Photogrammetric techniques for deformation measurements on reservoir walls

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Abstract:

Methods of digital close range photogrammetry have been used intensively for the determination of 3-D coordinates in a large number of industrial applications during the past decade. Using high resolution solid state sensor cameras, redundant imaging, thorough geometric and stochastic modeling and self-calibrating bundle adjustment techniques, accuracies beyond 1 : 100’000 of the object dimension have been achieved. This accuracy potential, combined with economic hardware component costs and fast data processing, does meanwhile make digital close range photogrammetry an interesting tool for 3-D deformation measurements on large structures.

The paper presents the results of pilot studies on the measurement of the 3-D coordinates of signalized targets on a large water reservoir wall in Switzerland. Although photogrammetry is not capable of solving all problems connected with deformation measurement and analysis tasks on reservoir walls, it may be a very useful tool for the densification of geodetic measurements, especially if the repeated measurement of a large number of points is required in short time intervals. If reasonable solutions can be found for signalizing reservoir walls, photogrammetric data capture can be finished within minutes from a helicopter; processing can be widely automated and the accuracy potential can be in the order of 2-3 millimeters.

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1. Introduction

Electrical power in Switzerland is to a large extent generated from water temporarily stored in reservoirs. Most of these reservoirs are dammed up by large concrete walls, which have to be monitored in regular intervals. With heights of more than 100 meters, these walls deform by up to 15 cm, depending on water level changes, temperature conditions and ice coverage. Deformations on reservoir walls have so far mainly been performed by geodetic measurements. 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 by theodolite and electrooptical distance metering is in the order of one millimeter. The use of GPS is restricted by limited satellite visibility.

Photogrammetric techniques have so far been considered not sufficiently accurate. Moreover, photogrammetric techniques cannot solve all problems connected with the task of deformation measurements on reservoir walls. Especially the comprehension of remote targets distributed over the full horizon, as required for reliable deformation analysis, poses severe problems to photogrammetric data capture. On the other hand, techniques of digital photogrammetry depict a fast, economic and versatile tool for 3-D deformation measurements, and the accuracy potential provided by large format solid state sensor cameras has reached a level which justifies a re-evaluation of photogrammetric techniques for deformation measurements on reservoir walls. Particularly when a large number of points has to be measured (e.g. for local shear analysis), the use of digital photogrammetry for the densification of conventional geodetic networks seems promising. For that reason, several pilot studies have been conducted (Fryer/Bartlett 1989, Fryer 1995, Kersten/Maas 1995). The results of these studies were not yet satisfactory, partly due to the use of conventional film-based cameras, and partly due to the limited accuracy potential of the digital cameras available in 1995. Meanwhile, digital cameras with up to 4096x4096 pixels are available, and accuracies beyond 1 : 100’000 of the object dimension have been achieved in several industrial applications of digital photogrammetry.

Fig. 1: Reservoir wall Nalps (Switzerland)

The pilot study presented in this publication was conducted in summer 1997 at the concrete reservoir wall of Nalps in the canton of Grisons, Switzerland. The wall (Fig. 1) has a height of approximately 100 meter on the air side and a crown length of 480 meter. The total concrete cubature of the wall is 593’000 m^3, the maximum water contents of the reservoir 44’500’000 m^3; the maximum expected deformation is 80mm in the center of the crown.

The aim of the pilot study was to test the applicability and the accuracy potential of today’s photogrammetric techniques to 3-D object coordinate determination on the wall.

2. Data acquisition

A total of 60 regularly distributed points were signalized and measured in the campaign. The points were signalized with plates consisting of a 25cm circular target, black background and a small centered target for theodolite reference measurements (Fig. 2). The size of the targets is to be considered a compromise between the requirements of the measurement technique (requiring rather large targets for subpixel accuracy image coordinate determination) and practical limitations (requiring small targets). The average diameter of the targets in the digital images was 3-5 pixels. The targets were glued to the wall in an abseiling action. For a professional use of the technique, the target design and the target application procedure can be optimized.

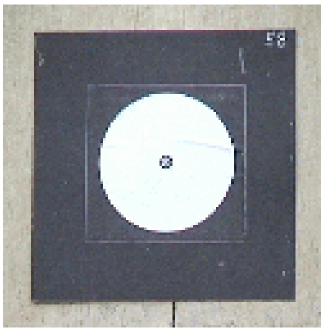
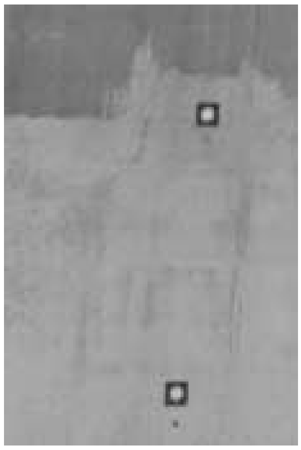

Fig. 2: Signalized points: close-up and part of measurement image

The camera used for photogrammetric data acquisition was a Kodak DCS460 digital stillvideo camera. The cameras has a 3060x2036 Kodak KAF6300 color CCD sensor with 9µmx9µm pixel spacing and 28x18mm^2 sensor format. 42 uncompressed images can be stored on an internal PCMCIA disk. Two indepent image datasets were acquired, one using a 18mm lens and one using a 28mm lens. In the first project, a total of 34 images was taken. The camera was equipped with a 18mm Nikkor non-autofocus lens with the focus fixed at infinity. To improve the network geometry, six of the 34 images were taken from a helicopter. As a repeatability test, a second set of images was taken with the same camera, but equipped with a 28mm lens. In this test, 41 images were taken, six of them from a helicopter. Due to time restrictions, the two campaigns were conducted on the same day and cannot be considered two epochs, so that they are only suitable for an analysis of the accuracy potential, but not for deformation analysis.

