Photogrammetric Techniques in Civil Engineering Material Testing and Structure Monitoring

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Abstract

Civil engineering material testing includes a wide range of applications requiring the determination of the three-dimensional shape of an object and changes thereof. Large structure monitoring will often include the necessity of determining object deformations at a large number of points. Photogrammetric techniques offer a large potential for the solution of a wide range of measurement tasks in this field. A modular toolbox consisting of digital cameras, computer interfaces, illumination systems, calibration devices, combined with subpixel accuracy image measurement operators, multi-image matching techniques, and self-calibrating bundle adjustment in a suitable user interface, depicts a very powerful tool for tailoring custom-made solutions for material testing labs. Due to the wide range and the repetitive nature of measurements tasks in civil engineering, these applications could depict a significant future market for photogrammetry.

This paper will briefly discuss the major hardware and software modules of a toolbox for civil engineering material testing and large structure monitoring. Based on several sample applications covering object dimensions from 10 cm to 500 meters, the potential of photogrammetric deformation measurement techniques will be shown. The major advantage of photogrammetric techniques can often be seen in the fact that they allow for highly automated measurements at a large number of points simultaneously. In many cases, object deformations can be determined at a precision in the order of 1:100,000 of the object dimension, based on off-the-shelf hardware components.

Introduction

Many tasks in material testing research require the monitoring of the geometric shape of test objects under varying conditions. Geometrical measurements are performed for the examination of the behavior of individual probes and for the verification of theories or mechanical models. This is often realized by static, quasi-static, or dynamic short and long time load experiments on probes. During these load tests, parameters and effects such as load, deformation, strain, stress, displacement, crack formation, and other defects have to be monitored. At present, displacement and deformation measurements are typically measured by wire strain gauges or inductive displacement transducers. These devices are considered proven techniques. They provide on-line results with a high geometric precision and reliability. A general disadvantage of these techniques, however, is their point-wise and one-dimensional measurement capability. If simultaneous two- or three-dimensional measurement at several locations is required, the instrumental effort becomes rather large. The techniques are generally not suited for tasks requiring a large number of measurement points distributed over an object surface or for complete surface measurements.

In these cases, techniques of digital photogrammetry depict a valuable option for the design of powerful and flexible measurement tools. The use of photogrammetry in material testing experiments will generally allow for the simultaneous measurement of deformation or displacements at an almost arbitrary number of locations over the camera's field of view. Data processing can be highly automated and fast, allowing for real-time monitoring at the camera image rate. The precision potential of photogrammetric techniques will usually show a linear dependency on the object dimension, with a coordinate standard deviation in the order of 1:100,000 of the object dimension being a realistic figure under controlled conditions. In deformation analysis, experiments allowing for data acquisition in epochs with repeatable system configuration, even a precision potential of up to 1:250,000 of the largest object dimension has been achieved (Maas and Niederöst, 1997; Albert *et al.*, 2002).

Photogrammetric techniques have been applied to a wide range of objects and tasks in civil engineering material testing and deformation measurement, ranging from the monitoring of hair cracks on small 10 cm × 10 cm textile reinforced concrete probes in load tests (Hampel and Maas, 2003), over the measurement of structural deflections of complex buildings (Fraser and Brizzi, 2003), and beam deflections in load tests (Whiteman *et al.*, 2002) to monitoring of seasonal deformations of large water reservoir dams (Maas, 1998).

While the measurement of the absolute coordinates and the movement of signalized targets on an object can be solved by commercial software packages, non-standard monitoring tasks or applications with real-time requirements will often necessitate the development of customized software tools. In the following, we will show a modular system which was developed for flexible use in a wide range of experiments in a civil engineering material testing

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laboratory. Next, the hardware components of the system (cameras, interfaces, illumination devices, mirrors, calibration tools) will be presented followed by a discussion of the modules for data processing, including image processing and image matching techniques, geometric modeling and calibration, as well as data analysis. Finally, a selection of practical applications is presented, demonstrating the range of application fields and the potential of photogrammetric methods in material testing. These applications include the determination of two- and three-dimensional displacement fields, the detection and measurement of fine subpixel-wide cracks in probes, and the analysis of the development of cracks using a high-speed camera. Test objects were of concrete, wood, brickwork, steel, and composite materials. Some objects were marked with artificial targets, but in most cases the natural object surface in combination with suitable illumination was used for measurements underlining the aspect of a non-contact measurement technique. In many cases the essential measurement requirements (precision, object dimension and measuring range, surface characteristics, and environmental conditions) pose challenges to the design of efficient photogrammetric measurement procedures.

