CASE STUDY OF BEAM DEFORMATION MONITORING USING CONVENTIONAL CLOSE RANGE PHOTOGRAMMETRY

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ABSTRACT

Deformation monitoring is an important procedure of measuring the structural health of completed civil engineering structures. Most traditional methods for measuring deflection occurring in structures require periodic access for designated inspectors to the particular area being monitored. As a remote sensing technique, photogrammetry does not need any contact with the objects of interest, and this can be a great advantage when it comes to the deformation monitoring of inaccessible or simply large structures. This paper shows a low-cost setup of multiple off-the-shelf digital cameras used for photogrammetric 3D object reconstruction for the purpose of deformation monitoring of structural materials. The setup was tested in two experiments, where concrete beams were being deformed at different loading conditions by a hydraulic actuator. The procedures necessary to measure the inflicted deflections consisted of: image data acquisition, collection of signalized target points, a single bundle block adjustment to establish the relative orientation for the multiple cameras, and a series of multiple light ray intersections in order to reconstruct the 3D object space coordinates of a set of sample points for each measurement epoch. The experiments proved that it was possible to detect sub-millimetre level deflections given the used equipment and setup.

KEYWORDS: civil engineering, geomatics engineering, remote sensing, close range photogrammetry, 3D object reconstruction, off-the-shelf digital cameras, structural deformation monitoring, concrete beam cracks and failure

INTRODUCTION TO DEFORMATION MONITORING

Whenever mechanical stress is applied to an object or a surface, this object or surface might be prone to changes in its shape and form, also known as deformations (e.g. elongation, compression or distortion). Deformation monitoring is a procedure of performing specific measurements of the object or surface of interest at regularly scheduled intervals in attempt to detect any changes that might have occurred. Structural deformation monitoring, i.e. monitoring the physical health of large and complex structures such as bridges, open-pit mines, dams, tunnels, high-rise buildings, etc., is necessary so that severe damage or complete destruction of infrastructure and what is worse – any casualties, are avoided as much as possible.

Traditional deformation monitoring techniques can be divided into geotechnical measurements and geomatics-based surveys (previously referred to as geodetic surveys). The geotechnical measurements are made with extensometers, tiltmeters, micrometers, etc., which yield the magnitude of the deformation relative to reference marks on the actual object being monitored. For this reason, they can only detect deformations in one dimension (1D), e.g. along lines or planes. On the other hand, geomatics-based surveys include traditional terrestrial surveying with precision levels, theodolites and electronic distance measurement (EDM) devices, global navigation satellite system (GNSS) positioning (DeLoach, 1989; Kim *et al.*, 2003; Lovse *et al.*, 1995) with geodetic grade receivers and antennas, and remote sensing techniques including airborne (Baltsavias *et al.*, 2001) and terrestrial laser scanning (González-Auilera *et al.*, 2008; Gordon and Lichti, 2007; Monserrat and Crosetto, 2008; Park *et al.*, 2007; Rosser *et al.*, 2005) and aerial or spaceborne (Fraser and Gruendig, 1985; Kääb, 2002) and close range photogrammetry (Fraser and Riedel, 2000; Jáuregui *et al.*, 2003; Lin *et al.*, 2008; Maas and Hampel, 2006; Mills *et al.*, 2001). The advantage of the geomatics-based surveys for deformation monitoring is that the instruments used allow for the determination of the deformation on an absolute scale, i.e. the points measured on the object of interest are tied to other points belonging to a reference coordinate frame. Also, these surveys can detect deformations in three dimensions (3D). Moreover, these methods allow for redundant measurements whose precision can be evaluated by a least squares adjustment. Other than the just described advantages, geomatics-based surveys can also be automated

(Bond *et al.*, 2008; Bond *et al.*, 2007). This can reduce the effects of any human errors due to performing tedious tasks during repetitious inspections. For example, the de la Concorde overpass in Laval, Quebec, collapsed a few hours after a structural inspection, which revealed no anomalies.

