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Photogrammetric 3-D Point Determination for Dam Monitoring

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Abstract
The use of terrestrial photogrammetry as a densification of geodetic networks for repeated monitoring of a large concrete dam is discussed in this paper. Photogrammetry promises to be a very economic technique for dam monitoring, especially if a large number of targets has to be measured frequently.
A pilot study of the Institute of Geodesy and Photogrammetry was conducted at a dam of 208 m height and 630 m length in Ticino (Switzerland), to perform photogrammetric 3-D point determination for dam monitoring with a digital high resolution still video camera Kodak DCS200 and with a metric camera Wild P31. The results of 3-D point positioning from a photogrammetric bundle adjustment will be given for each of the cameras, showing the accuracy potential of the method; in addition, some application relevant handling issues will be addressed. For comparison, and as a reference, the 3-D object coordinates of the photogrammetrically determined targets were measured by surveying techniques with a theodolite and a high precision distance meter ME5000, as traditionally used for dam surveillance.

1. Introduction

The determination of deformations on dams has so far been performed by geodetic measurements. Besides nadir plumbing, strain gauge and measurements of alignments the determination of 3-D coordinates of signalised points by geodetic net measurements is mostly used. Under good conditions accuracies of less than one millimetre can be obtained from geodetic surveillance. However, the use of conventional surveying methods is time and cost expensive. Due to the flexibility, portability and speed of CCD cameras during image data acquisition and the capability of automated in-house data-reduction, digital photogrammetric techniques promise a cost-effective alternative or supplement for dam monitoring, especially when a large number of targets has to be measured frequently and if highest accuracies are not requested. *Fryer/Bartlett (1989)* and *Fryer (1995)* report on the ongoing surveillance of a concrete water storage dam with multi-station convergent photography, using a medium format camera and retro-reflective targeting. They report that image data acquisition for this dam requires only one man for a period of time not exceeding half a day, while for further data processing a total of less than two man-weeks was required. In comparison a conventional measuring campaign takes more than four man-weeks period *(Fryer, 1995)*. Photogrammetric equipment of highest accuracy was used by *Dold et al. (1993)*. They used a Rollei LFC 23 x 23 cm^2 camera and a digital mono comparator Rollei RS1-C for deformation measurements on a masonry wall and achieved standard deviations of 0.01 mm in the planimetry and 0.02 mm for the depth coordinates related to a measurement region of 4 x 2 m^2. Extrapolated to the dimensions of a dam with a height of 208 m and a width of ~400 m, this would mean standard deviations of 1 resp. 2 mm.
To be able to judge the functionality and performance of camera systems in monitoring of a large scale engineering structure, a pilot study was conducted by the Institute of Geodesy and Photogrammetry, ETH Zurich, on the arch dam Luzzone. This paper focuses on practical investigations on the use of two cameras often employed in terrestrial photogrammetric applications for dam monitoring: the digital high resolution still video camera Kodak DCS200 and the metric medium format camera Wild P31. The goal was the determination of 3-D coordinates of 28 object points, which were signalised on the wall of the dam.
After a brief characterisation of the dam in section 2, the photogrammetric signalisation and geodetic measurements at the dam, and the two cameras used in this pilot project are described. Section 5 presents the image data acquisition, while in section 6 the results of image data processing are presented.

