Pilot studies on photogrammetric bridge deformation measurement

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Abstract. The analysis of the stability of bridges or similar structures includes the measurement of deformations under defined load and the determination of amplitude and frequency of vibrations caused by traffic and/or wind. Digital photogrammetry is a rather suitable technique for these measurement tasks: It offers the capability of simultaneous monitoring of a large number of signalised or non-signalised points; in addition, many cameras offer the inherent capability of image sequence acquisition. The processing of deformation monitoring image sequences can be largely automated, and a precision potential in the order of 1 : 200,000 of the largest object dimension can be predicted.

The paper will present the results of two pilot studies on bridge deformation measurement. The goal of the studies was the verification of the practical applicability and accuracy potential of photogrammetric techniques. The image sequences were taken by a high resolution stillvideo camera and a megapixel machine vision camera. Due to the primarily one-dimensional nature of the expected deformation patterns, data acquisition and processing could be restricted to tracking in monocular image sequences. The 3-D coordinates of the targets to be tracked as well as the camera orientation parameters can be determined beforehand by photogrammetric techniques based on bundle adjustment. As a consequence of the relative nature of deformation measurement, the accuracy potential is hardly influenced by systematic errors of the imaging system, making it relatively easy to achieve the predicted accuracy potential.

Key words: Optical 3-D measurement techniques, least-squares matching, digital photogrammetry

1 Introduction

The monitoring of the actual state of existing structural buildings, e. g. bridges, has a high importance regarding to the assessment of the reliability and availability. This becomes of increasing economic and social relevance under the general shortage of financial resources, the natural aging process of buildings and increasing standards on construction and current use. The large number of structural buildings in an old age and/or poorly condition show the necessity to advance the methods of online measuring and monitoring deformations.

Photogrammetric techniques offer the potential of 3-D measurement of deformations of a large number of signalised points or natural texture on structural buildings by using at least two cameras or images taken from at least two different positions of one camera. The object coordinates can be calculated in a photogrammetric stereo model by bundle adjustment. This techniques are applied, when deflections in all directions are expected (e. g. Maas 1998, Benning et al. 2000, Hampel et al. 2001). Another possibility to get a photogrammetric stereo model, and thus 3-D coordinates, for small-dimension objects is to split the visual field of one camera with two prisms (Albert et al. 2002).

An advantage of photogrammetric techniques is the non-contact measuring; the tested objects are not affected by the measuring device and the objects do not have to be accessible. Furthermore the measuring range can be adjusted individually to the task.

If primarily one-dimensional or two-dimensional deformations are expected and the dimensions of the monitoring building are acceptable, a single camera can be sufficient (Fig. 1).

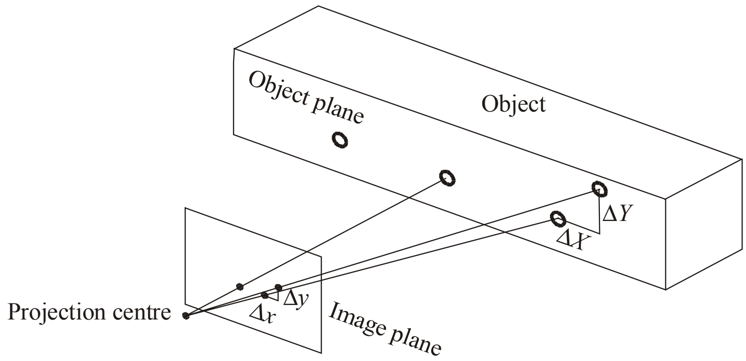

Figure 1: Principle of the single-camera deformation measurement

To process monocular image sequences, the 3-D coordinates of the targets and the exterior camera orientation parameters can be determined beforehand, e.g. by multi-camera bundle adjustment. In case of parallelism between image plane and object plane, it is sufficient to take the scale factor (magnification factor) by one known distance of two targets on the object. A full reconstruction of the exterior orientation is not needed, it should only be constant over the measuring period, or the changes should be determined by stable reference points in the object space. The movements ΔX, ΔY of object points are given by the measured image coordinates Δx, Δy and the magnification factor β:

$$\Delta X = \beta \cdot \Delta x$$
$$\Delta Y = \beta \cdot \Delta y \quad (1)$$

In case of low deflections - in comparison to the field of view - systematic errors such as lens distortion and the CCD chip will hardly influence the deformation measurements due to their relative nature. A calibration of the imaging systems is not required, the interior orientation may be unknown.