The disadvantage of the terrestrial surveying and the GNSS positioning techniques for deformation monitoring is that due to the nature of the used instruments only very few points can be observed, and this is why they have to be carefully selected by structural experts. In addition, the measurements must be performed by rarely found and thus highly paid professionals who specialize in engineering surveying. On the other hand, the remote sensing techniques of doing precise measurements (i.e. laser scanning and photogrammetry) are capable of reconstructing entire surfaces, and not just specific points (Lichti *et al.*, 2000). They also have an even further advantage – there is no need to access the object being monitored. For example, photogrammetry (i.e. the reverse process of photography) uses multiple 2D images of a 3D object taken from different locations to reconstruct that object as a digital model. In addition, current photogrammetric reconstruction systems can be built from inexpensive and replaceable sensors, which are two highly desired criteria of current structural monitoring systems. This is because low-cost off-the-shelf digital cameras are now flooding the market for electronic products, and they are replacing the expensive metric cameras used in close-range photogrammetry. The use of such digital cameras is becoming a convenient and an inexpensive alternative for 3D reconstruction applications such as cultural heritage documentation, facial reconstruction, biomedical imaging, and also – structural deformation monitoring. This study is thus motivated to investigate the potential for deformation monitoring of structural materials using photogrammetric 3D object reconstruction via a multiple digital camera setup. The next sections will describe the multiple camera setup, the conducted experiments, and the results, which will be followed by the final conclusions and recommendations for future work.

METAL FRAME AND MULTIPLE CAMERA SETUP

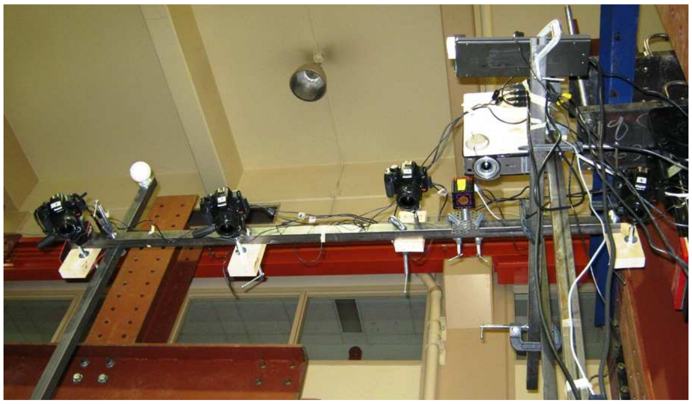
A multiple camera setup needed to be established on both sides of a hydraulic actuator (see Figure 1a) in a civil engineering laboratory. It was to be used to photograph a concrete beam (see Figure 1b) being statically loaded by the hydraulic actuator. In order for the cameras to be able to photograph the beam along the direction at which it is being loaded (i.e. from above as opposed to on the side of the beam), a metal frame (see Figure 1c) had to be designed, and built around the actuator.


(a) (b) (c)

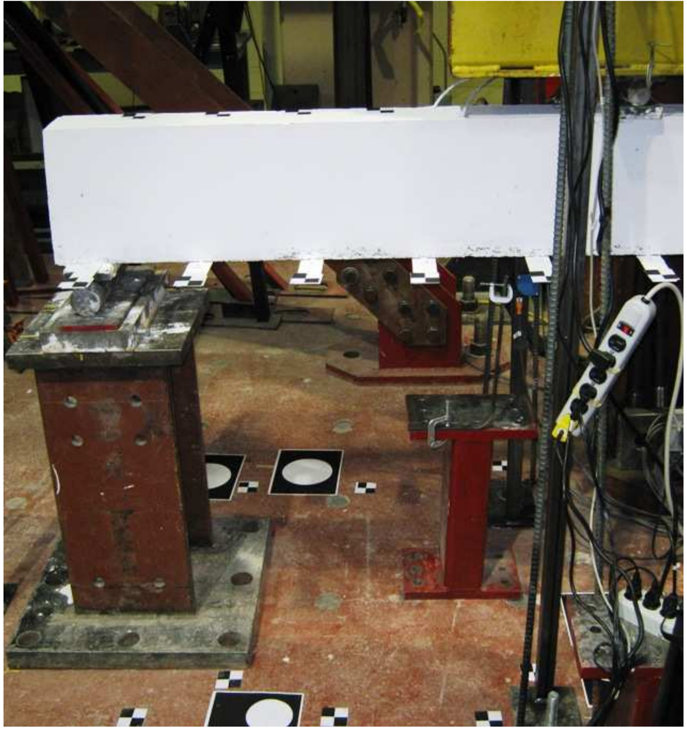
Figure 1. Examples of the hydraulic actuator (a), a concrete beam (b), and part of the metal frame (c).

