GEOMETRIC CALIBRATION OF THE HASSELBLAD H3D MEDIUM FORMAT CAMERA

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ABSTRACT:

The Hasselblad H3D digital camera, which is designed for professional studio shootings, is equipped with a 39 megapixel digital back. It would be desirable to use this very high geometric resolution in photogrammetric applications. Unfortunately, the digital back does not have a tight connection to the camera body. In addition, the unknown internal image processing algorithms and the autofocus lens make it difficult to obtain a reliable camera calibration. In this paper, we investigate whether the Hasselblad H3D camera can be calibrated for use in photogrammetric applications. Repeated calibrations were performed using a 2D (planar) target as well as a 3D test field. Results of the individual calibration projects are compared in order to analyze the stability of the camera over time. We also investigate if there is a fixed pattern of systematic image residuals (after removal of radial distortion), which could be described by a distortion grid. Software tools were developed for semi-automatic calibration using the MATLAB programming environment. This calibration software consists of a graphical user interface supporting automated and precise measurement of circular point targets, robust calculation of initial orientation parameters and bundle adjustment with self-calibration capabilities. The commercial software package PhotoModeler (Eos Systems Inc./Vancouver) was also used for comparison to derive calibration parameters based on the planar target.

1. INTRODUCTION

In this paper we present repeated geometric calibrations of a Hasselblad H3D digital SLR camera (see Fig. 1). The H3D digital back holds a 39 megapixel image sensor (36.7 x 49 mm) and can be detached from the camera body for maintenance. Our equipment includes three HC lenses, i.e., 3.5/35 mm, 3.5/50 mm, and 2.8/80 mm. Image data can be stored on internal CF cards (type II) or on external storage media (Imagebank or computer). Image data (16 bit, color) is stored in lossless compressed Hasselblad 3F RAW file format. Automatic autofocus must be switched off for photogrammetric work. The internal tilt sensor must also be disabled for proper photogrammetric image orientation. Hasselblad FlexColor software (version 4.6.7) is needed for further image processing. Digital correction of the (lateral) effect of color aberration is carried out by “Digital APO Correction” (DAC).

Figure 1. Hasselblad H3D with fixing bar applied

Raw image data was converted to RGB 8 bit TIFF for further photogrammetric processing. The final image size was 5412 x 7216 (file size of 111 MB for uncompressed storage).

The H3D has been successfully used in terrestrial photogrammetric projects, e.g. for glacier monitoring and architectural projects, and in helicopter based mapping projects (Raggam et al., 2007). A relative accuracy of point positioning of at least 1:10000 is needed for such applications. A reliable camera calibration must thus be performed for all three available lenses. Furthermore, we wanted to investigate the stability of the H3D camera by comparing repeated calibrations (in total four calibrations during 9 months).

In order to derive calibration parameters from images taken of 2D or 3D targets in reasonable time, it was necessary to implement a (semi-)automatic workflow for point measurement, calculation of approximate exterior orientation (EO) parameters and final bundle adjustment. This was done in a master thesis (Fauner, 2008) and a bachelor thesis (Längauer, 2008). Results were cross checked by the commercial PhotoModeler software package of Eos Systems Inc. (PhotoModeler, 2008).

Another aim of this study was to evaluate the quality of calibration results using a low cost planar (2D) target and to compare it with the results from a 3D test field. Special investigations were carried out to evaluate systematic image errors caused by the eccentricity error of the ellipse operator and distance dependant lens distortion.

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2. CAMERA CALIBRATION

2.1 Calibration using a movable planar target

The calibration target is made of a stable planar wooden board, sized 140 x 120 x 2.5 cm. Because of its low weight (<10 kg) it can be easily moved to any location suitable for calibration, indoor or outdoor. The layout of the present 2D target is based on the target used by PhotoModeler. However, the square layout of the original target was modified by adding two additional columns of markers on the left and right side (see Fig. 2). The four coded markers can be identified uniquely in images taken from arbitrary viewing directions.