In the following, the application of a single CCD camera for time-resolved two-dimensional deformation measurements of many points simultaneously on bridges or parts of bridges will be described.

2 Test facility at Bauhaus University

To analyse the accuracy potential of the monocular digital photogrammetric techniques and the capacity of online visualisation, an experiment on the assessment of load bearing safety has been monitored. The deformation of a concrete block of 2 m in length has been measured under defined load at three positions by conventional inductive length gauging sensors on the one hand and several digital cameras on the other hand. The load was imposed manually in a hydraulic loading device in which the concrete block was placed in at its ends. The brought in load was measured separately with a force transducer (Fig. 2).

Parallel to the increasing load, image sequences were taken by a still video camera Kodak DCS 660 (3040 x 2008 pixel) and a 1024 x 768 pixel machine vision camera at an image rate of 1 Hz. The targets are represented by white circles of 14 mm in diameter on black background (Fig. 2, 3). The dimension of the circles corresponds to 7 pixel in the lower resolution camera. The targets were fixed on the block and additionally on the loading device to observe its possibly deformations. Further on non-signalised natural textures on the concrete block should be evaluated.

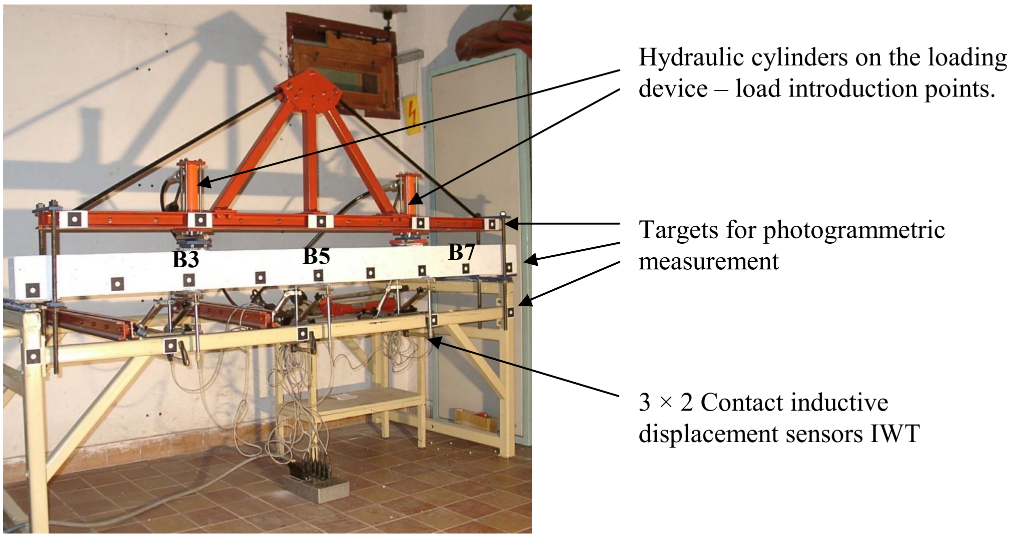

Figure 2: Test facility with a 2 m concrete block at the Bauhaus University

The cameras were positioned nearly vertical to the concrete block and nearly levelled, in order to achieve a homogeneous magnification. The scale factor could be calculated by comparing the known distance of two targets on the concrete block and in the image. As only small deformations with primarily two-dimensional nature (vertical due to loading, horizontal due to cracks) had to be measured, the precision of the scale factor in the single-camera setup is not critical. The object deformations are given directly by image coordinate differences, multiplied with the scale factor (Eq. 1). Because of low deflections, rough knowledge on camera calibration parameters is sufficient.