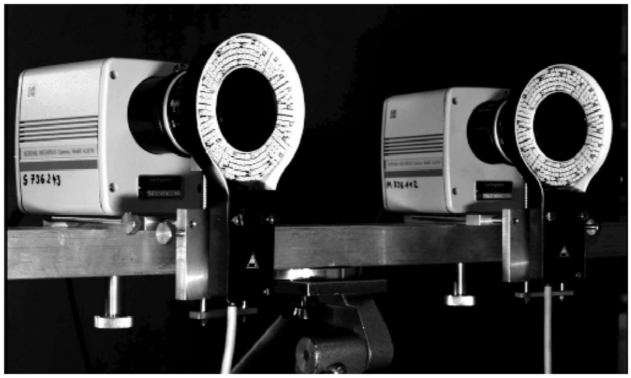

Figure 1. Kodak Megaplus 2.0i digital camera pair.

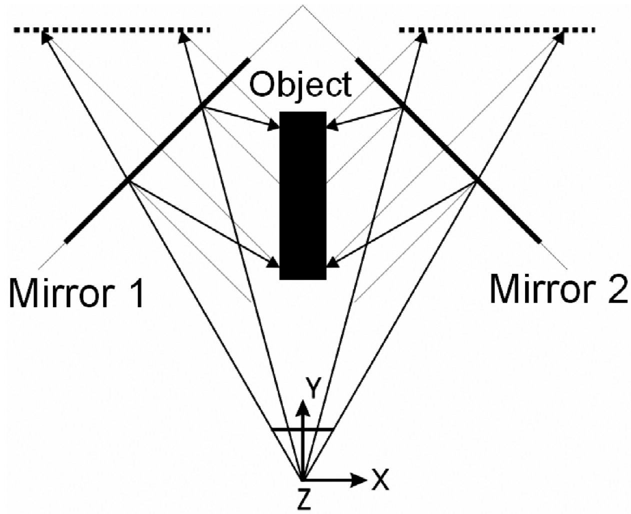

Figure 2. Photogrammetric recording scheme with mirrors.

Data Acquisition Systems

A wide range of digital cameras, which are suitable for high-precision measurements in online or real-time photogrammetric systems, are available on the market. Depending on the requirements of the application, the user may select a low-cost standard cameras for less than $500 USD off-the-shelf high-resolution cameras offering resolutions up to 4000 pixels × 4000 pixels, or high-speed cameras offering a temporal resolution beyond 1,000 images per second. As most image analysis techniques are based on intensity rather than color, black-and-white cameras will usually be a suitable choice; these cameras also avoid degradations introduced by one-chip color image sensors. Dynamic 3D deformation measurement tasks require the synchronization of two or more cameras. Applications with real-time processing demands necessitate a permanent connection between camera and host computer. This may be realized using a Firewire interface (limiting the stereoscopic image acquisition rate) or by a frame grabber, which is often more flexible in terms of simultaneous acquisition of image data from multiple cameras. In the application shown later, a Kodak Megaplus 2.0i digital camera pair with 2000 pixels × 2000 pixels resolution at a frame rate of 2 HZ was used (Figure 1).

Many applications require customized illumination devices. Proper illumination will often be a pre-requisite for obtaining consistent experiment data and enabling reliable and fast automatic data processing. As an example, flashed LED ring lights (Figure 1) are often used in photogrammetric material testing systems to generate shade-free images of rugged surfaces or for optimal imaging of retroreflective targets.