The rectangular pattern of 10 x 14 black markers (∅ 2cm) allows acquiring single images fully covered by markers. This facilitates measurement of the effect of lateral chromatic aberration (cp. Kaufmann & Ladstädter, 2005).

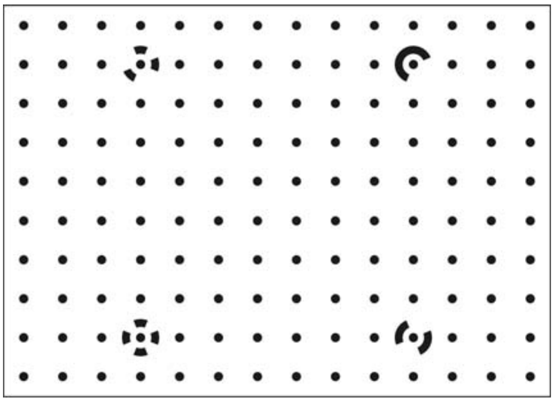

Figure 2. Layout of the 2D calibration target

For calibration purposes, images should be taken from various directions, viewing angles and distances. It is also recommended to take images with the camera rotated 90°. Using such an image configuration, it is possible to de-correlate calibration parameters from EO parameters (e.g. focal length/object distance and principle point/rotation angles). The target should not be moved during calibration in order to avoid deformation.

We performed three independent calibrations, on June 25, 2007, on July 1, 2007, and on March 19, 2008. Series of 16 to 31 images were taken handheld for each of the three lenses (see Table 1). Using daylight, it was not necessary to use a tripod which speeded up the whole process. Images were taken using the far end (∞) of the focusing ring. This is a repeatable setting, which corresponds more or less to an infinite object distance. However, this setting causes blurred images because of the close distance (max. 3m) of the calibration target, especially for the 80mm lens. A high f-number (f/27) was therefore used to minimize blurring.

2.2 Calibration using a 3D test field

Two separate calibrations were performed on August 1, 2007 and on March 19, 2008 (on the same day as for the second 2D calibration) in the in-house calibration room of Vexcel Imaging Graz (see Fig. 3), which is routinely used for calibration of the UltraCamX digital aerial camera.. The size of the test field is approximately 8m x 2.5m x 2.5m. A total of 394 circular markers are glued on aluminum bars mounted on a concrete wall, floor and ceiling. The coordinates of all the targets have been determined by a geodetic survey with a precision of +/- 0.05 mm. In contrast to the 2D calibration target, no coded markers exist in the test field.

Figure 3. Calibration room of Vexcel Imaging Graz

Images were taken from three positions (left, middle, right), with different viewing directions. Again, additional images were taken with the camera rotated 90°. Series of 15 to 35 images were produced for each lens (see Table 2). A high f-number (f/27) was also used for the 3D test field. The limited lighting required relatively long exposure times (~0.7sec) and thus the use of a tripod. Because of the room dimensions, the maximum distance to the back wall is limited to 8m.

2.3 Automated marker measurement

Automated and precise measurement of circular markers requires an algorithm that is capable of fitting an ellipse in the image. Such an algorithm, described e.g. by Luhmann (1986), was implemented as a MATLAB function. Given a starting point somewhere inside the marker, the algorithm first determines the approximate (maximum) diameter of the ellipse, then performs a radial search for edges in various directions and finally fits an ellipse to the previously located points (see Fig. 4). Our test results show that the center of the ellipse can be determined with an accuracy of at least one tenth of a pixel and that the algorithm also works with low contrast or noisy images.

