The accuracy potential of large format stillvideo cameras

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Abstract:

High resolution digital stillvideo cameras have found wide interest in digital close range photogrammetry in the last five years. They can be considered fully autonomous digital image acquisition systems without the requirement of permanent connection to an external power supply and a host computer for camera control and data storage, thus allowing for convenient data acquisition in many applications of digital photogrammetry. The accuracy potential of stillvideo cameras has been extensively discussed. While large format CCD sensors themselves can be considered very accurate measurement devices, lenses, camera bodies and sensor mounts of stillvideo cameras are not designed for photogrammetric purposes and may cause severe accuracy problems. Moreover, some cameras use compression techniques in image storage, which may also affect the accuracy potential.

This presentation shows recent experiences from accuracy tests with a number of large format stillvideo cameras, including a modified Kodak DCS200, a Kodak DCS460, a Nikon E2 and a Polaroid PDC-2000. The tests of the cameras include absolute and relative measurements and were performed using strong photogrammetric networks and good external reference. The results of the tests indicate that very high accuracies can be achieved with large blocks of stillvideo imagery especially in deformation measurements. In absolute measurements, however, the accuracy potential of the large format CCD sensors is partly ruined by a lack of stability of the cameras.

Keywords: stillvideo camera, calibration, accuracy

1. Introduction

High resolution digital stillvideo cameras have found large interest among photogrammetrist during the past few years. Offering a high resolution CCD sensor integrated into a mirror reflex camera housing with A/D conversion, digital data storage capabilities, power supply and camera control, high resolution stillvideo cameras can be considered autonomous devices for the acquisition of digital imagery without the necessity of permanent connection to a host computer and avoiding the time consuming process of film development and scanning. These advantages make stillvideo cameras very suitable for outdoor applications like architectural photogrammetry, but also for a number of measurement tasks in industrial quality control and in engineering applications. Photogrammetrists have been using high resolution digital stillvideo cameras in a large number of applications since 1993 (e.g. Peipe et al., 1993; van den Heuvel, 1993; Fraser/Legac, 1994; Fraser/Shortis, 1994; Maas/Kersten, 1994) and have also reported about the results of accuracy tests (e.g. Grün et al, 1995; Fraser, 1995). The by far most used cameras are the cameras of Kodak's DCS-series (DCS200/410/420/460), which are also part of commercial photogrammetric measurement systems (e.g. Beyer, 1995, Brown/Dold, 1995). Meanwhile, several other manufacturers have launched high resolution stillvideo cameras following similar concepts. Two of these other cameras and two DCS cameras could be tested and compared in a study on the accuracy potential and the geometric stability of high resolution stillvideo cameras performed at ETH Zurich.

2. Technical data of the cameras

The following high resolution stillvideo cameras were available for the test:

2.1. Kodak DCS200

The Kodak DCS200 was the first high resolution digital stillvideo camera to come onto the market in 1992. It consists of a modified Nikon 8008s camera body with a 1524 x 1012 pixel CCD sensor with 9 µm pixel size in the imaging plane. The camera is offered alternatively with a black-and-white or a one-chip color CCD sensor; images can be stored on a 2 MB DRAM or on a 80 MB internal harddisk, which offers storage capacity for 50 uncompressed images. The model used for these studies was the DCS200mi with color sensor, internal 80 MB harddisk and a Nikkor 18 mm lens. Due to the chip size of 14 x 9 mm^2 the opening angle of the Nikkor 18 mm lens corresponds to a 45 mm lens on a normal SLR camera. The digital images can be transferred from the internal camera harddisk into a host computer via SCSI interface in an internal format, which can be converted into different standard image formats e.g. via a module in Adobe Photoshop on a Macintosh or Aldus Photostyler on a PC. Meanwhile Kodak has replaced the DCS200 by the DCS420 with the same sensor, but more convenient image storage on PCMCIA disks and a more reliable power supply.