In some applications, objects have to be imaged from the front and backside simultaneously. This can either be accomplished by a multi-camera system or by mirrors (Figure 2). Stereoscopic imaging of a complex object from all sides may require a large number of cameras, if images can not acquired sequentially due to the dynamic behaviour of an object. An elegant alternative solution may be provided by mirrors placed in the field of view of a single camera. In this case, the mirrors can be considered multiple virtual cameras with different viewing geometries and their images recorded by one single sensor.

Off-the-shelf digital cameras will usually be un-calibrated. Moreover, their interior orientation changes if the camera is focused or if the lens is exchanged. Most lenses show significant lens distortion: while the measurement precision of subpixel accuracy image analysis operators may reach 0.05 pixel to 0.01 pixel, lens distortion of wide-angle lenses will often be in the order of five to ten pixels. Further systematic errors may be introduced by camera electronics or analogue camera-computer interfaces (El Hakim, 1986). This discrepancy between the measurement precision potential in image space and systematic errors introduced by camera body, lens, electronics, and interface necessitates the application of suitable camera calibration techniques. Camera calibration can, for instance, be achieved by self-calibrating bundle adjustment based on taking multiple images of the same object from different viewing directions and orientations with each camera to be calibrated. For applications, which have to be repeated frequently, the design of a reference object with known geometry and clearly identifiable targets, which can be imaged before, during, or after an experiment, may be advantageous. Reference body calibration allows for the calibration of a camera by single image spatial resection and may also be used for permanent checking of the calibration during long-term experiments.

Data Processing Techniques

According to the variety of applications in civil engineering material testing, a wide range of photogrammetric data processing techniques may be employed. Fully automatic data processing at high reliability is crucial for experiments measuring effects at many locations on an object over many epochs in mass experiments. Subpixel accuracy image measurement operators form a pre-requisite for exploiting the accuracy potential of calibrated digital cameras.

Some tasks may be solved by placing discrete targets onto an object, significantly simplifying data processing when suitable illumination techniques are used. The measurement of retroreflective targets with coded point numbers, for instance, can be considered a standard task, which can be solved automatically and reliably by off-the-shelf commercial photogrammetric measurement systems. In many cases, however, the placement of targets onto an object is not desired, or the characteristics of an experiment do not allow for the prediction of locations where targets should be placed. In these cases, full field measurement techniques can be accomplished by applying image matching techniques, which exploit natural or artificial surface texture to find homologous points in images from different views or in consecutive images of an image sequence. While image matching techniques employed for the generation of digital terrain models from aerial imagery can be distinguished into feature-based and area-based techniques, photogrammetric techniques applied for image matching in material testing applications are usually area-based techniques. In many cases, cross correlation or least squares matching are applied:

- Cross correlation offers the advantage of very high speed. In some of the experiments described later, a measurement rate of up to 60,000 points per second could be achieved on a standard 2 GHZ PC. However, cross correlation is limited to the determination of two patch shift parameters and will show a severely reduced accuracy potential when applied to convergent stereo images.
- Least squares matching offers the advantage of effectively approximating the projective transformation between two small planar patches by an affine transformation and is therefore better suited for general applications. As an adaptive technique based on least squares adjustment, it allows for the determination of statistical parameters describing the quality of data and results.

In material testing applications, the techniques are often used for the generation of surface models and for the determination of displacement fields:

- A surface model of an object can be determined automatically by matching techniques measuring homologous points in images of two or more cameras viewing the object from different directions (spatial matching). With a sensor format of 2000 pixels $\times$ 2000 pixels and a patch size of 11 pixels $\times$ 11 pixels, for instance, a 40,000 points surface model can be determined.
- Two-dimensional in-plane displacements can be determined by applying matching techniques to consecutive images of an image sequence of a single camera (temporal matching).
- Three-dimensional displacement fields can be determined from stereoscopic image sequences by combination spatial and temporal matching.

Both signalized target measurement techniques, as well as image matching techniques, offer a subpixel accuracy measurement potential in the order of 0.02 pixel. The precision potential for the measurement of small displacements in image space will often be higher than the precision potential of stereoscopic parallax measurement. This is due to the absence of deviations from the assumed model of projective patch transformation and the local correlation of sensor errors (such as sensor surface topography) not covered by the geometric camera model.