Seven available off-the-shelf digital cameras were mounted on tripod heads, and attached to the top part of the metal frame (see **Figure 2**a). There were three prerequisites that had to be fulfilled before the employed cameras could be used for this project. First, they had to be geometrically calibrated and deemed stable; second, they had to have their relative orientation estimated; and third, they had to be synchronized to operate simultaneously.

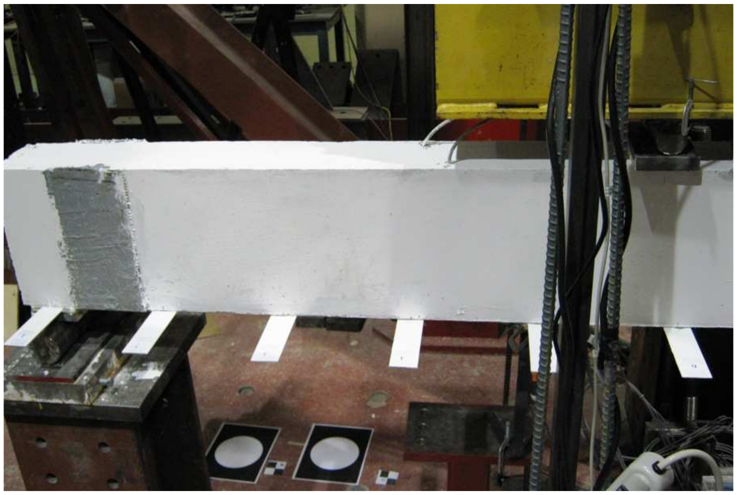
The objective of the geometric camera calibration process is to obtain the camera's internal characteristics or interior orientation parameters (IOPs), which include the principal point coordinates, the principal distance, and the lens distortion parameters (Habib and Morgan, 2003). The methodology and the procedures during the camera calibration were previously discussed in Detchev *et al.* (2010). In addition to the geometric calibration, the cameras also had to undergo a stability analysis procedure, which served to verify that the estimated IOPs would not change significantly over time. The stability analysis procedure was necessary, because the cameras were not originally designed for metric applications (Habib and Morgan, 2005; Habib *et al.*, 2005). The methodology for the camera stability testing were explained in detail in Detchev (2010). The location and orientation, i.e. the exterior orientation parameters (EOPs), of each camera station were obtained through a bundle block adjustment procedure using signalized target points spread out on both the floor of the civil engineering lab and on the actual concrete beams (see **Figure 2**b). Since the cameras were rigidly mounted on the metal frame, their relative EOPs were assumed to stay the same for the full duration of the experiments. Thus, the bundle block adjustment for estimating the relative orientation of the cameras was done only once before the beginning of each of the two conducted experiments, and the target points on the beam were removed right before the commencement of the actual testing (see **Figure 2**c).



(a)



(b)



(c)

Figure 2. Examples of the multiple camera setup (a), the distribution of signalized target points (b), and the removal of the targets from the beam for the rest of the testing (c).

