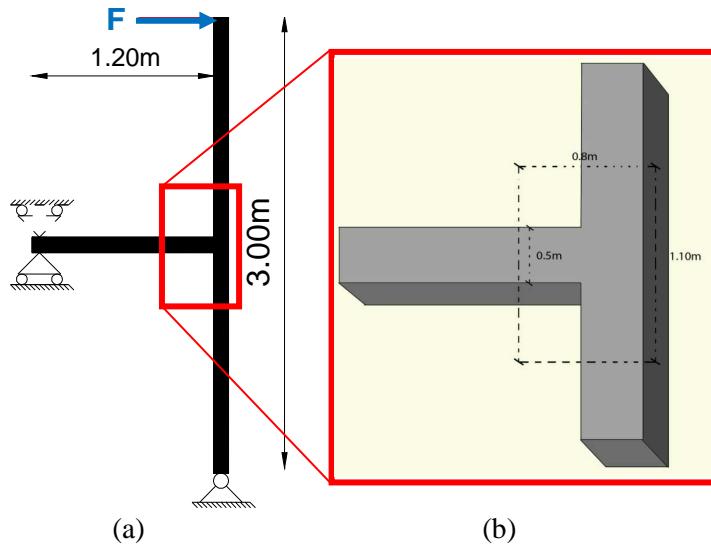


Figure 2: Representation of the beam; (a) the dimensions and the location of the force (F) are shown, and (b) detail of the intersection and dimensions of the area under study



Figure 3: Photo of the cameras setup. The base of the two cameras on a stable tripod, and the PC for the operation control and the storage of the image frames

Beside the photogrammetric targets, nine reflective targets were placed to serve as control points. Due to lack of stable areas around the beam, 5 of the reflective targets were placed on the beam itself. Finally, in photogrammetric resection adjustment only 6 of these control points were used (3 on the beam's surface), the location of which is numbered and marked with a yellow outline in Figure 4.



Figure 4: A photo of the beam with the area under study, with the distribution of points to be monitored (rectangular b/w targets) and control points (numbered and marked in yellow), at load-free state

A configuration of two calibrated and synchronized Basler A404k/kc digital cameras were used for the image acquisition. In order to keep their relative orientation stable during the loading test, the two cameras are mounted on a stable base, at a distance of approximately 60cm from each other; the base and the cameras are marked in red outline in Figure 3. Interior orientations of the two cameras are calculated automatically with bundle adjustment by processing stereo pairs of a 2D chess-board (Prokos, 2012); the results are given in Table 1.

Table 1: Interior orientations of the left (l) and right (r) camera respectively

$c_x_l = 4078.04 \text{ pix} \pm 0.91$	$c_x_r = 4088.94 \text{ pix} \pm 0.91$
$c_y_l = 4072.23 \text{ pix} \pm 0.89$	$c_y_r = 4091.10 \text{ pix} \pm 0.90$
$x_o_l = 22.19 \text{ pix} \pm 1.39$	$x_o_r = 3.76 \text{ pix} \pm 1.36$
$y_o_l = 13.18 \text{ pix} \pm 1.29$	$y_o_r = -12.53 \text{ pix} \pm 1.25$
$k1_l = -6.572313e-009 \pm 1.031158e-010$	$k1_r = -6.953950e-009 \pm 1.008159e-010$
$k2_l = 9.255619e-017 \pm 4.921238e-017$	$k2_r = 3.044703e-016 \pm 4.606968e-017$
$p1_l = -4.130962e-007 \pm 3.318374e-008$	$p1_r = -6.484428e-007 \pm 3.319799e-008$
$p2_l = 1.926336e-007 \pm 2.702347e-008$	$p2_r = -1.758409e-007 \pm 2.552702e-008$

Each one of the cameras contains a high quality CMOS sensor with 2352x1726 pixels (4MB), with optical size of $1\frac{1}{4}$ " (3.175 cm) and pixel size 7 μm . A basic characteristic is that they have a very high frame rate (96 fps at full resolution). Thus, a dense acquisition of synchronized image pairs becomes possible, for the creation of a video recording of the loading test. In general, the system is appropriate for the monitoring of dynamic phenomena as a camera frame grabber is used to collect and evaluate the data, and connect the camera and the PC via the special Camera Link® interface, which enables a maximum data transmission rate of 680 MB per second.