In cases of insufficient surface texture, an artificial pattern applied or projected onto the surface may support matching techniques. Pattern projection techniques will, however, be limited to pure surface model determination tasks; they are not suitable for the determination of full two- or three-dimensional displacement fields.

Some effects to be monitored in material testing are of two-dimensional nature. Cracks in a flat surface, for instance, will develop on the surface and need not to be observed three-dimensionally. In these cases, single camera measurements will be sufficient. In many load tests, however, forces and vibrations induced into the experimental facility will change the position and orientation of a test object during the experiment. In these cases, a reference frame around the object allows for the considerations of rigid object movements by a dynamic projective transformation (Hampel and Maas, 2003) transforming all images of an image sequence into the same datum.

Application Examples

The hardware components and software modules previously presented allow for the design of flexible measurement tools for a wide range of tasks, which may arise in a civil engineering material testing laboratory or in large structure monitoring tasks. An engineer, who is able to handle these tools, will have the possibility to develop rather powerful measurement techniques for a wide range of applications, including measurement tasks, which could hitherto not be solved at all.

In the following, some examples will be presented to demonstrate the range of applications and the potential of photogrammetric techniques in material testing and structure monitoring tasks.

Load Tests on Road Pavement During Long-term Experiments

The goal of this experiment was the analysis of the stability of road pavement under local force induced by breaking vehicles. During a long-term experiment simulating one million load test cycles, a deformation vector field had to be determined in regular intervals. The object surface could be signalized with targets (Figure 3) simplifying subpixel-accuracy image measurement and reducing the effect of surface discontinuities in combination with illumination effects on displacement vectors.

Due to the characteristics of the deformation, the out-of-plane component of the deformation could be expected to be insignificant in this experiment, so that the measurement of the two in-plane components of the deformation vector field was sufficient. The two-dimensional deformation information could be obtained by the analysis of a monocular image sequence. The transformation from image to object space becomes basically a rectification, with the camera orientation and calibration parameters determined from a calibration frame or from self-calibrating bundle adjustment based on a single-camera image block acquired before the first epoch of the image sequence. A long focal length in combination with a large imaging distance reduces the remaining effects of out-of-plane displacements. In the course of the experiment, the camera orientation could not be kept perfectly stable as a consequence of slight vibrations and temperature changes, introducing errors in the same order of magnitude as the actual displacements. These effects were