Obviously the precision of image coordinate difference measurement is crucial for the accuracy potential of the method. For optimal evaluation, over-exposure of the targets has to be avoided. Two techniques were used for the measurements of the image coordinates and the image coordinate differences (e. g. Luhmann 2000):

- Image coordinates of the signalised points were measured by an ellipse operator.
- Image coordinate changes of signalised points or surface patches with sufficient local image contrast were determined by least-squares matching (LSM).

Both operators offer the potential of sub-pixel accuracy measurements, allowing to exploit the high geometric accuracy of CCD sensors.

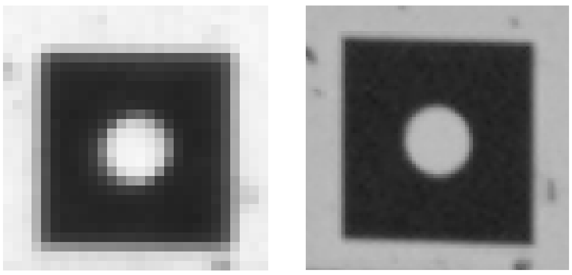

Figure 3: Circle target B4 (machine vision camera left; still video camera right)

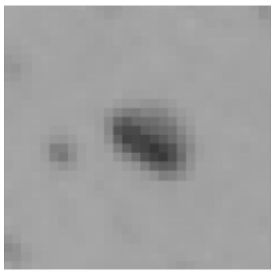

Figure 4: Natural texture on the concrete block (still video camera)

	Machine Vision Camera The Imaging Source	Still Video Camera Kodak DCS 660
Resolution	1024 x 768 pixels	3040 x 2008 pixels
Maximum frame rate	21 frames/s	1 frame/s (max. 3 frames) 0.1 frames/s
Scale factor	2.06 mm / pixel	0.74 mm / pixel
Standard deviation of measured target coordinates	0.017 pixel (EF)	0.010 pixel (LSM)
Standard deviation of measured natural texture	-	0.015 pixel (LSM)
Relative accuracy	1 : 60,000	1 : 300,000

Figure 5: Technical data of the used cameras, and results of image processing with least-squares matching (LSM) and ellipse fitting (EF)

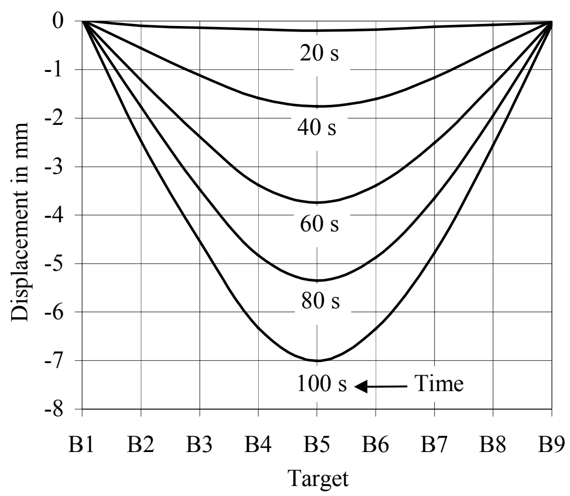

Figure 6: Photogrammetrically measured deformations of the concrete block up to maximum load

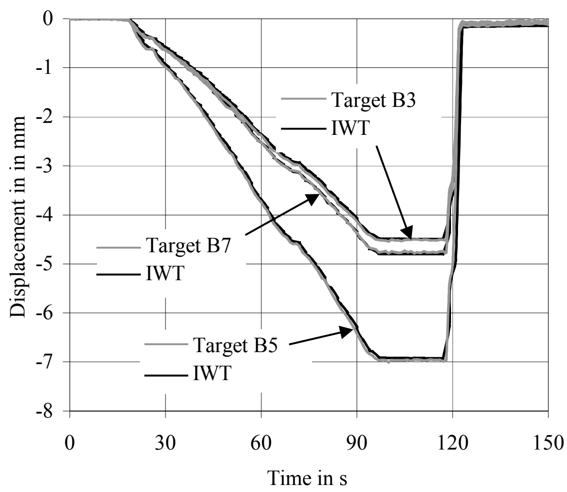

Figure 7: Comparison of photogrammetrically (targets B3, B5, B7) and inductively measured deformations (IWT)