The approximate distance between the cameras' base and the beam was set at 2m, so the pixel size of the images is 0.5 mm in object space and the image scale approximately 1:70. That way the prerequisites to achieve the accuracy requirements are fulfilled. As the position of the configuration was desired to be stable during the whole test, the use of a remote control for the acquisition of the stereo-pairs was considered necessary.

The geodetic measurements on the control points were conducted with a use of an industrial total station Leica TDA 5005, of high accuracy specifications: the angle accuracy is 1.5^{cc} and the distance accuracy is $1 \text{ mm} \pm 2 \text{ ppm}$. The three dimensional object coordinates of the control points were determined through multiple resections with rms errors less than 0.7 mm, which are quite satisfactory.

The loading test begun with the acquisition of the first pair in the load-free state (0-epoch). Afterwards, the beam is imposed to mechanical strain until shear failure occurs. It was strained successively by forces of altering direction (e.g., the force at the 1st epoch was +18Nt, at the 2nd epoch -32 Nt and so on) and of gradually increasing value. Thus, the value of the strained force varied from +18 Nt at the 1st epoch to +143 Nt at the 31st epoch, and from -32 Nt at the 2nd epoch to -157 Nt at the 32nd (last) epoch. It took 32 loading epochs and 7 hours to reach ultimate breakage. Two additional stereo-pairs were acquired at the end of the test

(images of the last epoch), due to verification causes.

4. DATA PROCESSING AND RESULTS

First the recording and storage of the image frames for each epoch took place; it was noticed that stereo-pair of the 24th epoch was not recorded. Measurements of the image coordinates of the 6 control points and the 34 points to be monitored (photogrammetric targets) at the load-free state (Figure 4) were made and the parameters of the exterior orientation of the cameras were calculated by photogrammetric resection; these parameters are considered to be stable for the rest of the loading test. The parameters and the rms error of the adjustment are given in Table 2.

Table 2: Results of the exterior orientations of the left and right camera respectively

	Left image	Right image
X _o	3.5884 m	4.1724 m
Y _o	1.9767 m	1.9977 m
Z _o	4.7483 m	4.7535 m
ω	0.0627 grad	0.0215 grad
ϕ	0.0025 grad	0.0163 grad
κ	-0.0049 grad	-0.0050 grad
σ	1.50 pixel	1.59 pixel

For the precise detection of the photogrammetric targets on the stereo-pairs of the 31 loading epochs is achieved using a software based on adaptive least squares correlation. Every time the template (the image of the target) is detected on the research window, the execution is interrupted and the precise positions of the template are calculated, accompanied by on-screen diagrams, providing visualization of the correlation process. In Figure 5 the diagrams of the changes of the parameters of the algorithm are shown in an example of fast and successful convergence.