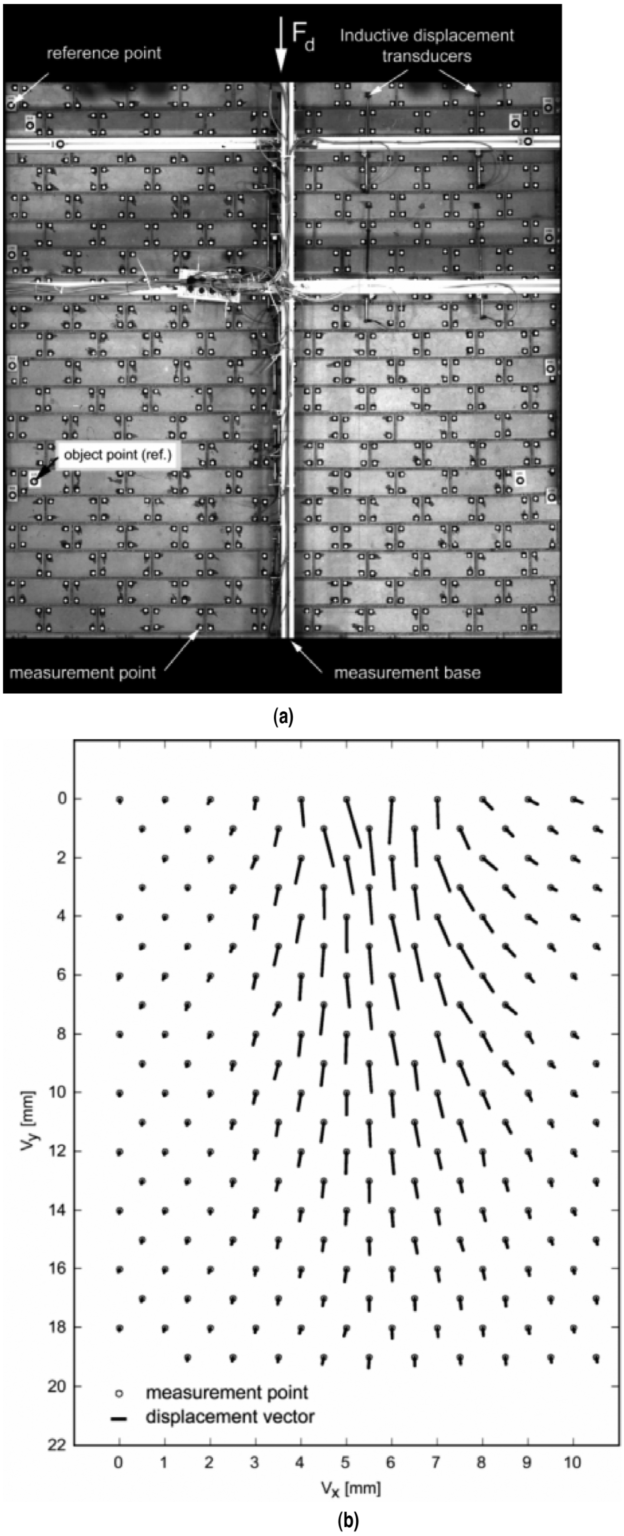

Figure 3. (a) Road pavement deformation measurement experiment (pavement with signalized targets), and (b) 2D deformation vector field.

compensated using a fixed reference frame in object space and transforming the results of each epoch into the coordinate system provided by this frame. The achieved precision, verified by the results of the inductive displacement transducers, was 0.05 mm to 0.1 mm, related to a field of view of 2.5 m × 2.5 m. Figure 3 shows an example for a displacement vector field with the enhanced displacement vectors transformed to the centers of individual pavement stones (Hampel and Maas, 2003).

Detection of Cracks and Measurement of Crack Width

The analysis of the behavior of concrete probes in tension or shear load tests will often contain the monitoring of the development of crack patterns on the surface of the probe. In most cases, this requires a two-dimensional measurement technique allowing for measurements of crack position and width at many locations, which are not known in advance. Digital image data form an ideal basis for this task. Cracks in monoscopic images may be detected by edge detection techniques (e.g., Riedel *et al.*, 2003). In many cases, however, cracks appear as hair cracks in an early stage with a width in image space much smaller than the camera pixel size. In an experiment reported in Maas *et al.* (2003), cracks on 10 cm × 10 cm textile reinforced concrete probes were monitored by a 2000 pixel × 2000 pixel camera pair (Figure 1). While the camera pixel size translated to the object surface was 50 μm, the requirement for the determination of crack location and width was 1 μm and 3 μm, respectively. Cracks with a width of only several micrometers in their early stage are not visible in the image. They can, however, be detected automatically by full field measurement techniques determining displacements of patches on a regular grid over the object surface with subpixel precision and a subsequent analysis of local discontinuities in the resulting displacement vector field.

Figure 4 shows the result of a 3D displacement measurement for one selected profile in tension-direction of a probe obtained from the displacement vector field resulting from image matching. The in-plane deformations indicate significant cracks, while no significant out-of-plane deformations were detected. The visualization of the image analysis results allows for an analysis of in-plane deformations, relative crack-positions and subpixel crack-width for arbitrary profiles (Figure 4) or for complete surfaces (Figure 5).

Bridge Deformation Measurement

Figure 6 shows an example of a bridge under load simulated by a heavy truck (Albert *et al.*, 2002). Deformation measurement is basically a one-dimensional problem in this application, but measurements should be taken at several locations along the bridge with the maximum deformation expected in the center. The expected deformation depends on the

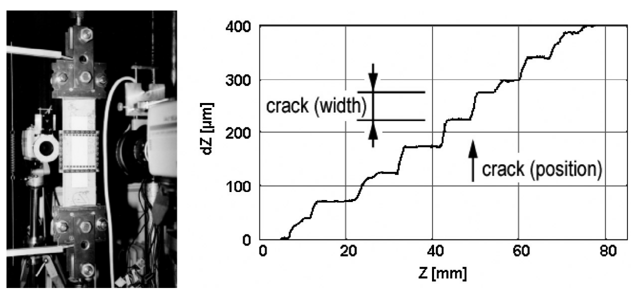

Figure 4. Imaging configuration for double-sided crack detection, probe profile obtained by deformation vector field analysis (approximately 1,600 points).