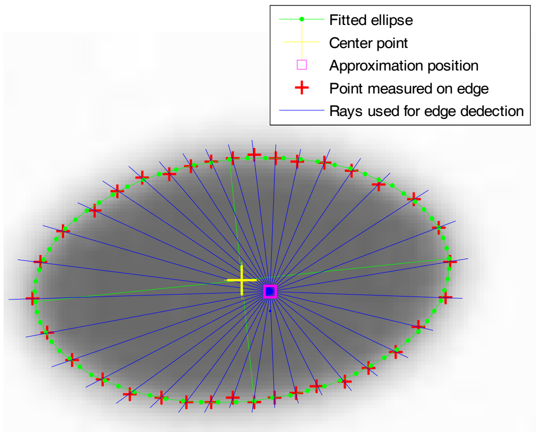

Figure 4. Ellipse fitting operator

It should be mentioned that the center of the ellipse does not exactly coincide with the projected center of the circular marker. This small eccentricity is a function of the viewing angle, marker size and focal length (Dold, 1997). The evaluation of this formula (see Fig. 5) showed that maximum eccentricity values of 1.25µm can be expected for the 2D target (80mm lens) and even lower values (below 0.25µm) for the 3D test field. The eccentricity error was therefore neglected for the purposes of our study.

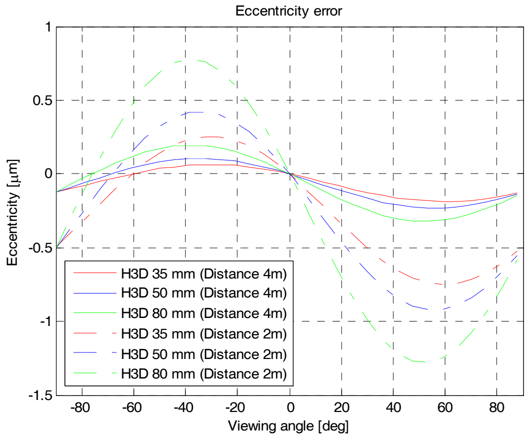

Figure 5. Eccentricity error of the ellipse operator

Another error source concerning the ellipse operator was also investigated. This error occurs when large radial distortion is present in the images and the markers are imaged at a large image scale. In this case distortion may change even within a single imaged marker, which causes a non-linear deformation of the ellipse, resulting in a positioning error. As can be seen from Fig. 6, this error is estimated to be well below 0.5µm for all lenses and can therefore also be neglected in this study.

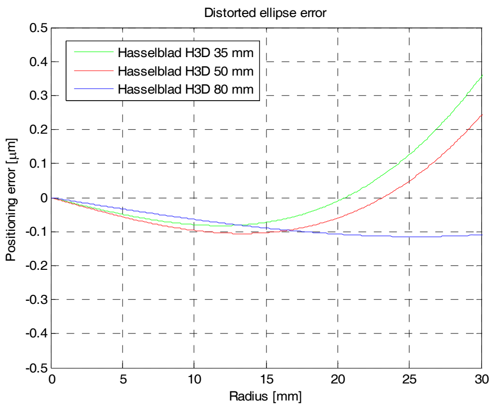

Figure 6. Influence of large distortion on the ellipse operator

The following steps are necessary in order to fully automate the process of marker measurement for a planar target (cp. Längauer, 2008):

1. Localization of (coded) markers in the image
2. Determination of a 2D projective transformation between image and object coordinates
3. Estimation of radial distortion (optional)
4. Calculation of approximate positions for each marker
5. Precise measurement using the ellipse operator
6. Determination of approximate EO parameters using a robust resection algorithm (Killian, 1955: 97-104)

This workflow was successfully implemented in a MATLAB tool (see Fig. 7). Image measurements for all images of the calibration project are exported to an ASCII file for further evaluation in the bundle adjustment.