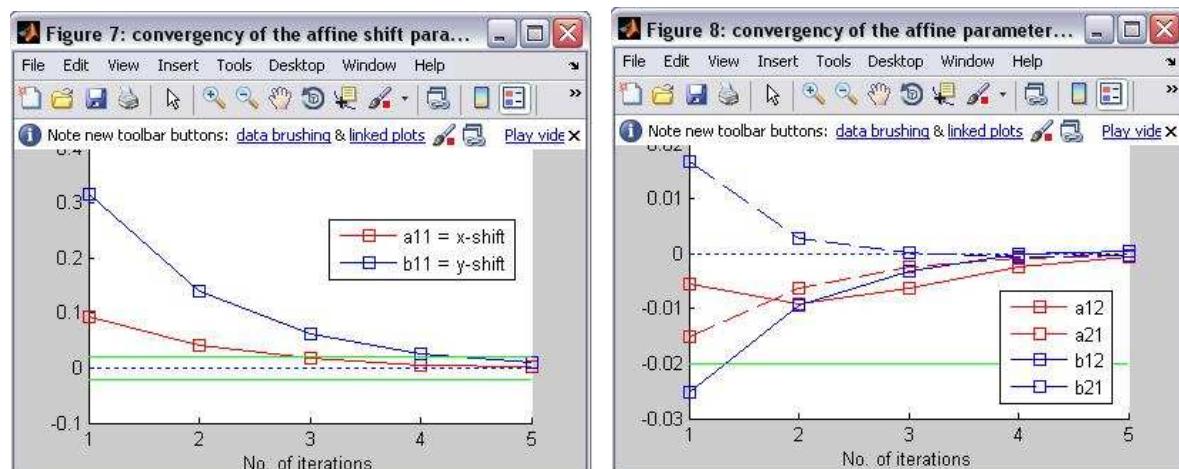


Figure 5: Example of convergence of the shift parameters (left) and the affine parameters (right)

During the execution of the second stage (precise detection) of the automatic detection

process the phenomenon of impossible and false correlation appeared in some cases. In Figure 6 a diagram is shown with an example of failure of convergence (left) and false detection of the target (right). The main cause was the low signal content of the parameters dataset, which originally derived from the weak lighting conditions throughout the loading test. That had a respectable impact on the whole process, thus creating dependence on manual measurements for the determination of image coordinates from one image to the other. However, the successfully tracked targets were calculated with subpixel accuracy.

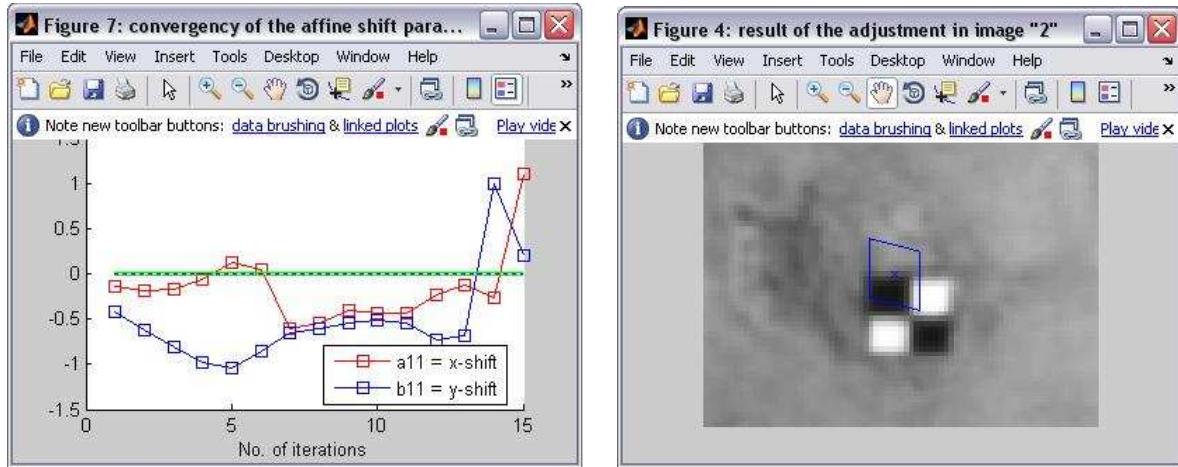


Figure 6: Example of low convergence or partial divergence of the shift parameters (left) and false detection of a target (right)