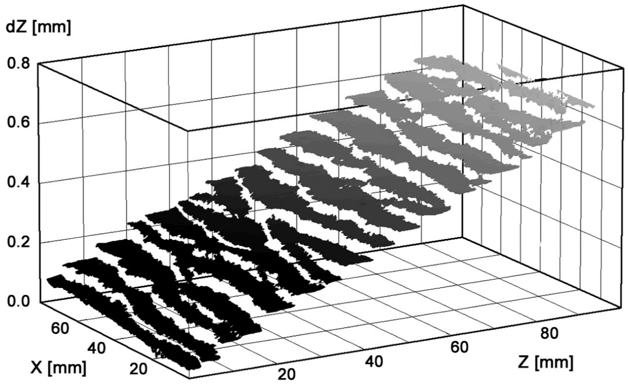

Figure 5. Results of full-field deformation and crack analysis (approximately 1.8 million measurement points).

Figure 6. Load test on a bridge (Albert *et al.*, 2002).

construction of the bridge and the load; it will often be in the range of a few millimeters. Both the pure measurement of deformations between two epochs in static load tests and the monitoring of vibrations in dynamic tests are of interest. Conventional geodetic techniques for bridge deformation measurements are often based on total station observations (e.g., Niemeier *et al.*, 1999) or on inductive gauges. While the latter require a bulky construction in order to attach the gauges between the bridge body and a static reference, total station measurements require expensive instrumentation and offer only a limited temporal and spatial resolution making them unsuitable for the dynamic measurement of deformations at a large number of locations.

The acquisition of a single camera image sequence may depict a powerful alternative for both static and dynamic bridge deformation monitoring. Due to the small displacements between images, area-based measurements can be performed at high precision, reliability, and speed. Bridges may be signalized with artificial targets to support measurement precision and reliability. If the natural texture allows for a reliable measurement, suitable surface patches can also replace the necessity of targeting.

Moderate precision requirements can be served by lowcost data acquisition systems. A minimum measurement system might for instance consist of a notebook and a 1300 pixel × 1000 pixel machine vision type camera with an image rate of 15 HZ (Figure 7) connected to the notebook using a Firewire interface. Such cameras offer the advantages of compactness, light weight, good geometric stability

Figure 7. Firewire camera.

and simple interfacing at low cost. They are available with a resolution between 640 pixel × 480 pixel and 4032 pixel × 2688 pixel and offer imaging rates between 8 HZ and 100 HZ.

As is evident, subpixel accuracy techniques are a crucial pre-requisite to warrant an acceptable measurement precision when using off-the-shelf cameras with a limited image format. A measurement precision of 0.01 pixel in image space will translate into a relative precision of 1:100,000 of the vertical field of view in object space. Imaging a 50-meter bridge section by a 1300 pixel × 1000 pixel camera, this translates into a standard deviation of 0.4 mm for the deformation vector. The scale information for the image to object space transformation of the deformation vector can be obtained easily by a rectification based on a rough distance measurement or from an *a priori* photogrammetric network adjustment.

This technique must warrant the geometric stability of the interior and exterior orientation of the camera over the whole measurement period. If suitable static reference points are available in the image, they may be used to check and correct for orientation changes. Such points may be provided by the foundation of a bridge; sometimes they can be found in a skyline behind a bridge. Like geodetic techniques, such as theodolite measurements, the monocular photogrammetric measurement is influenced by atmospheric effects such as refraction or turbulence. While the systematic effect of refraction is largely compensated by the character of a merely relative measurement, stochastic effects of turbulence can be partly compensated by the acquisition and processing of short image sequences rather than single images. In this case, the length of the image sequences can be adapted to the time scales of atmospheric turbulence, which will usually be in the order of seconds which is acceptable for load tests lasting over minutes or hours.