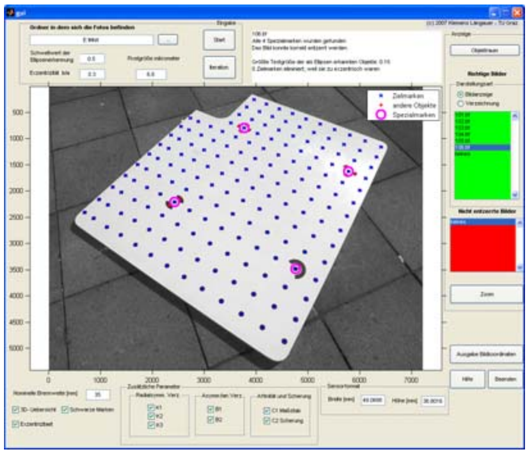

Figure 7. MATLAB tool for automated 2D measurements

The following table gives an overview of the H3D calibration projects performed using the planar target:

Date	Lens	Focus	# Images	# Points
June 25, 2007	35mm	∞	16	2450
	50mm	∞	20	3150
	80mm	∞	19	2900
July 1, 2007	35mm	∞	17	2800
	50mm	∞	18	3000
	80mm	∞	18	2800
March 19, 2008	35mm	∞	31	5200
	50mm	∞	23	3660
	80mm	∞	22	2950
	35mm	1.5m	28	4660
	50mm	2m	24	3800
	80mm	2m	19	2100

Table 1. Statistics of the 2D marker measurements

Automation of marker measurements is much more complicated for a 3D test field. We therefore decided to use a semi-automated approach where a limited number of manual measurements must be made for each image. Again, the necessary steps were implemented in a MATLAB tool (see Fig. 8):

1. Manual measurement of at least four markers
2. Determination of approximate EO parameters using the robust Müller/Killian resection algorithm (modified after Killian, 1955: 171-179)
3. Determination of refined EO and IO parameters and radial distortion by a single image bundle adjustment (using additional manual measurements)
4. Re-projection of all visible markers into the image gives approximate positions for the ellipse operator
5. Automated precise marker measurement using the ellipse operator

Steps 3 to 5 can be performed iteratively until all markers have been successfully measured. It is also possible to carry out steps 1 to 4 for all images of the calibration project in advance and run the (time consuming) automated marker measurement as a batch job. Image measurements, approximate EO parameters and marker coordinates are exported to ASCII files, which can directly be used for bundle adjustment.

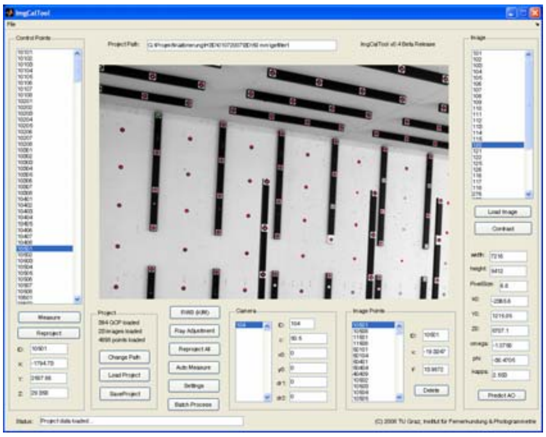

Figure 8. MATLAB tool for automated 3D measurements

The following table gives an overview of the H3D calibration projects using the Vexcel test field:

Date	Lens	Focus	# Images	# Points
August 1, 2007	35mm	∞	15	4780
	50mm	∞	23	4900
	80mm	∞	16	1900
March 19, 2008	35mm	∞	35	10600
	50mm	∞	20	4960
	80mm	∞	21	3100
	50mm	5m	18	4500
	80mm	5m	23	3100

Table 2. Statistics of the 3D marker measurements

2.4 Determination of calibration parameters

The camera calibration parameters were determined using the in-house developed bundle adjustment software PhoBA (**Pho**togrammetric **B**undle **A**djustment). The following commonly used camera calibration parameters (cp. Luhmann et al., 2006) can be determined:

1. Focal length: c
2. Principal point: x_0, y_0
3. Radial distortion: coefficients k_0, k_1, k_2, k_3
4. Tangential distortion: coefficients b_1, b_2
5. Affinity and shear: coefficients c_1, c_2