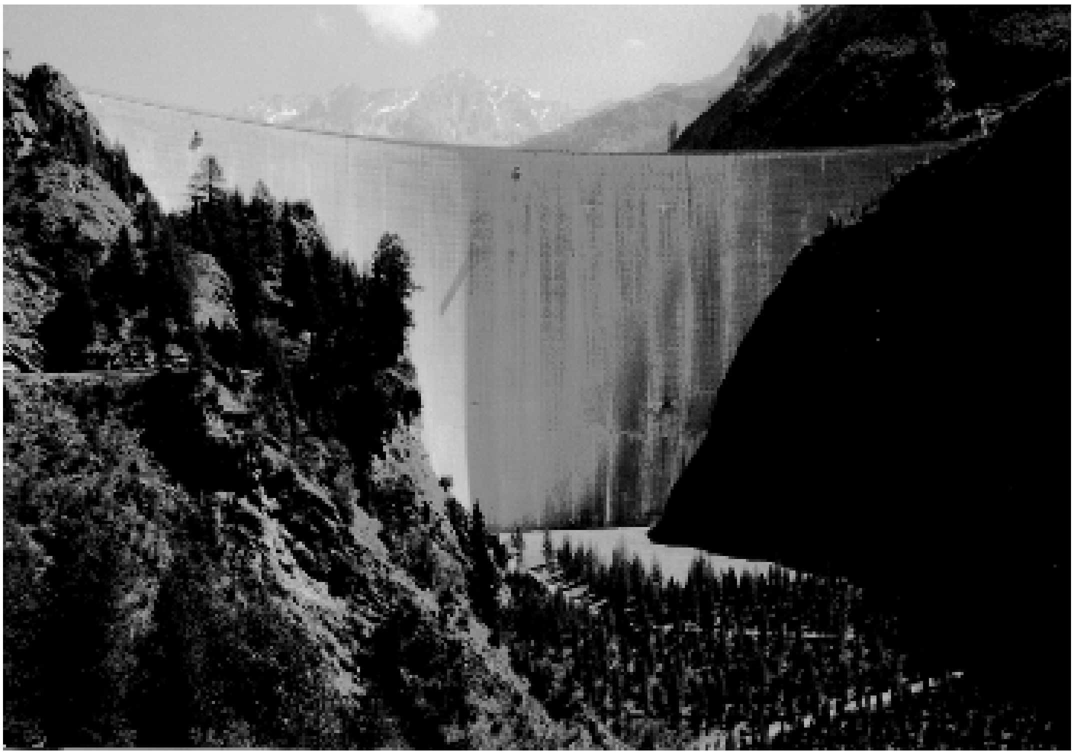

Figure 1: Arch dam Luzzone at Lago di Luzzone in Ticino (Switzerland)

2. Arch Dam Luzzone

The arch dam Luzzone (Fig. 1) is located 1500 m a.s.l. in the northern part of Blenio Valley, Ticino. The total height of the dam is 208 m and its length is 630 m at the wall coping, while the width of the wall coping is 10 m and 36 m at the base. The dam was built from 1960-62 and an upgrade of the wall by about 15 m is planned. Deformations of the wall are mainly caused by variations of the water content of the dam (180 m difference between maximum and minimum water-level). In two measuring campaigns (autumn 1993 and spring 1994) a total deformation of 8 centimetre was determined by geodetic means at the middle of the wall coping.

3. Photogrammetric Signalisation and Geodetic Measurements

The contrast conditions on the surface of the wall require a signalisation of all points to be measured for both, geodetic and photogrammetric point determination. For the photogrammetric signalisation 28 white PVC-targets were fixed on the wall with special adhesive, in a distribution illustrated in Fig. 2. These 28 points were located in four rows across the dam wall. It has to be noted that distribution and number of targets are far from ideal in this pilot study. Target installation though, was limited by safety considerations during abseiling, which did not allow to install targets in the centre of the wall. The size of the targets was 40 x 40 cm^2, which was a compromise between the target size requirements of the two cameras. In the centre of the PVC-plates a measuring mark (Fig. 3) was placed for precise geodetic measurements and for the P31. The 3-D coordinates of the targets, later used as reference values for the photogrammetric point determination, were determined with combined direction and distance

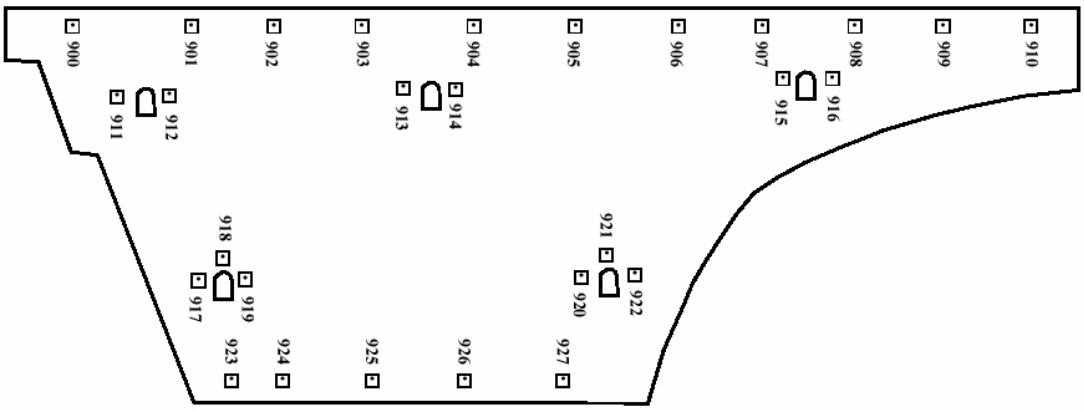

Figure 1: Arch dam Luzzone at Lago di Luzzone in Ticino (Switzerland)

measurements in a local coordinate system using a Kern E2 theodolite and a high precision distance meter ME5000. The geodetic net was adjusted using minimum datum control with a standard deviation (max. values) of 3.3 mm in plane and 1.8 mm in height *(Schmassmann, 1994)*. Four of the 28 points were determined with only two rays. These results are not representative for dam surveillance and the accuracy potential of geodetic methods are not totally exhausted, but they are sufficient as reference values for the following comparisons.