A pilot study on photogrammetric bridge deformation measurement using a lowcost data acquisition system is shown by Albert *et al.* (2002) which imaged a 32.5 meter section of a bridge (Figure 6) by a 1300 pixel × 1000 pixel camera at an image rate of 1 HZ. Simultaneous inductive gauge measurements were used to verify the accuracy potential of the photogrammetric measurements. The RMS deviation between the photogrammetric deformation measurement of signalized targets and inductive gauge measurements was 0.1 mm to 0.2 mm (Figure 8), which corresponds to an image space measurement precision beyond 0.01 pixel.

Water Reservoir Wall Deformation Measurement

Large concrete water reservoir walls with heights between 100 meters and 200 meters show water level dependent and

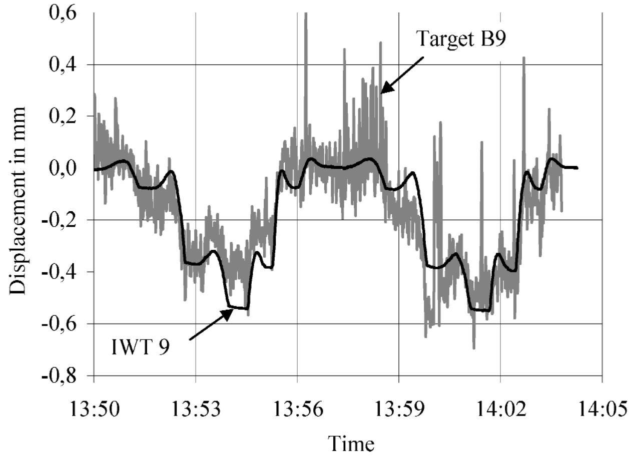

Figure 8. Comparison of inductive gauge (IWT 9) and photogrammetric (B9) deformation measurements at one target on the bridge shown in Figure 6 over a 15 minute load test with two load cycles (Albert *et al.*, 2002).

Figure 9. Water reservoir wall (Nalps/Switzerland).

seasonal deformations which may reach up to 15 cm. For safety reasons, these deformations have to be monitored in regular time intervals. Besides nadir plumbing, strain gauges, and alignment techniques, geodetic network measurements on the air side of the walls are usually applied. The accuracy potential of network measurements applying total stations is in the order of one millimeter. The use of GPS is often restricted by limited satellite visibility in narrow valleys. Although geodetic network measurement can be considered a proven technique for water reservoir wall monitoring, photogrammetric techniques may depict an interesting alternative or completion to geodetic techniques, as they allow for an efficient measurement of deformations at a large number of points.

The applicability of photogrammetric techniques was tested in a pilot study on the water reservoir wall of Nalps in the Swiss Alps (Figure 9; Maas, 1998). The wall has a length of 480 meters and a height of 100 meters on the air side. Maximum deformations are known to be in the order of 80 mm. Due to the lack of suitable contrast on the concrete surface, signalized targets were used. A total of 60 points were signalized, with a target diameter of 25 cm warranting for a target image size of 4 to 5 pixels as a pre-requisite for achieving subpixel accuracy image coordinate measurement precision by template matching. The 3D coordinates of the targets were determined in a photogrammetric network, based on a total of 41 images acquired by an off-the-shelf 3000 pixel × 2000 pixel still video camera. Besides terrestrial images, some images were taken from a helicopter to optimize network geometry. The network was fit into a frame of control points determined by geodetic techniques.

A self-calibrating bundle adjustment based on the 41 images and an average of 14 image rays per point yielded a standard deviation of 2 mm to 3 mm in all three coordinate directions which could be confirmed by geodetic reference measurements. Some sub-optimalities in the pilot study concerning network geometry and targeting give room for a slight further improvement of the precision potential (Maas, 1998). Nevertheless, some limitations of the applicability of photogrammetric techniques may be given in cases where the founding rock is also subject to deformation. In these cases, the combination of photogrammetric techniques with GPS measurements or with geodetic network measurements including remote targets well distributed over the horizon may provide a suitable solution with the main task of photogrammetric measurements being the densification of geodetic measurements.