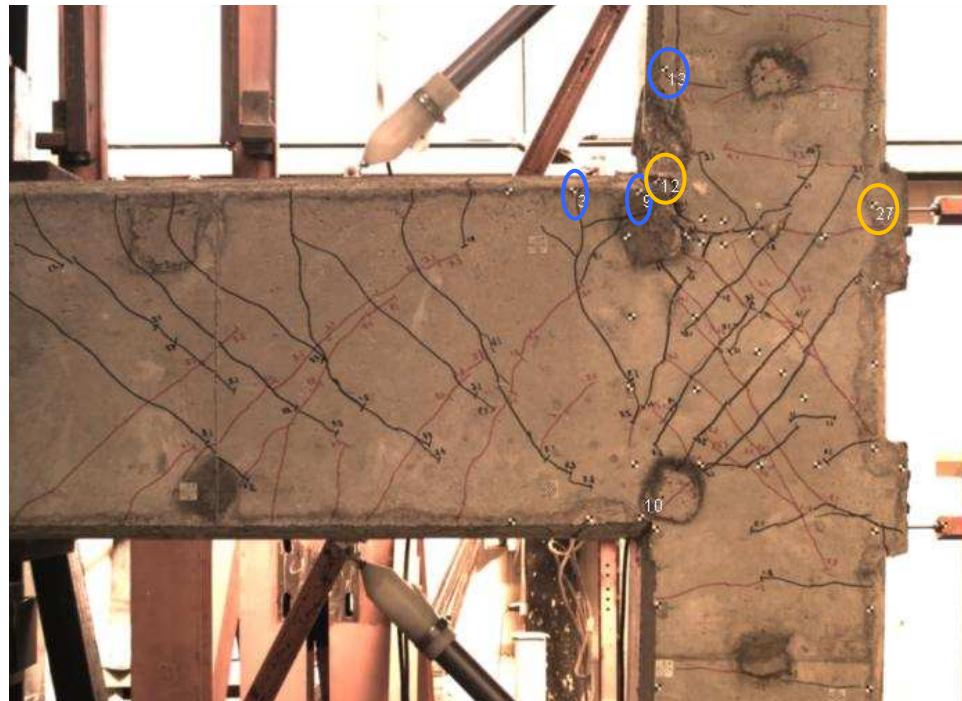


Figure 7: Left image of the 22nd epoch's stereo-pair; cracks are marked on the beam. The points 12 and 27 for which displacement diagrams are given, are marked in yellow circle; the points from which the upper angle of the beam was calculated are marked in blue circle

Until the 21 epoch 34 (photogrammetric) targets still existed, were detected and measured; between the 21 and the 22 epoch 7 targets were added in the region close to the upper angle of the beam, where the most and bigger cracks had happened (Figure 7). In the last four (29th - 32nd) epochs several targets were detached, especially at the corners of the beam, due to a surface damage of the material. 3D object coordinates of all points to be monitored are calculated by intersection solutions for every stereo-pair. The accuracy of the determined coordinates with the proposed procedure varies from point to point, but generally it is better than 1mm. Furthermore, the comparison between the 3D object coordinates of the 32nd (last) epoch and those derived from each one of the three additional stereo-pairs (which were acquired successively after the end of the loading test) showed insignificant deviation in point displacement, confirming the reliability of the results.

Diagrams of the 3D displacements of points in object space through the loading epochs were constructed; dx-along the horizontal leg of the beam, dy-along the vertical axis in object space, dz-along the axis which is vertical to the beam. In Figures 8 and 9 the diagrams of the displacements per axis and the movement on the beam's surface plane through the epochs, for the points 12 and 27 are shown; point 12 lies very close to the upper angle of the beam while point 27 is close to the edge of the vertical leg of the beam. From those diagrams but also from the study of the relevant diagrams of all monitoring points, it is derived that the displacement along the third axis (dz) it reaches, and in some cases it exceeds, 1cm (from the load-free state). So, the displacement in this direction is significant, usually of the same size with the dy displacement, and it should not be ignored during the study of the behaviour of the beam, as it practically happens when the measurements of the displacements are made with methods that provide results only for one of two dimensions.

One more parameter that is of significant importance for the detection of the behaviour of the beam and can be calculated with the proposed procedure without additional measurements are the angles formed by the two legs of the beam. It is sufficed to place targets along the horizontal and vertical edges of the beam. For example in this test the upper angle of the beam is shaped by the lines defined by the points 3-9 and 13-12 respectively. At a load-free state the value of this angle is very close 100 grad (the difference is due to construction weaknesses). In Figure 10 the fluctuation of the value of the angle through the epochs is shown.