CONDUCTED EXPERIMENTS AND RESULTS

There were two beam deformation monitoring experiments conducted. One of them used a concrete beam and the other one – a concrete beam with a polymer sheet support. Both beams were white-washed, three metres long, and were statically loaded by the hydraulic actuator. Each of the experiments had three phases:

1). Phase I – settling the beam on the given support by loading it from 0 mm load stroke up to 3 mm load stroke and releasing it back down to 0.8 mm load stroke two consecutive times;
2). Phase II – loading the beam up to 65 mm load stroke (or until failure) at regular intervals of 5 mm load strokes, and
3). Phase III – releasing the beam down to 0 mm load stroke (i.e. until the beam separated from the spreader beam attached to the actuator).

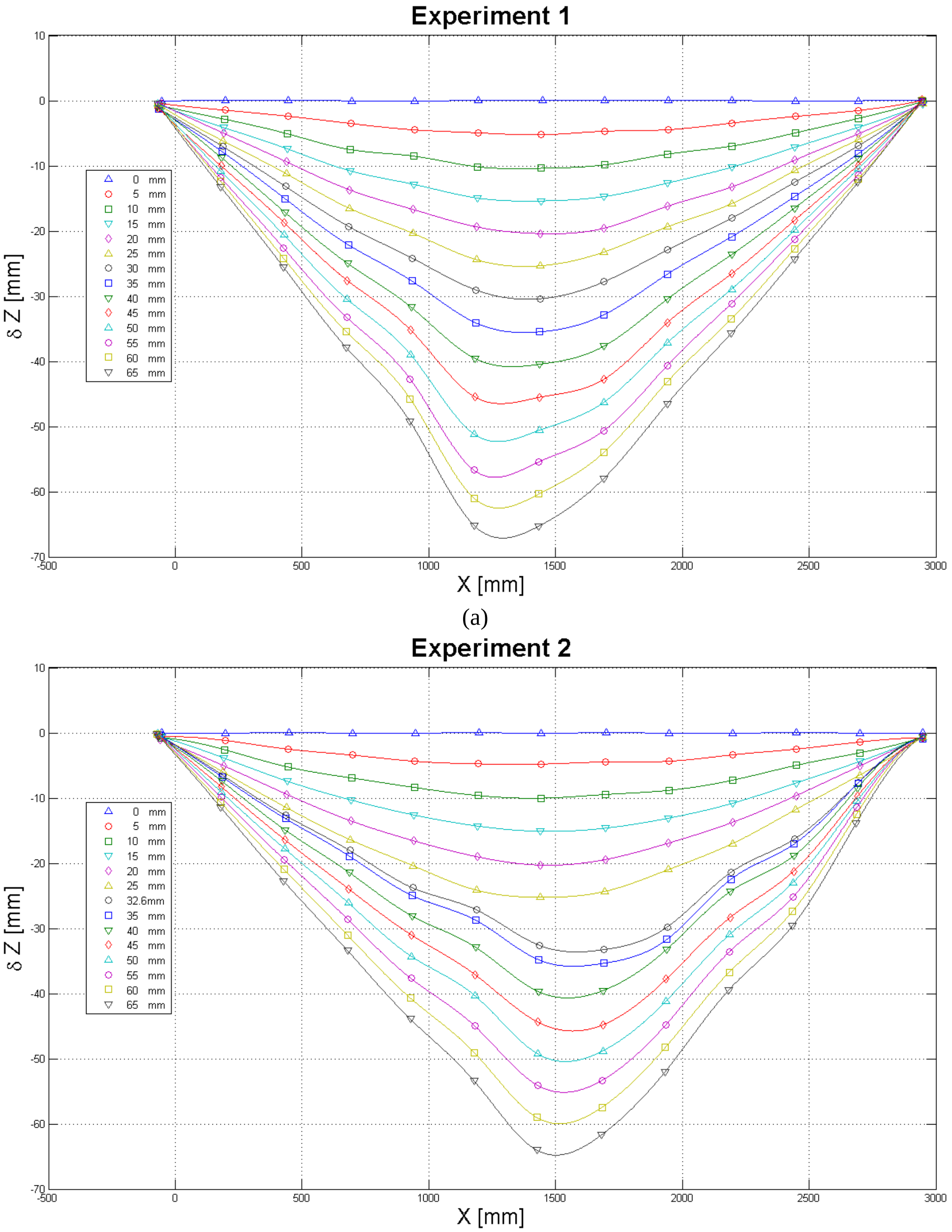
For each of the loading epochs there were several sensors collecting data in order to measure the beam deflections:

- Three 1D laser transducers (positioned under plates 5, 7, and 9);
- Seven digital cameras (and two projectors);
- Two terrestrial laser scanners, and
- Two range cameras.

During the two experiments, the spreader beam attached to the hydraulic actuator, and the hydraulic actuator itself, were obstructing the field of view of the cameras. So instead of observing the top surface of the beams, the cameras observed 5 cm x 15 cm white-washed aluminum plates attached at 25 cm intervals to the bottom of the beams. These metal plates served effectively as offset witnesses to the real beams.

So far, only the data from the 1D laser transducers and some manual photo measurements have been processed. The manual photo measurements involved collecting the image coordinates for the four visible corners of each aluminum plate at each loading epoch, and thus reconstructing the four most outside corners of these offset witness plates. Averaging the X, Y and Z object coordinates for the reconstructed four plate corners produced the object space location for the centroids of each plate. Subtracting the Z value of the centroids of each plate for the first epoch from the Z values of the centroids for the same plates for the rest of the epochs yielded the beam deflections (δZ) at each plate for each epoch. Example plots of Phase II for the two experiments can be seen in **Figure 3**.

In order to check the quality of the photogrammetric reconstruction, the δZ values for plates 5, 7, and 9 from the manual photo measurements were compared to the δZ values from the 1D laser transducers (see Table 1 and Table 2). For the first experiment, the mean for the difference values ranged between -0.3 mm and +0.2 mm, with standard deviations of ±0.2 mm and overall root mean square errors (RMSE) of 0.3 mm to 0.4 mm. The results for the second experiment were not as good – the mean for the difference values ranged between -0.5 mm and 2.0 mm, with standard deviations of ±0.5 mm to ±1.7 mm and overall RMSE of 0.7 mm to 2.6 mm. The reason for the higher deviations for the second experiment was that after the 25 mm load stroke, the polymer sheet separated from the second beam, and the metal plates got tilted, so their centroids were no longer valid offset witnesses to the true beam deflections.



(a)

(b)

Figure 3. Plots of the beam deflections for the first (a), and the second (b) experiments using the manual photo measurements.

Table 1. Experiment 1 deflection differences between the 1D laser transducers and the manual photogrammetric reconstruction for plates 5, 7, and 9

Phase	**Load Stroke**	**δZ Differences [mm]**		
		Plate 5	**Plate 7**	**Plate 9**
I	0 load	0.000	0.000	0.000
	3 mm	-0.390	0.121	-0.093
	0.8 mm	-0.215	-0.030	-0.364
	3 mm	-0.475	0.126	-0.166
	0.8 mm	-0.274	-0.186	-0.351
II	5 mm	0.127	0.200	0.106
	10 mm	-0.211	0.339	-0.459
	15 mm	-0.300	0.318	-0.078
	20 mm	-0.159	0.328	-0.389
	25 mm	-0.334	0.295	-0.592
	30 mm	NaN	0.325	-0.496
	35 mm	NaN	0.446	-0.474
	40 mm	NaN	0.393	-0.454
	45 mm	NaN	0.462	-0.419
	50 mm	NaN	0.506	-0.699
	55 mm	NaN	0.331	-0.294
	60 mm	NaN	0.225	-0.672
	65 mm	NaN	0.161	-0.440
III	60 mm	NaN	0.044	-0.112
	55 mm	NaN	0.182	-0.166
	50 mm	NaN	0.196	-0.125
	0 load	NaN	-0.321	-0.309
Stats	**Min**	**-0.475**	**-0.321**	**-0.699**
	Max	**0.127**	**0.506**	**0.106**
	Mean	**-0.248**	**0.212**	**-0.335**
	St. dev.	**0.171**	**0.207**	**0.210**
	RMSE	**0.295**	**0.293**	**0.393**