2.2. Kodak DCS460

Kodak KAF6300 CCD sensor

Since 1995 Kodak offers the DCS460 as the high-end model of its series of stillvideo cameras. The DCS460 is based on the same Nikon N90 camera body as the DCS420, but is equipped with a 3060 x 2036 pixel Kodak KAF6300 CCD sensor with 9 µm pixel size, thus currently offering the highest resolution on the stillvideo camera market. The chip size is 28 x 18 mm^2 and comes close to the size of small format amateur film. This fact widens the palette of useful lenses; for the tests the camera was equipped with a Nikkor 28 mm AF lens, but with the autofocus switched off. The camera was equipped with a color sensor, but like for all other cameras in this test the images were transformed to monochrome images. The acquisition burst rate is two images in two seconds, with 8 seconds pause to store an image onto the PCMCIA disk.

2.3. Nikon E2

The Nikon E2 (and an identical model from Fuji) is a digital mirror reflex stillvideo camera equipped with a 2/3” 1280 x 1000 pixel color CCD sensor. To adapt the sensor size to the Nikon lens palette, a reduction optical system (condensor lens) is integrated into the camera body. Images are stored on 15 MB memory cards with a capacity for 5 uncompressed images or up to 84 images at different lossy JPEG compression ratios. Due to vignetting effects of the reduction optics the usable lenses are restricted to focal lengths of larger than 35mm; for the test the camera was equipped with a 35-70 mm zoom lens at 35 mm; the autofocus was switched off. Images can be downloaded via Adobe photoshop or with a special browser.

2.4. Polaroid PDC2000

The Polaroid PDC2000 is the cheapest one of the tested cameras and depicts a different type of stillvideo camera: It features a very compact, lightweight design and is not a mirror reflex camera. It is equipped with a 9 x 7 mm^2 CCD sensor with 1600 x 600 pixels. In a 'highresolution mode' these pixels are binned to an image format of 800 x 600 pixels; optionally a 1600 x 1200 pixel image can be derived from the same sensor by interpolation techniques in a 'super high resolution mode'. The camera is equipped with an 11 mm lens (or optionally wit a 17 mm lens); the autofocus can only be switched off when the camera is focused to infinity. Images are downloaded with a convenient browser.

3. Test on accuracy potential and stability

To test the accuracy potential of the cameras, a number of images were taken with each camera from a reference field at ETH Zurich (Fig. 1). The image coordinates of the signalized points were determined with subpixel accuracy by least squares template matching, using some coded targets in the reference field and known 3-D coordinates for an automated dataflow. Employing self-calibrating bundle adjustment techniques, camera model parameters were determined simultaneously with camera orientation data and 3-D object point coordinates; see e.g. (Grün/Beyer 1992) for an overview on the theory of self-calibrating bundle adjustment. The sensor model used in the test was a parameter set introduced by (Brown, 1971), containing three parameters of interior orientation (camera constant and principle point coordinates) and five parameters describing radial and decentering lens distortion:

$$\bar{x}_i' = x_i' + dx_i \qquad \bar{y}_i' = y_i' + dy_i$$

$$dx_i = x_i' \cdot (k_1 r_i'^2 + k_2 r_i'^4 + k_3 r_i'^6) + p_1 \cdot (r_i'^2 + 2x_i'^2) + 2p_2 x_i' y_i' \qquad r_i'^2 = x_i'^2 + y_i'^2$$

$$dy_i = y_i' \cdot (k_1 r_i'^2 + k_2 r_i'^4 + k_3 r_i'^6) + 2p_1 x_i' y_i' + p_2 \cdot (r_i'^2 + 2y_i'^2)$$

x', y' : image coordinates [mm]
k_1, k_2, k_3 : radial lens distortion
p_1, p_2 : decentering lens distortion

This model was extended for the use in digital close range photogrammetry by two additional parameters of an affine transformation, modeling a horizontal scale factor and a non-orthogonality of the image coordinate axes (e.g. El-Hakim, 1986; Beyer, 1987); these parameters do mainly cover deviations of the pixel shape from the designed values and effects of the A/D conversion.

$$\tilde{x}_i' = a_1 \bar{x}_i' + a_2 \bar{y}_i' \qquad \tilde{y}_i' = \bar{y}_i'$$

a_1: horizontal scale factor , a_2: shear factor

The 3-D coordinates of 186 signalized points on the reference field had been determined with a standard deviation of 0.02-0.03 mm using a theodolite system. Some of the targets were designed as coded targets (Niederöst/Maas, 1997) to allow for an automatic dataflow in camera calibration. The reference field was used in two modes:

- In the mode 'free network' a self-calibrating bundle adjustment was performed as a free network adjustment, including the 3-D coordinates of the signalized as unknowns into the adjustment process. This allows for the derivation of figures on the theoretical precision of photogrammetrically determined object point coordinates. Moreover, from comparisons with the reference coordinates statements on the practical accuracy can be drawn. However, the chosen self-calibration procedure is based on the assumption of one constant camera parameter set for all images.
- In the mode 'resection' the known coordinates of the signalized points were used as control points and spatial resections were performed from each image individually. Allowing for the determination of one independent parameter set for each camera, this procedure is useful for examinations on the geometric stability of the cameras in a sequence of images taken from different locations under different orientations.

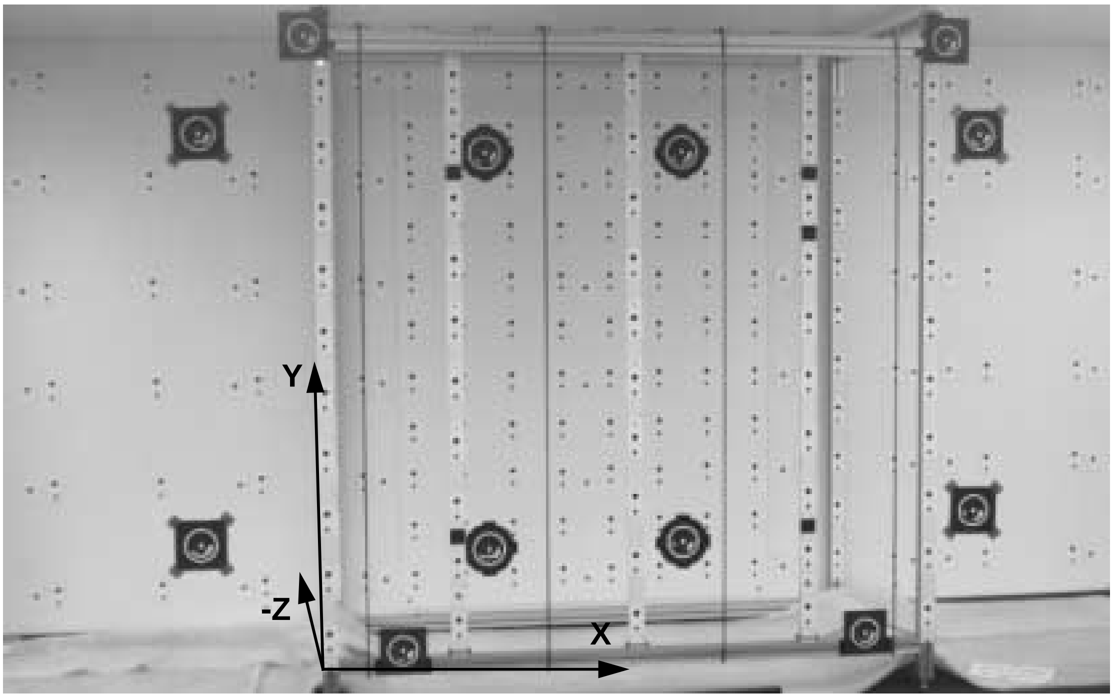

Fig. 1: ETH camera calibration field with coded and uncoded targets

The following camera tests were performed:

- **DCS200-1**: A total of 15 images at three roll angles was taken from five camera stations with an unmodified DCS200.
- **DCS200-2**: After a thorough test of the DCS200 in a former study (Grün et al., 1995) and the results of the test DCS200-1, it was suspected that the sensor mount inside the camera body was insufficient and allowed for movements of the sensor. For that reason the sensor was mechanically fixed for a second test of the camera. In this test a total of 24 images was taken.
- **DCS460**: A total of 15 images at three roll angles was taken from five camera stations with an unmodified DCS460 in a network similar to the one of the test DCS200-1.
- **Nikon-1**: Due to the limited storage capacity of the Nikon E2, the fact that images are stored as RGB color images and the lack of local data download facilities at the calibration field, only five uncompressed images could be taken with the Nikon E2. As one of the images was spoiled by an unexplained error during data transfer, only four images could be used. Therefore the results achieved with uncompressed Nikon imagery are not very meaningful.
- **Nikon-2**: In a second test with the Nikon E2 a total of 19 images was taken and stored in the compression mode ‘good’. The compression ratio was in the order of 1:2 (in relation to monochrome images as used in the test), which can be considered a very low compression.
- **Polaroid-1**: A total of 24 images in a network configuration similar to the one used in DCS200-2 was taken with the Polaroid PDC2000. Polaroid-1 refers to the processing of 1600x1200 pixel images in the interpolated ‘super high resolution mode’.
- **Polaroid-2**: The dataset described in Polaroid-1 was also processed with 800x600 pixel images in the binned ‘high resolution mode’.