Fig. 3: Kodak DCS460 digital stillvideo camera

Reference coordinates of the wall targets were determined by forward intersections with theodolite observations from three stations. A standard deviation of 2mm in all three coordinate directions was achieved for most of the targets; due to visibility restrictions and suboptimal network geometry, the standard deviations of the points on the very left and right sides of the wall were significantly larger.

3. Data processing

The stillvideo image data was processed semi-automatically: Signalized points were identified interactively by a human operator in all images and then measured automatically with subpixel accuracy by least squares template matching. Using these image coordinate and geodetically determined control point coordinates, 3-D object coordinates of all targets were determined by self-calibrating bundle adjustment. Using object coordinates from former epochs in deformation measurements, this task can be reduced to the manual identification of 3-4 points per image with a first bundle adjustment using only these few points, subsequent projection of all targets into the thus oriented images, fully automatic measurement of all remaining targets and final bundle adjustment with all observations. A full automation of the image measurement process might be achieved via coded targets containing a binary coded point number around the actual target; however, such coded targets would have to be rather large and to not depict a realistic option on large structures.

The targets could be measured in 6 ... 23 images, with an average of 14 rays per point and an average of 22 points per image. Various control point versions were tested in the bundle adjustment, using the geodetically determined coordinates of the remaining points for an external accuracy check. Additional parameters were introduced to compensate lens distortion, interior orientation and other systematic errors of the camera. The DCS460 camera is known for its mechanical stability problems, leading to an instable interior orientation. It has been shown in (Maas/Niederöst, 1997) that this instability may severely reduce the accuracy potential of the camera. For that reason, the self-calibration was handled very carefully, paying attention to the checkpoint deviations. The problem of the instable interior orientation was regarded by introducing one common parameter set for lens distortion and a partly constrained set of interior orientation parameters for each image, thus working partly projectively and increasing the control point requirements.

4. Results

The results of photogrammetric data processing (Auf der Maur et al., 1996/97) are summarized in the following table. Note that the X-direction is the direction perpendicular to the wall and thus the direction with the largest deformations. Due to the relatively bad reference coordinates of the outer points on the wall, the checkpoint analysis was limited to 20 points in the central part of the wall. Although the outer points did also suffer from suboptimal network conditions in the photogrammetric datasets, they were not discarded from the adjustment. With a more extensive use of the helicopter, which is recommended for a professional use of the technique, the network configuration can be improved easily.

Project	images	av. scale	co	ch	ray	ap	$\hat{\sigma}_0$ [µm]	theoretical precision [mm]			checkpoint RMS [mm]		
								$\hat{\sigma}_X$	$\hat{\sigma}_Y$	$\hat{\sigma}_Z$	μ_X	μ_Y	μ_Z
DCS460-18	34	8’200	12	20	14.7	7 + 34x3	0.58	3.0	3.0	1.9	3.7	2.8	2.4
DCS460-28	41	6’400	12	20	13.8	7 + 41x3	0.55	2.7	2.8	1.6	3.5	1.8	2.5

co: number of control points
ch: number of check points
ray: average number of rays per point
ap: number of additional parameters (see chapter 3.)
theoretical precision: average standard deviation (from covariance matrix)
checkpoint RMS: RMS of checkpoint coordinate differences

Related to the width of the wall, the standard deviations of the photogrammetrically determined 3-D coordinates indicate a precision beyond 1 : 100;000. Nevertheless, the standard deviation of unit weight (~$^1/_{15}$ of a pixel) is still suboptimal if compared to industrial applications of digital close range photogrammetry, where $^1/_{50}$ pixel has often been achieved using CCD cameras with similar sensors. Several factors might explain this relatively low precision:

- The size of the targets has to be considered a compromise and was rather small. With larger targets, a better measurement accuracy in image space can be expected.
- The sensor topography of the Kodak KAF6300 CCD sensor was not modeled.
- The terrestrial images, the helicopter images and the theodolite data had to be acquired on three different days with rather different weather conditions and sun irradiation; this might already have caused small deformations of the wall.

Using 12 control points, the network geometry was strong enough to support the determination of an independent, constrained interior orientation for each image; thus, the instability effects of the stillvideo camera body could be at least partly compensated. However, this parametrization does weaken the network geometry; simulations showed that with a geometrically stable camera, a higher object space precision might be achieved using less control points. Nevertheless, thanks to the large number of observations per point, the precision is already acceptable, though not yet fully satisfactory. With improved targeting, optimized network design and possibly a camera model containing sensor topography, these results obtainable with the same camera can probably be significantly improved.

The 20 check points used for the analysis of the differences between geodetically and photogrammetrically determined coordinates yield an RMS of 1.8 - 3.7 mm for the three coordinate directions. It has to be noted that internal precision figures of the geodetic coordinates are not much better than those of the photogrametrically determined coordinates and cannot be regarded as reference coordinates.

5. Conclusion

Although the results are not yet fully satisfactory, the pilot study has proven that digital photogrammetry may be an interesting option for the determination of 3-D coordinates and deformation vectors of signalized targets on large masonry reservoir walls. The RMS coordinate differences between photogrammetrically determined 3-D coordinates and geodetically determined coordinates are in the order of only 2-3 mm for all three coordinate directions. With the continuing progress in solid state sensor technology on one hand and some suboptimalities concerning targeting, network configuration and mechanical stability of the camera present in the pilot study on the other hand, a further improvement of the accuracy potential can be predicted. Although photogrammetric techniques cannot solve all problems occuring with deformation measurements on reservoir walls, they may depict a viable alternative for a densification of geodetic networks.

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