4. Cameras used for Images Data Acquisition

4.1 Kodak DCS200 still video camera

The high resolution still video camera Kodak DCS200 consists of a modified Nikon 8008s camera body with a 1524 x 1012 pixel CCD sensor (14 mm x 9.3 mm) in the imaging plane. The camera is offered alternatively with a black-and-white or a colour CCD sensor; images can be stored on a 2 MB DRAM or optionally on a 80 MB internal hard disk, which offers storage capacity for 50 uncompressed images. The model used for these studies was the DCS200 with a colour sensor and internal 80 MB hard disk (Fig. 4). For image acquisition at the dam, 18 mm and 28 mm Nikkor lenses were used. Due to the small chip size the field of view of the Nikkor 18 mm lens corresponds to a 45 mm lens and the Nikkor 28 mm lens to a 70 mm lens of a normal SLR camera.

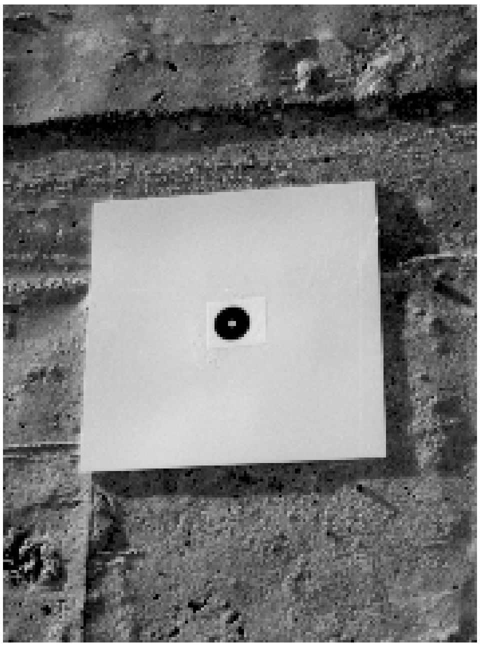

Figure 3: Installed target

Figure 4: Kodak DCS200 still video camera

4.2 Metric camera Wild P31

In addition to the DCS200, a metric camera Wild P31 was used with wide angle lens (f = 100 mm) for image acquisition at the dam. The radial distortion of this lens has been determined as less than ±2 µm by the manufacturer. The P31 operates with 102 mm x 127 mm glass plates. Due to the heavy weight of the camera, a tripod is required for image acquisition. For image data acquisition in this pilot study, black and white negative glass plates Agfa Avipan 100 were used.

5. Images Data Acquisition

For the DCS200, three camera stations at the wall coping, five stations in front of the wall and four stations from a cable car were used (Fig. 5). The P31 was also placed on stations No. 1-8. Two additional stations, one on the grass field in front of the wall and another in a further distance from the object, were included into the P31 net. Due to its handling, the P31 could not be used from the cable car. Images with both cameras were acquired over a two day period. To image all targets of the wall with the DCS200, several images with panned camera axis had to be taken from each station. Additionally, to improve the network geometry for simultaneous calibration, some additional images with rotated camera axis (90 and 180 degrees) were also taken from some stations. Due to the given a priori calibration no additional images with rotated camera axis were taken with the P31. Due to the much wider opening angle most of the targets could be imaged on one glass plate of the P31, so that no additional images with panned camera axis were required. A total of 10 images was taken from 10 stations with P31, while 74 images from 12 stations were acquired with the DCS200 (53 images with 18 mm lens, 21 with 28 mm lens).