All tests include convergent images taken from several camera stations and images taken with the camera rotated by +/-90^{o} around its optical axis. Due to spatial restrictions and limitations of the storage capacities of the individual cameras, the number of images and the photogrammetric network design was not identical for all cameras.

The results achieved it the tests are summarized in Table 1 and Table 2:

Table 1: Results of free network adjustment

	$\#_{img}$	$\hat{\sigma}_0$	$\hat{\sigma}_X$	$\hat{\sigma}_Y$	$\hat{\sigma}_Z$	μ_X	μ_Y	μ_Z
DCS200-1	15	0.34	0.047	0.041	0.091	0.143	0.121	0.169
DCS200-2	24	0.37	0.042	0.037	0.110	0.166	0.069	0.194
DCS460	15	0.88	0.049	0.043	0.114	0.203	0.135	0.292
Nikon-1	4	0.30	0.086	0.081	0.223	0.236	0.138	0.364
Nikon-2	19	0.29	0.050	0.043	0.151	0.239	0.182	0.299
Polaroid-1	24	0.34	0.049	0.045	0.144	0.120	0.127	0.210
Polaroid-2	24	0.43	0.057	0.054	0.178	0.120	0.115	0.241

Table 2: Results of individual resections

	$\#_{img}$	$\hat{\sigma}_{0(1)}$	$\hat{\sigma}_{0(n)}$	Δx_p	Δy_p	Δcc
DCS200-1	15	0.41	0.30	0.063	0.101	0.012
DCS200-2	24	0.39	0.36	0.028	0.044	0.013
DCS460	15	1.10	0.32	0.097	0.113	0.027
Nikon-1	4	0.39	0.36	0.020	0.029	0.006
Nikon-2	19	0.38	0.31	0.081	0.045	0.015
Polaroid-1	24	0.39	0.34	0.039	0.052	0.015
Polaroid-2	24	0.47	0.43	0.054	0.032	0.011

with the notions

$\#_{img}$: number of images

$\hat{\sigma}_0$: standard deviation of unit weight [µm]

$\hat{\sigma}_{X,Y,Z}$: standard deviation of object point coordinates [mm]

$\mu_{X,Y,Z}$: rms of control point differences [mm]

$\hat{\sigma}_{0(1)}$: standard deviation of unit weight in resection with one constant parameter set [µm]

$\hat{\sigma}_{0(n)}$: standard deviation of unit weight in resection with $\#_{img}$ individual parameter sets [µm]

Δx_p, Δy_p : range of principle point coordinates in individual parameter sets [mm]

Δcc : range of camera constant in individual parameter sets [mm]

It has to be noted that only one test was performed per camera, and that the results are probably not perfectly reproducable. Nevertheless, the results allow for manifold statements on the geometric accuracy potential of the cameras. Table 1 shows a clear discrepancy between internal and external precision parameters for all cameras. The theoretical internal precision figures $\hat{\sigma}_{X,Y,Z}$ obtained from the covariance matrix of the bundle adjustment can only be considered representative if the underlying geometrical and stochastical model is met, while the deviations from checkpoint coordinates $\mu_{X,Y,Z}$ give a better impression on the practical accuracy potential. Discrepancies between internal and external figures indicate non-compliance with the mathematical model. Surprisingly, the cheapest of the cameras (Polaroid) performs even slightly better than the most expensive camera (DCS460) as far as checkpoint residuals are concerned. Table 2 shows that the standard deviation of unit weight is significantly improved for all cameras and versions if one individual parameter set is introduced for each image in the resection. In that case the principle point coordinates of the individual parameter sets vary by several pixels, indicating an instability in the interior orientation of all cameras; this instability means a non-compliance with the geometric model used in the self-calibrating bundle adjustment, which assumed a constant camera model for all images.