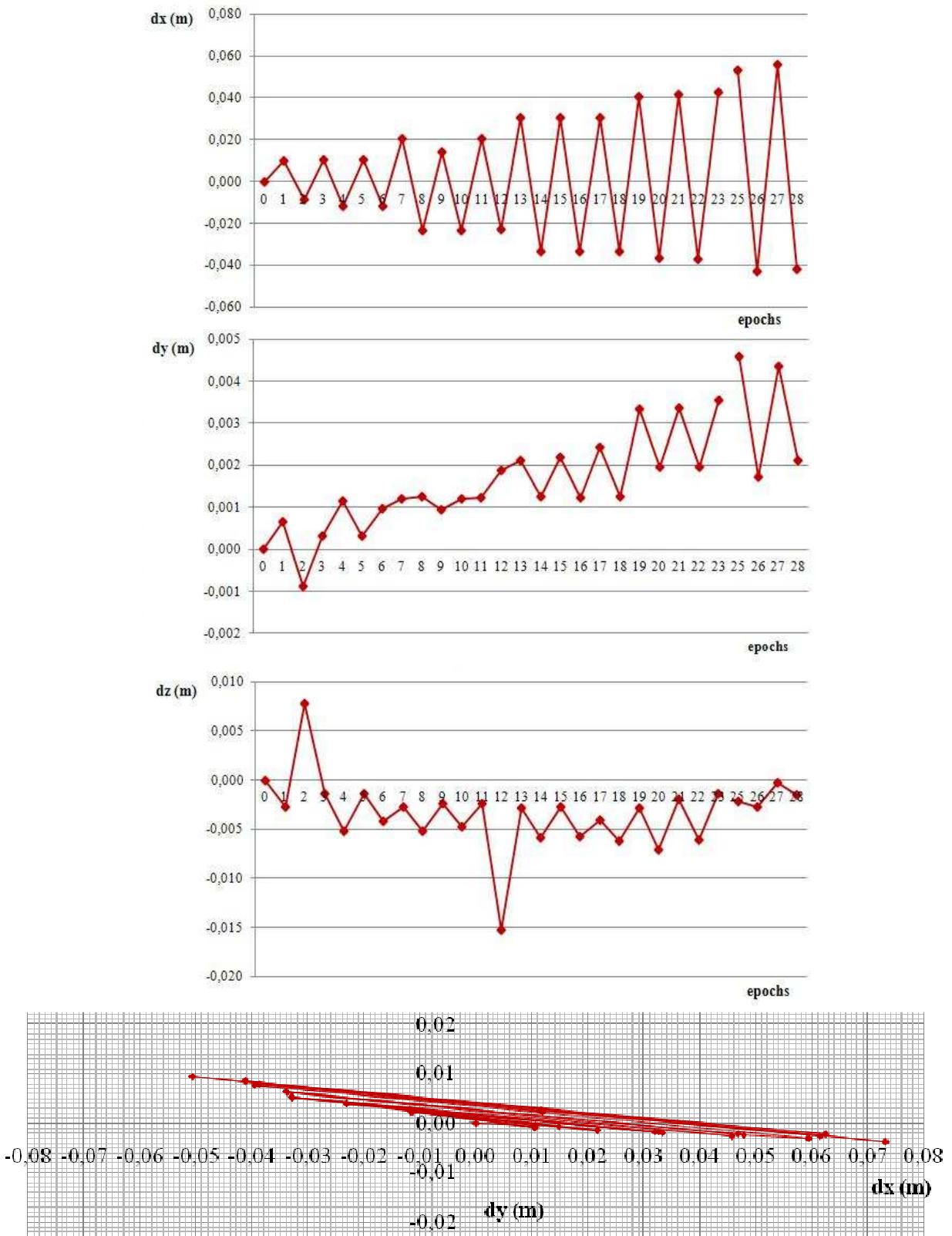


Figure 8: Displacements diagrams of point 12 through the epochs, along the dx , dy and dz axes. At the bottom the movement of the point on the beam's surface plane through the epochs is shown