Figures 5 to 7 show the results of the photogrammetric measurements. The precision potential in image space was between 0.01 and 0.02 pixel, translating into approximately 0.01 mm in object space for the higher resolution camera. The gauge measurements showed good accordance with the photogrammetric measurements at most targets, with outlier (< 0.1 mm) which can be explained by geometric misalignment between target and gauge.

Both operators show a high precision potential. In the course of the pilot study, image sequences were recorded and processed off-line. Implemented in a suitable user interface, both offer the potential of real-time image sequence processing of a large number of targets in the application. Least-squares matching offers the advantage that it is not limited to the measurement of signalised points with a known shape. Natural surface texture, as it can often be found on concrete surfaces (Fig. 4), provides a good signal for precise matching. The inherent sensitivity of least-squares matching towards non-planar patches in standard photogrammetric stereo matching applications is irrelevant in this application with constant viewing geometry and rather small object deformations.

3 Test facility Franckebrücke Erfurt

The second test object is a street bridge of the Franckestraße over the Flutgraben in Erfurt (Thuringia) (Fig. 8). It is a non-reinforced concrete bow bridge with a longitudinal bearing distance of 27 m and a transversal breadth of bow of 12.5 m. The bridge was built about 1900 and the owner plans an extensive restoration. For this reason, the load bearing safety of the bridge should be tested. The Chair of Surveying of the Weimar Bauhaus University had the possibility to participate in the experiments and to take its own photogrammetric measurements.

The basic idea of the experiment is to put load onto the structure or a part of it step by step in a detailed test program, and to monitor its reactions, e. g. by measuring the deformations. This has to be performed online in order to be able to stop the experiment in time in case of unforeseen events. In the normal test program the load is increased until it reaches the ultimate testing load (UTL). This UTL is defined as that load just before a level which would cause permanent damage in the tested structure. The level of UTL can be considerably higher than the safe load (Schwesinger et al. 2000). In case of the Franckebrücke, the UTL was not reached.

For the experiment, the bridge was barred completely for traffic on a Saturday for three ours. The load was imposed by three trucks, each one loaded to a weight of 44 tons. In a detailed time regime, the trucks drove separately backwards from the west side onto the bridge. In more sessions, increasing loads were imposed step by step by different routes and number of set in trucks. Figures 8 and 10 only show the last session, which is now described in detail: The first truck drove slowly up to the middle of he bridge and stopped. Then the second and third truck followed until all trucks were on the middle of the bridge. After a space of time of 30 seconds the trucks drove off the bridge, in reverse order. The session was repeated once.

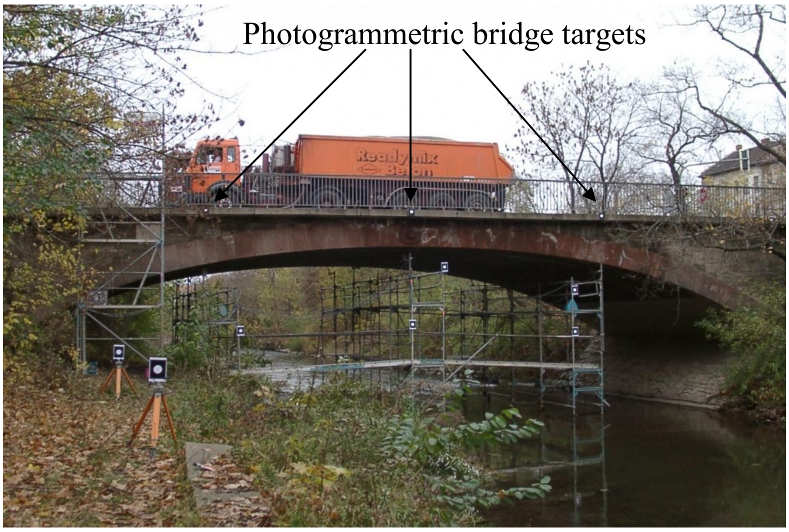

Figure 8: Franckebrücke at Erfurt with the trestle for fixing the inductive gauging sensors, the targets for the photogrammetric measurement and the trucks