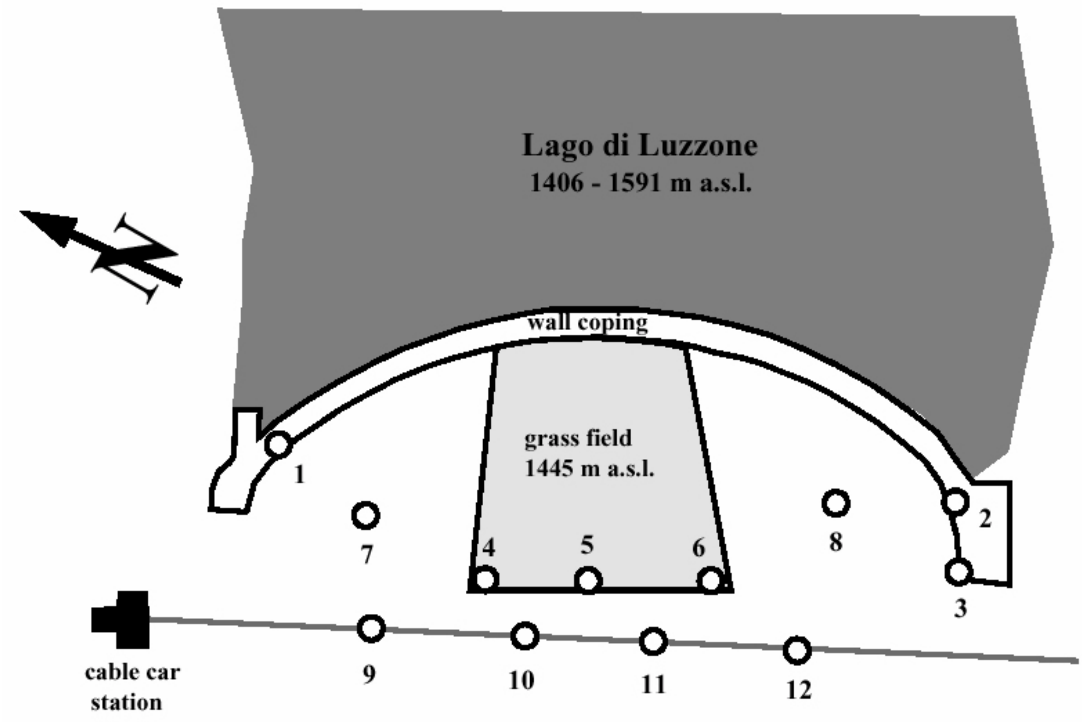

Figure 5: Configuration of camera stations for DCS200 at dam Luzzone

6. Data Processing and Results

The digital image data of DCS200 was processed semi-automatically using methods of digital photogrammetry *(Gruen/Beyer, 1990)*. Approximate orientation parameters and approximate pixel coordinates of signalised points (Fig. 6) were defined interactively, while the fine measurements were performed by least-squares template matching *(Gruen, 1985)*. The 3-D coordinates of 27 targets were determined by bundle adjustment with self-calibration, using a datum defined by geodetic measurements to some of the targets. Point number 910 (Fig. 2) was not used.

Measurements in all 10 P31 glass plates were performed on the analytical plotter Leica AC3 in mono comparator mode *(Piezzi, 1994)*. Due to the higher resolution of these negatives the whole PVC targets were imaged too large (up to 2 times the size of the largest measuring mark) on the analytical plotter, but in most images it was possible to measure the centre of the measuring marks, which was designed for geodetic measurements. The 3-D coordinates of the targets were also determined by bundle adjustment with self-calibration.

The results of the 3-D point positioning with both cameras in this pilot study are summarized in Table 1. The empirical accuracy measures (μ_X, μ_Y, μ_Z) are derived from a comparison of geodetic measured and photogrammetrically determined points. For this pilot study a redundant datum was fixed on eight control points in the corners of the wall. The a posteriori standard deviation of unit weight σ_0 of the bundle adjustment was 0.8 µm for DCS200, which corresponds to approximately $1/10^{th}$ of the camera pixel spacing. This is significantly worse than the results achieved in other applications. In other projects under factory floor conditions *(Kersten/Maas, 1994)* a 1/20th of pixel spacing was achieved, while under laboratory conditions even better results (1/30th - 1/50th of pixel

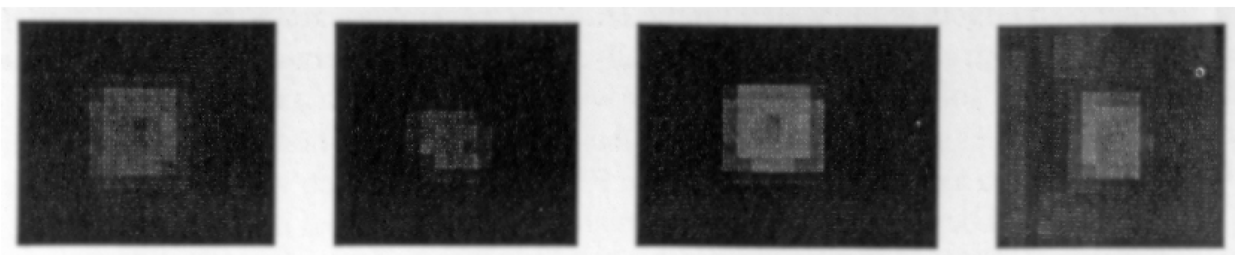

Figure 6: Targets in DCS images under various scale, contrast and illumination conditions