In a first run, all of the calibration projects were adjusted using the complete set of calibration parameters (except k_0, which is 100% correlated with the focal length c). Gross errors were automatically removed by the built-in data snooping feature of PhoBA. From the analysis of these preliminary results, we could draw the following conclusions:

1. Parameters b_1, b_2, k_3 and c_2 are not significant and can be eliminated from the adjustment.

2. Parameter c_1 describing the deviation from a square pixel (scale in x) is significant but varies slightly within the different projects. Pixel size is a physical constant, so we decided to fix this parameter at a mean value, resulting in a pixel size of 6.8 x 6.801 µm.

3. The principal point offset is relatively large, which causes problems when the principal point of symmetry (PPS) is assumed to be at the image center. We therefore set the PPS equal to PPA for all calibration projects.

In a second and final run, all calibration projects were adjusted using only the five significant parameters (and parameter c_1 fixed at a given value). The remaining calibration parameters are highly significant and much less correlated than the original parameter set. The following tables present focal length and principal point parameter values and sigma naught obtained from the bundle adjustment:

June 25, 2007				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.663 ± 0.0007	-50.1 ± 0.4	279.6 ± 0.4	0.9
50 mm	50.286 ± 0.0011	-98.7 ± 0.0006	240.1 ± 0.8	1.2
80 mm	82.354 ± 0.0056	-176.7 ± 3.1	302.3 ± 4.6	2.9
July 1, 2007				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.642 ±.0012	-88.0 ±0.6	184.6 ±0.7	1.5
50 mm	50.280 ±0.0020	-137.1 ±1.1	140.5 ±1.2	2.1
80 mm	82.272 ± 0.0083	-198.1 ±5.0	196.9 ±6.0	4.2
March 19, 2008				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.668 ± 0.0012	-70.4 ± 0.5	294.9 ± 0.3	0.7
50 mm	50.251 ± 0.0008	-105.8 ± 0.3	233.3 ± 0.5	0.7
80 mm	82.292 ± 0.0042	-203.8 ± 2.0	281.6 ± 2.7	2.0

Table 3. Calibration parameters obtained from the 2D target

August 1, 2007				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.652 ± 0.0004	-72.9 ± 0.2	225.3 ± 0.3	1.3
50 mm	50.251 ± 0.0004	-117.1 ± 0.4	153.5 ± 0.5	1.5
80 mm	82.297 ± 0.0017	-174.2 ± 1.3	270.5 ± 1.6	1.4
March 19, 2008				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.651 ± 0.0002	-38.33 ± 0.2	288.33 ± 0.2	1.0
50 mm	50.256 ± 0.0006	-85.99 ± 0.4	225.85 ± 0.4	1.3
80 mm	82.301 ± 0.0011	-132.47 ± 1.1	314.26 ± 1.0	1.1

Table 4. Parameters obtained from the 3D test field

Radial distortion coefficients k_1, k_2 are not given here explicitly. Fig. 9 shows the unbalanced radial distortion curves derived from these parameters.

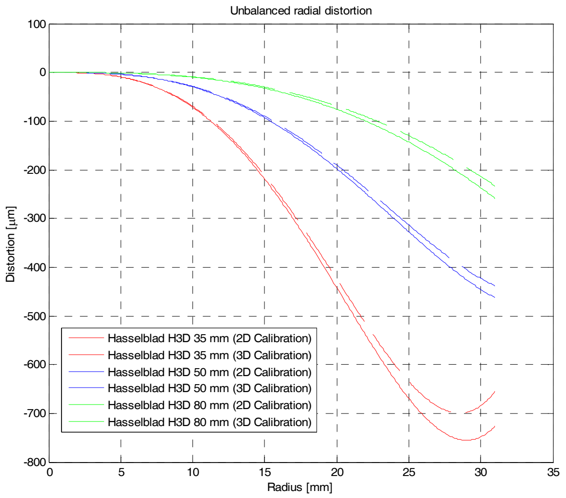

Figure 9. Unbalanced radial distortion curves

A clear difference can be seen between the 2D and 3D calibration methods for all three lenses (calibration on March 19, 2008). This is caused by the high correlation of the radial distortion parameters with other parameters in the bundle adjustment (focal length, EO parameters), especially for the 2D target. Errors will also propagate into the object coordinates (model deformation).