Some more statements can be drawn from the results: The mechanical fixation of the sensor in the version DCS200-2 does only partly solve the problems; this indicates that problems are not only caused by the instable sensor mount, but also by the camera body and the lens mount which are not designed to be used as a metric camera. The most obvious discrepancies between constraind and unconstrained solutions occur with the DCS460. Due to the larger opening angle of the DCS460 with a sensor format of 28 x 18 mm^2 and a 28 mm lens, the problems do also become more evident in the standard deviation of unit weight of the free network solution. Moreover, it has to be suspected that the 28 mm Nikkor autofocus lens shows a smaller stability than the 18 mm Nikkor lens which was used on the DCS200. In the results of the resections with the DCS460 images even the decentering distortion showed significant variations between consecutive images. In some versions the principle point coordinates show a clear dependency on the roll angle; this applies especially to the y-coordinate of the principle point in the version DCS200-1, but also to the version Nikon-2. Surprisingly, the large principle point movements of the DCS460, which are statistically significant, do not show a correlation with the roll angle - a fact which might also be interpreted as an indication for an instability of the 28 mm AF lens. The results of the version Nikon-1 cannot be considered representative as there was only one rolled image among the four images of that test. The checkpoint deviations of the version Nikon-2 increase strongly towards the edges of the calibration field; this indicates systematic effects caused by the condensor lens in the optical system of the Nikon E2, which are not covered by the mathematical model.

A parametrization of the free network adjustment with one individual parameter set for each image as used in the resections cannot be considered an option to deal with the instability of the principle point coordinates in 3-D coordinate measurement tasks as this would depict an overparametrization of the bundle and lead to singularities. Instead, several versions were parametrized with one common parameter set for all images of the block and an independent principle point for each image. The results are summarized in Table 3:

Table 3: Results of free network adjustment with individual principle point coordinates

	$\#_{img}$	$\hat{\sigma}_0$	$\hat{\sigma}_X$	$\hat{\sigma}_Y$	$\hat{\sigma}_Z$	μ_X	μ_Y	μ_Z
DCS200-1	15	0.28	0.041	0.036	0.077	0.085	0.065	0.096
DCS200-2	24	0.35	0.050	0.041	0.108	0.110	0.091	0.168
DCS460	15	0.45	0.030	0.025	0.061	0.081	0.047	0.096
Nikon-1	4	0.29	0.340	0.354	0.372	0.715	0.580	0.617
Nikon-2	19	0.28	0.065	0.051	0.154	0.448	0.213	0.447
Polaroid-1	24	0.30	0.052	0.044	0.131	0.135	0.137	0.198

While there is a significant gain in the rms of the checkpoint deviations for the DCS cameras (especially for the DCS460), no significant improvement can be achieved for the Polaroid. The version Nikon-1 is too weak for the determination of individual principle points; the results of the version Nikon-2 indicate again that the accuracy problems of the Nikon E2 are at least partly caused by the condensor lens system. The introduction of weak additional constraints into the bundle adjustment (like few control points or few distance observations) did not lead to a significant improvement of the remaining discrepancies between interior and exterior precision figures.

From these tests one can conclude that the accuracy potential of stillvideo cameras and their suitability for absolute 3-D coordinate measurement tasks is severely degraded by instabilities of the interior orientation. This has to be taken into account when planning network configurations and when specifying performance parameters of systems.

4. Performance in relative measurements

All the above statements on the problems of the use of stillvideo cameras for photogrammetric 3-D coordinate measurement tasks refer to absolute measurements in unconstrained or very weakly constrained networks. Due to high local correlations of the degrading effects it can be expected that the exterior precision parameters become much better in relative 3-D measurements like tracking applications or deformation measurements with small displacement vectors to be determined rather than absolute coordinates.

To show the accuracy potential of a stillvideo camera for 3-D relative measurement tasks a study was performed on the deformation of concrete parts in a dehydration process. The parts were signalized with a number of targets which had to be measured in seven epochs over six months. Deformations were expected both in X-direction (due to fissures) and Z-direction (due to bending effects). To protect the concrete parts from exterior disturbances and to provide a basis for static reference points the parts were enclosed by solid steel bars. For the automation of the process some coded targets were also attached to the steel bars, allowing for an automated dataflow after the interactive measurement of the first epoch in a process of coded target detection and measurement, determination of raw orientation data, projection of mass points into image space, image coordinate determination and self-calibrating bundle adjustment (Niederöst/Maas, 1997).