Highspeed Cameras

Highspeed cameras allow image rates of 1000 frames per second and beyond, extending the applicability of photogrammetric techniques to highly dynamic scenes. As shown in tests (Figure 10), digital highspeed camera image sequences allow for an exact temporal localizability and interpretability in case of sudden failure events during load tests. The image rates of digital highspeed cameras produce extremely high data rates of up to 1 Gigapixel per second. Due to the high cost of such cameras, experiments will often be limited to two-dimensional quantitative analysis. An alternative to obtain three-dimensional information can be given by mirror systems, stereoscopic beam splitters or by an integrated camera-projector system, where the projector is treated as an inverse camera.

Conclusions

In a number of research projects and pilot studies, photogrammetric techniques have proven a broad potential for measurement tasks in civil engineering material testing and large structure monitoring. Photogrammetry offers the advantages of a versatile and efficient full field three-dimensional measurement technique, offering a high precision potential at reasonable cost. As a by-product, imaging techniques deliver a documentation of an object, allowing for *a-posteriori* changes in the measurement program if required.

For certain applications, photogrammetric techniques have meanwhile been accepted as standard measurement techniques. The potential of the application of photogrammetric techniques is however by far not yet exploited. Measurement tasks in material testing labs are characterized by a large diversity and often by a high complexity. As a consequence, commercial measurement systems cover only a small range of clearly defined measurement tasks, while there is a lack of general commercial solutions. A toolbox consisting of hardware and software modules has shown in this paper handled by an experienced engineer, may allow for custom-made solutions and cover a wide range of application fields. The wide range of measurement tasks in civil engineering material testing and structure monitoring,

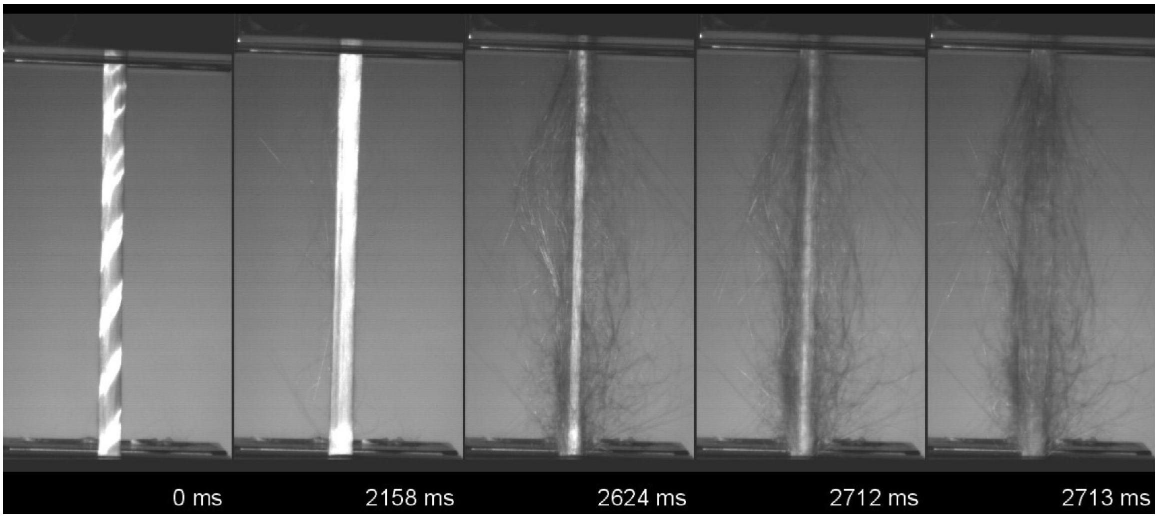

Figure 10. Five out of 4,000 images of a 1,000 HZ highspeed camera image sequence showing the failure of a glass fibre roving for textile reinforcement of concrete parts.

in combination with the necessity of repeated measurements, could depict a significant future market potential for photogrammetry.

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