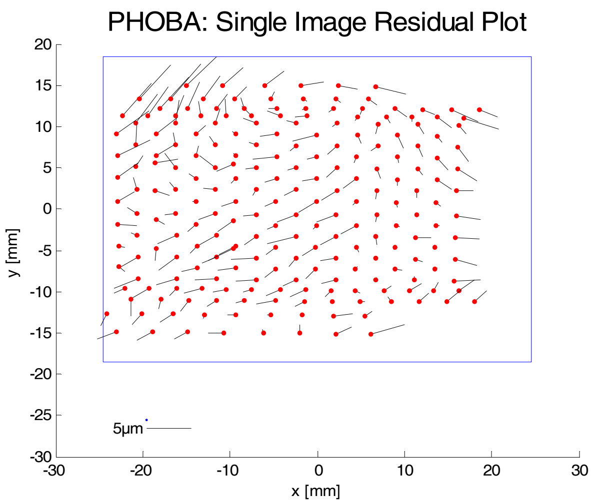

Figure 10. Systematic image residuals (3D target, 50mm lens)

We observed small but systematic errors in some of the projects when plotting image residuals for a single image (see Fig. 10). We tried to model them by distance-dependent radial distortion parameters (cp. Dold, 2007) in the bundle adjustment.

As can be seen from Fig. 11, the effect of a distance-dependent variation of radial distortion is not very significant. Maximum values of 3µm (for the 2D target) are reached, but only in the very corners of the image. The effect is even smaller for the 3D target (2µm).

In an additional experiment, we performed complete calibrations with lenses focused at a mean object distance (2D target: 2m, 3D test field: 5m). Focal length parameters differ by about 0.4% for the 35mm lens, 0.7% for the 50mm lens and 4.0% for the 80mm lens (see Table 5). With lenses focused at 5m, the differences are 0.2% and 1.4% (for the 50mm and 80mm lens, respectively, see Table 6).

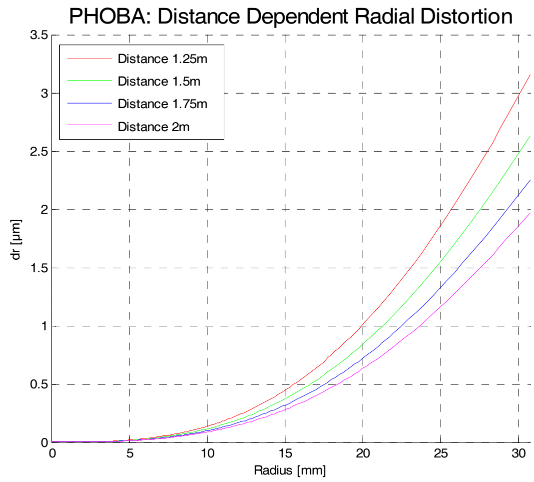

Figure 11. Distance dependent distortion (2D)

Calibration results cannot be improved significantly and the same systematic residuals can be observed in the images. For the 80mm lens and the 2D target, however, results are much better, because we get sharp images with the focused lens.