Table 2. Experiment 2 deflection differences between the 1D laser transducers and the manual photogrammetric reconstruction for plates 5, 7, and 9

Phase	**Load Stroke**	**δZ Differences [mm]**		
		Plate 5	**Plate 7**	**Plate 9**
I	0 load	0.000	0.000	0.000
	3 mm	-0.226	-0.228	0.163
	0.8 mm	-0.142	-0.173	0.129
	3 mm	-0.286	-0.234	0.057
	0.8 mm	-0.149	-0.113	0.333
II	5 mm	-0.170	-0.250	0.024
	10 mm	-0.508	-0.014	0.173
	15 mm	-0.669	0.036	0.164
	20 mm	-0.825	0.227	0.118
	25 mm	-1.110	0.168	0.031
	32.6 mm	-0.474	-0.130	3.527
	35 mm	-0.797	-0.344	3.746
	40 mm	-1.003	-0.450	1.918
	45 mm	-1.374	-0.682	3.329
	50 mm	-1.504	-0.875	3.448
	55 mm	-1.511	-1.028	3.728
	60 mm	-1.898	-1.088	3.826
	65 mm	-2.145	-1.128	4.209
III	60 mm	-1.876	-1.022	3.876
	55 mm	-1.918	-1.018	3.389
	50 mm	-1.595	-1.064	3.316
	0 load	-1.586	-1.267	2.912
Stats	**Min**	**-2.145**	**-1.267**	**0.024**
	Max	**-0.142**	**0.227**	**4.209**
	Mean	**-1.036**	**-0.508**	**2.020**
	St. dev.	**0.672**	**0.488**	**1.731**
	RMSE	**1.226**	**0.697**	**2.633**

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper explored the use of consumer grade cameras for deformation monitoring of structural materials. The aim of the two conducted experiments was to set up multiple cameras on a metal frame in order to be able to detect deflections in concrete beams caused by a hydraulic actuator. After performing a photogrammetric reconstruction using manually collected image coordinates, it was shown that sub-millimetre precision for the beam deflections could be achieved in object space. Future work will include processing the data from the terrestrial laser scanners and reprocessing the image data by performing semi-automated surface reconstruction of the full plates and the visible beam surfaces.

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REFERENCES

Baltsavias, E.P., Favey, E., Bauder, A., Bösch, H. and Pateraki, M., 2001. Digital Surface Modelling by Airborne Laser Scanning and Digital Photogrammetry for Glacier Monitoring. *Photogrammetric Record*, 17(98): 243-273.

Bond, J., Chrzanowski, A. and Kim, D., 2008. Bringing GPS into harsh environments for fully automated deformation monitoring. *GPS Solutions*, 12(1): 1-11.

Bond, J., Kim, D., Chrzanowski, A. and Szostak-Chrzanowski, A., 2007. Development of a Fully Automated, GPS Based Monitoring System for Disaster Prevention and Emergency Preparedness: PPMS+RT. *Sensors*, 7(7): 1028-1046.

DeLoach, S.R., 1989. Continuous Deformation Monitoring with GPS. *Journal of Surveying Engineering*, 115(1): 93-110.

Detchev, I., 2010. Implementation of a Close Range Photogrammetric System for 3D Reconstruction of a Scoliotic Torso. M. Sc. Thesis, UCGE Report Number 20316, Department of Geomatics Engineering, University of Calgary, Calgary, Alberta, 157 pp.