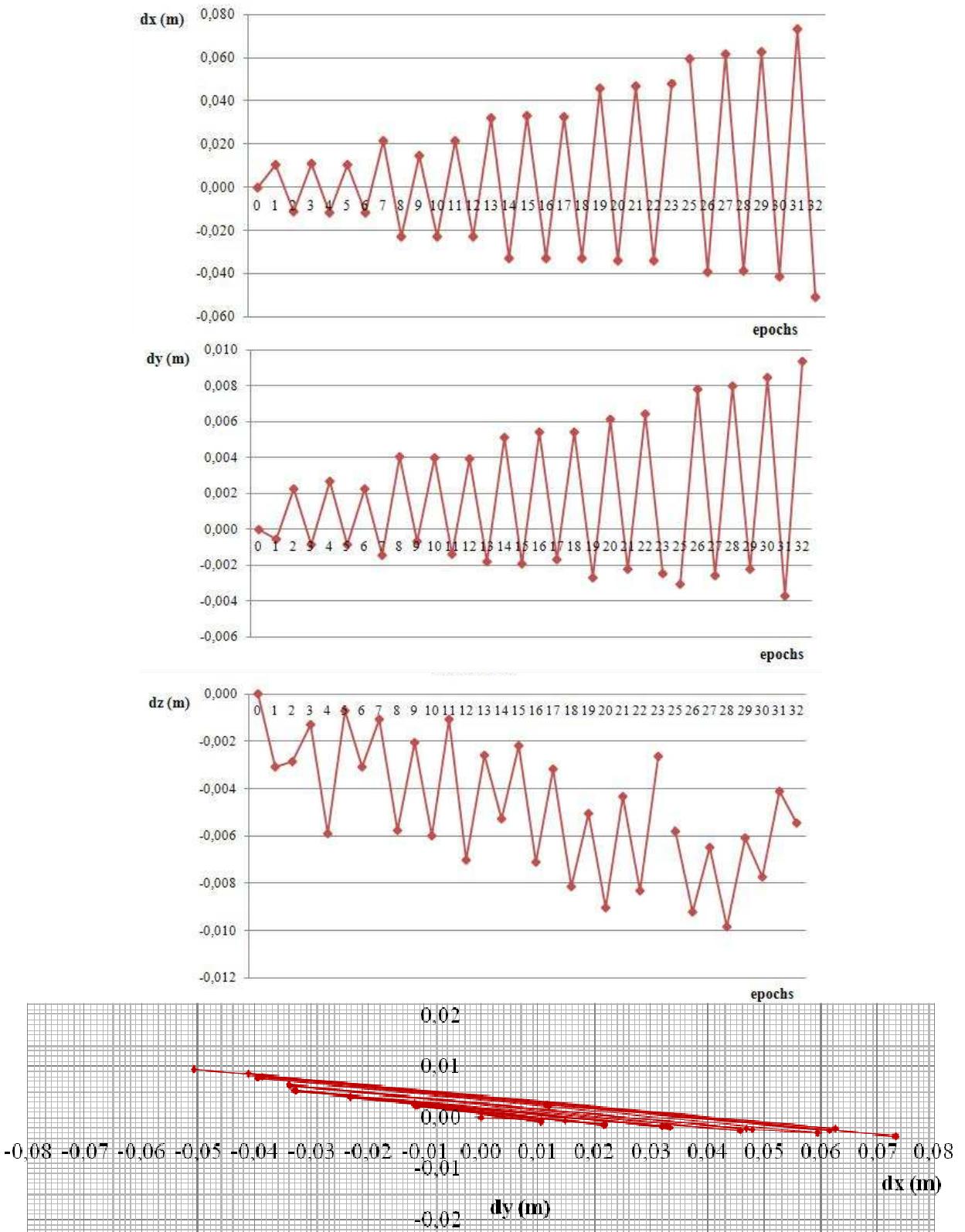


Figure 9: Displacements diagrams of point 27 through the epochs along the dx , dy and dz axes. At the bottom the movement of the point on the beam's surface plane through the epochs is shown