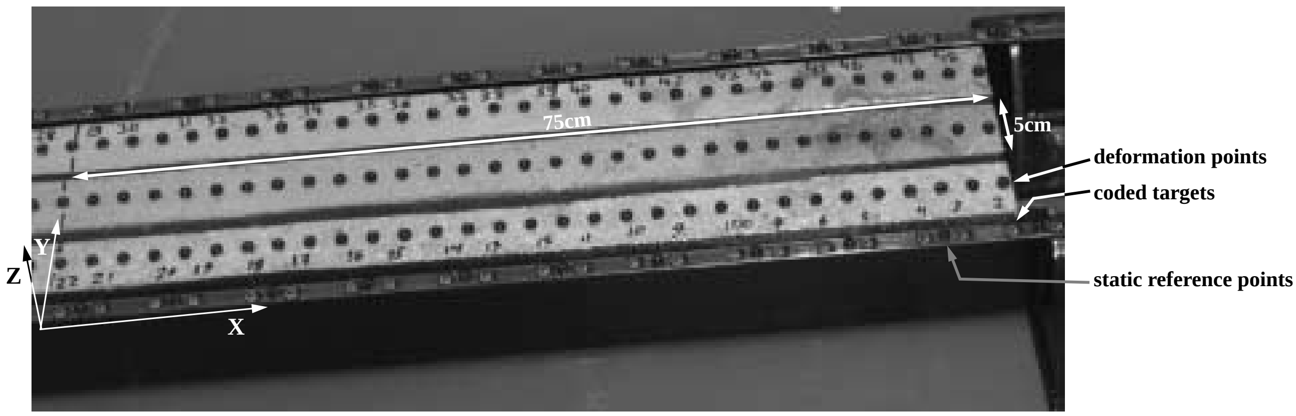

Fig. 2: Targeted concrete parts in deformation test

In every epoch 26 images of the object were acquired with an off-the-shelf DCS200, arranged in two convergent stripes parallel to the direction of the concrete bars. In the final data processing, the target coordinates of all points in all epochs were determined simultaneously, introducing one set of coordinates for the deformation points and one camera parameter set for each epoch and keeping the coordinates of the reference points fix over all epochs. For the coded targets on the steel bars which were not subject to deformations, one set of coordinates was introduced for each epoch; this allows for an external accuracy check by examining the rms deviations of the coordinate differences between the epochs from zero. The results of the study are summarized in Table 4:

Table 4: Results of deformation measurement

$\hat{\sigma}_0$ [µm]	$\hat{\sigma}_X$ [mm]	$\hat{\sigma}_Y$ [mm]	$\hat{\sigma}_Z$ [mm]	rms_X [mm]	rms_Y [mm]	rms_Z [mm]
0.28	0.0031	0.0034	0.0095	0.0031	0.0032	0.0062

In contrast to the absolute measurements shown before, these relative measurements show very high accuracy and good consistency between internal and external accuracy parameters. The fact that in depth direction (Z) the external accuracy is better than the internal figure can be explained by correlations between coordinates caused by the introduction of self-calibration parameters. Related to the length of the observation area of ~80 cm, the achieved accuracy corresponds to a relative accuracy of better than 1 : 250’000. With this accuracy potential, relatively low instrumental effort and the possibility of fully automatic data processing, digital photogrammetry depicts an unrivaled tool for this kind of measurement task.

5. Conclusion

A number of practical tests with different types of digital high resolution stillvideo cameras for absolute 3-D coordinate determination using multiple images of a scene in self-calibrating bundle adjustment have shown discrepancies between internal and external accuracy figures caused by instabilities of the interior orientation. These problems cause severe degradations to the accuracy potential of the cameras and pose limitations for their use in high precision 3-D measurement tasks. By proper parametrization of the bundle and strong networks with three-dimensional extension, the effects can only partly be compensated. In contrast to absolute measurements, very high accuracies beyond 1 : 250’000 could be achieved in relative measurements.

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