Figure 9: Machine vision CCD camera

The vertical deformation of the bridge under load was measured conventionally by nine inductive length gauges, each with a range of 10 mm. The measuring points were fixed at the bottom side of the bridge to a raster of 3 x 3 points. In longitudinal direction, the measuring points quarter the bow of the bridge. The distances were measured to an immovable trestle on which the sensors were mounted. The construction of the trestle under the bridge took two days. The stability was tested before starting the experiment by continuous measurements over several minutes. Further measurements contained the temperature over and under the bridge, sound-waves and the width of a crevice - the only measurement of longitudinal deflections. The vertical deformation was visualised online in time-deflection diagrams. The maximum deflection observed was only 2 mm in the middle of the bridge. Due to this unexpected stability of the bridge the whole experiment could be realised without time delay.

For the photogrammetric measurements, a grey level machine vision camera of 1300 x 1030 pixel (Fig. 9) was positioned on the west bank of the river Flutgraben in a distance of 32 m to the bridge, with a field of view of 32.5 m at the bridge. The images were taken with a frequency of one image per second. The were white circles of 100 mm in diameter on black background. Three targets were mounted from the upper side of the bridge in the quarter points of the bow. Further targets were fixed at the trestle and on tripods in front of the bridge to observe the trestle and to get stable reference points to detect possible camera orientation changes.

Because of the viewing direction of the camera to the bridge, the image scale changes from left to right. The camera was nearly levelled, so that the magnification can be calculated with sufficient accuracy by comparing the known distances of the targets on the bridge (6.75 m) and in the image. The center magnification is about 25 mm per pixel, thus the maximum measured deformation of the bridge of 2 mm corresponds to only 0.08 pixel.

Image coordinates of the targets in all images of the sequence were determined by the ellipse operator. The quality of image data processing was slightly deteriorated by an overexposure of the targets and changes of the natural illumination despite an overcast sky. Nevertheless a standard deviation in the order of 0.1 - 0.2 mm can be estimated from the noise of the trajectory of a sample target (Fig. 10) and the comparison of the photogrammetric results with gauge measurements. Related to the field of view, this corresponds to a relative precision in the order of 1 : 200,000, or 1/160 of a pixel in image space.

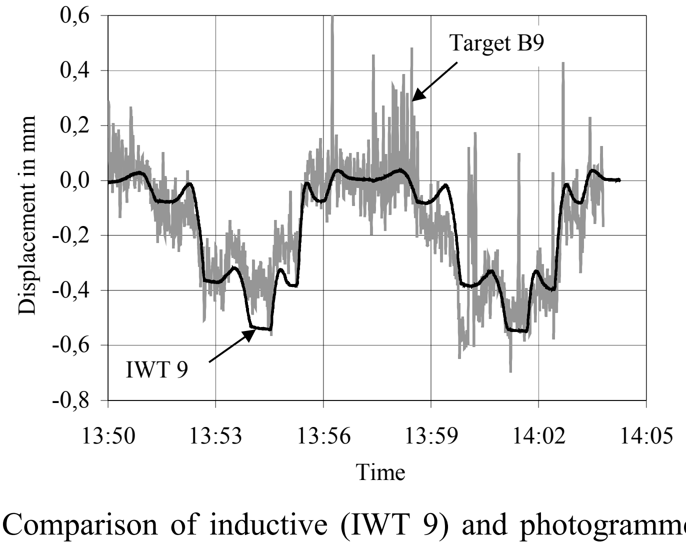

Figure 10: Comparison of inductive (IWT 9) and photogrammetric deformation measurements (B9) of the right bridge target in fig. 8

The photogrammetric system was ready to measure in short time, because only the camera must be set up and the connecting computer has to be started. The targets could be fixed on the bridge temporary without a special trestle.