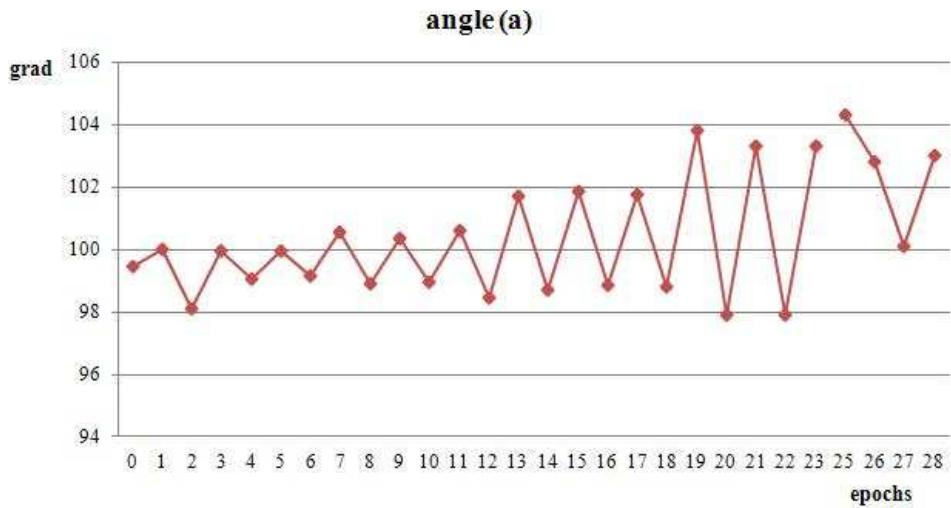


Figure 10: The size of the upper angle of the beam (angle between lines 3-9 and 13-12)

5. CONCLUSIONS

In this paper a simple and low cost technique is developed for the deformation monitoring of a concrete beam during a loading test. The major advantages of the proposed procedure are the calculation of displacements in three dimensions and the achievement of high accuracies in monitoring of a great number of points scattered on the surface of the beam by using a non contact method. In the described application test the displacements of the points are calculated with accuracies better than 1mm in the object space.

The necessary hardware for the application of this method is only two cameras. It is better to use large format synchronized cameras so that the acquisition of images from a larger distance (which would reduce the accuracy of the calculated displacements) will be avoided. Also, instead of doing accurate geodetic measurements (where there is a need for specialized hardware) the object coordinates of the control points can be derived from the use of specific calibrated constructions, e.g., frame(s) with pre-signed points of known coordinates, which should be placed around or close to the beam. By this way the establishment of a fully automated process is facilitated. Especially if this is combined with the use of appropriate coded targets for the points to be monitored and lighting conditions in the test field so that the matching techniques will lead to accurate automatic detection and localisation without weak or false correlation results. In addition, results better than 0.5 pixel that were achieved with the localisation algorithm used, will provide the use of multi-patch correlation, utilizing neighbourhood conditions, with the adjacent patches controlling and stabilizing each other, as well as the incorporation of additional geometrical constraints, such as the collinearity condition or the use of epipolar geometry.

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BIOGRAPHICAL NOTES

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Surveyor Engineer, graduate (2011) of School of Rural and Surveying Engineering, National Technical University of Athens (NTUA). Her main field of interest pertains to photogrammetric research and applications. Her diploma thesis focused on deformation monitoring using photogrammetric procedures. She is currently working at private sector on survey projects.

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1992-1996: Co-chairman of Commission VI -WG2-'Computer Assisted Teaching' in ISPRS.

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His research interests focus on terrestrial and satellite photogrammetry, aerial triangulations, digital orthophotos, applications of digital photogrammetry on the cadastre and GIS. He has authored more than 100 papers in the above fields, and has given lectures in related seminars both in Greece and abroad.

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