Camera	I	R	Co	Ch	σ_0 [μm]	Precision from adjustment			Accuracy from check points		
						Object space [mm]			Object space [mm]		
						σ_X	σ_Y	σ_Z	μ_X	μ_Y	μ_Z
P31	**10**	**5.6**	**8**	**19**	**4.6**	**10.2**	**6.1**	**4.3**	**10.8**	**6.7**	**6.9**
DCS200	**74**	**16.8**	**8**	**19**	**0.8**	**9.7**	**9.6**	**6.3**	**8.7**	**11.5**	**10.7**

I	Number of images	σ_0	Stand. dev. of the bundle adjustment a posteriori
R	Number of rays per image		
Co	Number of control points	σ_{XYZ}	Theoretical precision in object space
Ch	Number of check points	μ_{XYZ}	Empirical precision in object space

Table 1: Results of 3-D point positioning at dam Luzzone with P31 and DCS200

spacing) were obtained *(van den Heuvel, 1993, Peipe et al., 1993)*. In a diploma thesis at the IGP, a σ_0 = 0.25 µm and a relative theoretical precision of better than 1: 200 000 in planimetry could be achieved under laboratory conditions using a photogrammetric block of 150 images *(Keller, 1995)*. The results in this pilot study were probably deteriorated by insufficient contrast and by partly too small signalisation. Furthermore, the compensation of systematic errors was weak, i.e. some of the additional parameters could not be determined, due to the small number and unfavourable distribution of image points in the DCS images and a small average number of targets per image.

For the analog P31 images σ_0 was 4.6 µm. The accuracy (RMS of check point differences = 11/7/7 mm in X, Y, Z) which was achieved with P31 compares more or less to the results of *Fryer (1995)*. At the frequently monitored dam Chichester (length 254 m, height 43 m) Fryer obtained an accuracy in the range of 15/12/8 mm (worst campaign) and 4.5/3.5/3 mm (best campaign) using the same number of photos with an equivalent camera. With the DCS200 an accuracy of 9/12/11 mm was obtained which is only slightly worse than the P31 results.

7. Conclusions

The results obtained in this pilot study are still not acceptable for determination of deformations on dams and they are not comparable to accuracies achieved with conventional geodetic methods. But in the photogrammetric technique, a significant potential of improvement is available. With the P31 and sub-optimal signalisation accuracies of 11/7/7 mm were achieved. If photogrammetric equipment of highest accuracy and resolution is being used, an improvement of accuracies to 1/1/2 mm can expected by extrapolating the results published by other authors *(Dold et al., 1993, Shortis et al., 1994)*.

The results achieved with the digital camera DCS200 were slightly worse than the results of the analog camera P31 although a much larger number of images had been taken; but a significant potential of improvement can be found here as well. Firstly, size and contrast of the targeting depicted a compromise, and the of 0.8 µm indicates that the accuracy potential of the DCS200 has not been used at all. Other authors *(van den Heuvel, 1993, Peipe et al., 1993; Kersten/Maas, 1994; Keller, 1995)* reported a σ_0 of 0.2 - 0.3 µm, which is by a factor of 3-4 better than the one achieved in this pilot study. Secondly, the successor model of the DCS200, the DCS460 has a factor of 2 larger sensor of 3000 x 2000 pixels. In addition, the distribution of targets on the wall was far from ideal; in combination with the small opening angle of the DCS this lead to a bad connectivity in the triangulation block and poor self-calibration network geometry. Taking all this improvement potential into account, accuracies of a few millimeters for deformation measurement on a 600 x 200 m dam can be expected using digital photogrammetric equipment already today.

Therefore, photogrammetry is suited for deformation measurements at large arch dam structures as described in this paper. Especially, if the requirements of photogrammetric targeting are already encountered during the construction of a dam (permanent signalisation), automatic or semi-automatic digital photogrammetric techniques may be a very efficient tool for deformation measurements as an option for the densification of geodetic networks measured by conventional surveying methods.

8. Acknowledgment

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