An additional advantage of the photogrammetric approach is the fact that the image sequences offer the possibility to detect the position of the trucks on the bridge in each image. This allows a better interpretation of the results.

4 Conclusion

The results of the two pilot studies were rather encouraging. The applicability of single image photogrammetric approaches to bridge deformation measurements could be shown. A precision potential in the order of 1 : 200,000 to 1 : 300,000 of the monitored field of view could be achieved. Depending on the size of the object, this accuracy potential is not fully comparable to the potential of gauges, but will be sufficient in many applications.

The advantages of the photogrammetric method are the fast and economic setup, combined with the potential of measuring a very large number of targets simultaneously. If least-squares matching is used for image coordinate difference measurement, signalised targets are not required on objects providing sufficient surface texture. Full automation of data processing was not the goal of the studies, but can be achieved. The operators are fast enough to allow real-time processing, providing a signal to stop load procedures before damage. Depending on the type of cameras, a temporal resolution from 1 Hz (e. g. for a 3000 x 2000 pixel high resolution camera) to 20 Hz (for a typical megapixel camera) can be achieved. Using high-speed cameras and sacrificing spatial resolution for temporal resolution, image rates of 1000 Hz and beyond can be achieved if required. Finally, the inherent documentation character of image data may simplify the interpretation of complex deformation patterns.

Future work should concentrate on the creation of a comfortable user interface for online measurements. Improvements in targeting and possibly in illumination could further improve the accuracy potential. Reliable methods have to be developed to detect possible camera orientation changes and to separate their effects from actual object deformation. 3-D coordinates of the targets determined before the actual experiment by a photogrammetric network will provide precise local scale information and may serve as a basis for spatial resections discovering changes in orientation.

References

Albert, J., Schlösser, M., Schwarz, W.: Measuring Systems for the high-precision alignment of planned Linear Colliders. 2nd Symposium on Geodesy for Geotechnical and Structural Engineering, Berlin 2002, technical session GCS

Benning, W., Görtz, St., Schwermann, R.: Photogrammetrie-gestützte Deformationsanalyse an Stahl- und Spannbetonbauteilen. Allgemeine Vermessungs-Nachrichten, 2000, Vol. 107: 346 - 352

Hampel, U., Schreiber, F., Flach, B.: Erfassung der Verformungs-, Riss- und Schädigungsentwicklung textilverstärkter Baukonstruktionen mit Hilfe digitaler photogrammetrischer Verfahren. 1. Fachkolloquium Textilbeton, RWTH Aachen, 2001: 265 - 276

Luhmann, Th.: Nahbereichsphotogrammetrie, Grundlagen, Methoden und Anwendungen. Herbert Wichmann Verlag, Heidelberg, 2000

Maas, H.-G., 1998: Photogrammetric techniques for deformation measurements on masonry reservoir walls. Invited Paper for the IAG Symposium on Geodesy for Geotechnical and Structural Engineering, Eisenstadt/Austria, 1998: 319 - 324

Schwarz, W.: Moderne Messverfahren in der Ingenieurgeodäsie und ihr praktischer Einsatz. Flächenmanagement und Bodenordnung, 2002, Vol. 64. In preparation

Schwesinger, P., Bolle, G.: EXTRA – A new experiment supported condition assessment method for concrete bridges. SPIE´s 5th International Symposium on Nondestructive Evaluation and Health Monitoring of Aging Infrastructure, Newport Beach USA, 2000, Vol. 3995: 180 - 190

Steffens, K. (edit.): Experimentelle Tragsicherheitsbewertung von Bauwerken in situ zum Zwecke der Substanzerhaltung oder Umnutzung. Abschlußbericht Hochschule Bremen 1995