Detchev, I., Ebeling, A. and Habib, A., 2010. Comparative Analysis of Alternative In-Door Calibration Techniques for Off-The-Shelf Digital Cameras. Proceedings of the ASPRS 2010 Annual Conference, San Diego, California, April 26-30.

Fraser, C.S. and Gruendig, L., 1985. The Analysis of Photogrammetric Deformation Measurements on Turtle Mountain. *Photogrammetric Engineering & Remote Sensing*, 51(2): 207-216.

Fraser, C.S. and Riedel, B., 2000. Monitoring the thermal deformation of steel beams via vision metrology. *ISPRS Journal of Photogrammetry & Remote Sensing*, 55(2000): 268-276.

González-Auilera, D., Gómez-Lahoz, J. and Sánchez, J., 2008. A New Approach for Structural Monitoring of Large Dams with Three-Dimensional Laser Scanner. *Sensors*, 8(8): 5866-5883.

Gordon, S.J. and Lichti, D.D., 2007. Modeling Terrestrial Laser Scanner Data for Precise Structural Deformation Measurement. *Journal of Surveying Engineering*, 133(2): 72-80.

Habib, A.F. and Morgan, M.F., 2003. Automatic calibration of low-cost digital cameras. *Journal of Optical Engineering*, 42(4): 948-955.

Habib, A.F. and Morgan, M.F., 2005. Stability analysis and geometric calibration of off-the-shelf digital cameras. *Photogrammetric Engineering & Remote Sensing*, 71(6): 733-741.

Habib, A.F., Pullivelli, A.M. and Morgan, M.F., 2005. Quantitative measures for the evaluation of camera stability. *Journal of Optical Engineering*, 44(3): 033605.

Jáuregui, D.V., White, K.R., Woodward, C.B. and Leitch, K.R., 2003. Noncontact Photogrammetric Measurement of Vertical Bridge Deflection. *Journal of Bridge Engineering*, 8(4): 212-222.

Kääb, A., 2002. Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: examples using digital aerial imagery and ASTER data. *ISPRS Journal of Photogrammetry & Remote Sensing*, 57(2002): 39-52.

Kim, D., Langley, R.B., Bond, J. and Chrzanowski, A., 2003. Local deformation monitoring using GPS in an open mine: initial study. *GPS Solutions*, 7(3): 176-185.

Lichti, D.D., Stewart, M.P., Tsakiri, M. and Snow, A.J., 2000. Calibration and Testing of a Terrestrial Laser Scanner. *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXIII(Part B5): 485-492.

Lin, S.-Y., Mills, J.P. and Golsling, P.D., 2008. Videogrammetric Monitoring of As-Built Membrane Roof Structures. *Photogrammetric Record*, 23(122): 128-147.

Lovse, J.W., Teskey, W.F., Lachapelle, G. and Cannon, M.E., 1995. Dynamic Deformation Monitoring of Tall Structure Using GPS Technology. *Journal of Surveying Engineering*, 121(1): 35-40.

Maas, H.-G. and Hampel, U., 2006. Photogrammetric Techniques in Civil Engineering Material Testing and Structure Monitoring. *Photogrammetric Engineering & Remote Sensing*, 72(1): 39-45.

Mills, J.P., Newton, I. and Peirson, G.C., 2001. Pavement Deformation Monitoring in a Rolling Load Facility. *Photogrammetric Record*, 17(97): 7-24.

Monserrat, O. and Crosetto, M., 2008. Deformation measurement using terrestrial laser scanning data and least squares 3D surface matching. *ISPRS Journal of Photogrammetry & Remote Sensing*, 63(2008): 142-154.

Park, H.S., Lee, H.M., Adeli, H. and Lee, I., 2007. A New Approach for Health Monitoring of Structures: Terrestrial Laser Scanning. *Computer-Aided Civil and Infrastructure Engineering*, 22(2007): 19-30.

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A. and Allison, R.J., 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal of Engineering Geology and Hydrogeology*, 38(4): 363-375.