March 19, 2008				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	35.820 ±0.0006	-61.9 ±0.3	278.8 ±0.3	0.7
50 mm	50.585 ±0.0007	-102.0 ±0.3	235.1 ±0.4	0.7
80 mm	85.465 ±0.0028	-243.0 ±1.1	256.5 ±1.6	0.9

Table 5. Results with focused distance 2m (2D target)

March 19, 2008				
Lens	c [mm]	x_0 [µm]	y_0 [µm]	σ_0
35 mm	-	-	-	-
50 mm	50.376 ± 0.0006	-86.3 ± 0.4	229.9 ± 0.4	1.2
80 mm	83.385 ± 0.0010	-112.9 ± 0.8	310.1 ± 0.9	1.0

Table 6. Results with focused distance 5m (3D target)

2.5 Quality check

In order to check the quality of the calibration process, all calibration parameters are fixed at their estimated values in the bundle adjustment. The 3D test field is now used to check both the 2D and 3D calibration results (of March 19). Only nine (well distributed) control points are used, the other 383 points are introduced as check points to evaluate the accuracy of point reconstruction (see Tables 7 and 8). Only three images are used, i.e., one for the left, middle and right position, which can be seen as a “common” (not highly redundant) stereo configuration.

Lens	RMS_X [mm]	RMS_Y [mm]	RMS_Z [mm]	σ_0
35 mm	±1.95	±1.08	±1.90	1.8
50 mm	±0.62	±0.34	±0.92	1.6
80 mm	±0.51	±0.62	±0.80	0.9

Table 7. Quality check of the 2D camera calibration

Lens	RMS_X [mm]	RMS_Y [mm]	RMS_Z [mm]	σ_0
35 mm	±0.30	±0.18	±0.64	0.5
50 mm	±0.34	±0.32	±0.64	0.6
80 mm	±0.19	±0.34	±0.59	0.5

Table 8. Quality check of the 3D camera calibration

3. CONCLUSIONS

Marker measurement can be fully automated using the planar 2D target. PhotoModeler and our in-house developed software give very similar results. In the 3D case, automation is more difficult and error prone. We will need to further improve our software in order to reduce the number of gross errors (up to 5%).

If the ellipse operator is used for automated point measurements, the marker size must be chosen carefully, depending on the image scales used. If the size of the imaged markers gets too small, the accuracy of the measurement will decrease. If markers get larger, systematic errors will increase (eccentricity error and ellipse deformation caused by radial distortion). A marker diameter of 20-50 image pixels has been found to be the optimal size.

Focal length and radial distortion are stable and can be determined very accurately using the 3D test field. Using the 2D target, these parameters show a much higher variation and lower significance. The principal point is very unstable, varying up to 50µm between calibrations. This has been expected because of the unstable connection between the camera body and the digital back. It is therefore necessary to recalibrate the camera each time the digital back has been removed (e.g. for sensor cleaning).

A significant scale difference (1.5E-4) has been determined for the x and y component of the sensor. This scale difference adds up to 7.2µm (more than one pixel) for the longer sensor dimension. This results in a non-square pixel size of 6.800 x 6.801µm.

Setting focus to infinity for calibration causes problems when close range targets are used. Images out of focus will be blurred, especially when narrow angle lenses are used and object distance gets too short. Although the ellipse fitting operator can handle blurred images to a certain extent, accuracy of image measurements will be reduced (e.g. for the 80mm lens using the 2D target).

The quality of the calibration can be checked independently only for the 2D calibration (in the 3D case, the same images are used for calibration and quality check). A relative accuracy of 1:10000 equals 0.8/0.5/0.4mm (for the 35/50/80mm lenses, respectively) in object space (planar component) and 0.25mm (z component). As can be seen from Tables 7 and 8 this quality criterion is not met for the 2D calibration, whereas relative accuracies of up to 1:20000 (planar positioning) and 1:4000 (Z component) are achieved using the 3D calibration.

The H3D camera can therefore be used for close range applications (e.g. architectural photogrammetry) without self-calibration. If parameters of a 2D calibration are used, self-calibration (focal length and radial distortion parameters) should be applied if reliable control points are available. This is also recommended for aerial (small scale) projects, even for 3D calibration.

4. REFERENCES

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5. ACKNOWLEDGEMENTS

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