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EXPERIMENTAL RESULTS OF DIGITAL CAMERA CALIBRATION

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ABSTRACT

Calibration of CCD camera is a prerequisite for the extraction of precise three-dimensional information from imagery in photogrammetry, computer vision, and other vision areas, which adopt the imaging component as a data acquisition tool. Bundle adjustment with self-calibration establishes itself as a precise technique for camera calibration in analytical photogrammetry. This technique has been systematically refined up to a point where relative accuracies exceeding 1 part in 1000000 (one million) are achieved with film based cameras. Up to now there is a general agreement, that is the calibration of digital cameras for photogrammetric purposes is not constant over time. That is to say the stochastic properties associated with the camera parameters are not stationary. In order to calibrate a 4k x 4k CCD camera using airborne platform and ground test field, bundle adjustment with self-calibration is performed and the influence of each calibration element is studied independently or in combination.

1 INTRODUCTION

CCD cameras are increasingly being used in photogrammetry for direct image acquisition and for digitization of hard copy film. The interior orientation of these cameras is not known. Since the cameras have offer substantial lens distortion, and we frequently refocused, they must be calibrated to meet photogrammetric accuracy requirements. A complete calibration model includes radiometric as well as geometric aspects.

This study deals with the geometric accuracy potential of a 4 k x 4 k CCD camera. This camera is currently used by the center for Mapping, The Ohio State University. This camera has a pixel size of 15 μm and 50 mm focal length. The flying height for this test is 328.636 meters and the pixel size on the ground turns out to be 0.098 meter. Bundle adjustment with self-calibration is the most versatile and accurate photogrammetric positioning and calibration method. Software developed at our department is used in this calibration process. This software is named " BSC" which stands for " Bundle adjustment with Self-Calibration". This software has the capability to solve for nine calibration elements, namely the principal point displacement (x_p,y_p), the focal length (c), two radial distortion parameters (k_1,k_2), two decentric distortion parameters (P_1,P_2), and two scale factors (S_x,S_y).

2 SELF-CALIBRATION OF A DIGITAL CAMERA

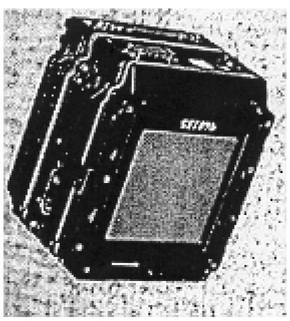
A digital camera is very much like a non-metric camera in many aspects, except for the substitution of the film with solid state sensor. Therefore, the images captured by a digital camera also suffers from certain distortions due to the systematic errors during imaging, that lead to inaccurate results. In order to exploit the potential of the photogrammetric techniques, camera calibration is necessary to determine the quality of the images and the imaging system and thus to be able to efficiently compensate for the systematic influence, which should lead to improve the final accuracy [4].

Self-calibration means that the interior geometric qualities of camera can be determined based on the relationship of two or more overlapping photographs without additional control requirement [4].

3 CAMERA DESCRIPTION

At the heart of the 4k x 4k high-resolution digital camera system is 4k x 4k area CCD sensor with 15-miron pitch (i.e. 60mm by 60mm imaging area), manufactured by Lockheed Martin Fairchild Semiconductors. The imaging sensor with a supporting data acquisition interface, it is integrated in the camera-back, mechanically compatible with an analogue film magazine and thus can easily be attached to a regular Hasselblad camera body [2].

The Hasselblad 553 ELX camera body features an electronic control system providing the necessary apparatus for a fully digital-computer-controlled-camera operation. Zeiss CF lenses with 50 mm and 80 mm focal lengths supplement the experimental system, offering wide and normal angle configuration [2].



BigShot Camera Back

4 QUALITY OF SELF-CALIBRATION

The more useful approach to examining the quality of calibration involves essentially three simple factors [5]: the distribution of points within the images, the photogrammetric network configuration, and the variance component after self-calibrating bundle adjustment. The first item relates specifically to lens distortion, which is known to behave poorly when extrapolating. Photogrammetric network design considerations for self-calibration is a well-established routine, among these a highly convergent imaging configuration, and the use of four or more images. Since the introduction of self-calibration , the ability to evaluate the fidelity of the camera self-calibration parameters has been limited by the accuracy of image coordinates measurement. The high degree of consistency between the a-priori and a-posteriori estimates of image coordinate precision has been maintained as image mensuration accuracies [5].

5 THE MODEL OF SELF CALIBRATION

The mathematical basis of the self-calibration bundle adjustment is the well-known extended collinearity model:

$$x - x_p + \Delta_x = -c\ (N_x / N_D)$$
$$y - y_p + \Delta_y = -c\ (N_y / N_D)$$

x, y : image coordinates
x_p y_p: principal point displacement
Δ_x Δ_y : image coordinates perturbation
c : focal length of the camera.

$$N_x = r_{11}(X-Xo)+ r_{21}(Y-Yo)+r_{31}(Z-Zo)$$
$$N_y = r_{12}(X-Xo)+ r_{22}(Y-Yo)+r_{32}(Z-Zo)$$
$$N_D = r_{13}(X-Xo)+ r_{23}(Y-Yo)+r_{33}(Z-Zo)$$

r_{ij} (ω,ϕ,κ): elements of the rotation matrix .
ω,ϕ,κ : attitude of the camera.
Xo, Yo, Zo : camera position on the ground.
X, Y, and Z: object coordinates.

In seeking appropriate parameters for the image coordinates perturbations functions Δx and Δy it is necessary to consider the four principals sources of departures from collinearity which are physical in nature. These are symmetric distortion, decentring distortion, image plane unflatness and in-plane image distortion. The perturbation model can be written as [5],

$$\Delta x = \Delta x_p - x_b c^{-1} \Delta c - x_b s_x + a y_b + x_b r^2 k_1 + x_b r^4 k_2 + x_b r^6 k_3 + r^2 + 2 x_b^2 p_1 + 2 x_b y_b p_2$$
$$\Delta y = \Delta y_p - y_b c^{-1} \Delta c + x_b a + y_b r^2 k_1 + y_b r^4 k_2 + y_b r^6 k_3 + r^2 + 2 x_b y_b p_1 + 2 y_b^2 p_2$$

with:

$$x_b = x - x_p,\ y_b = y - y_p,\ r = (x_b^2 + y_b^2)^{.5}$$

Δ_p, Δ_p, Δc : change of interior orientation parameters.
S_x : Scale in x.
a : shear.
k_1, k_2, k_3 : first three parameters of radial symmetric distortion.
p_1, p_2 : first two parameters of decentring distortion.

6 PARAMETERS ESTIMATION

In this experiment only the geometric calibration is carried out. The estimation of the unknowns and the calibration parameters are formulated through Gauss-Markov model as:

$Y= A \xi + e \quad e\sim N(0, \Sigma)$

Y : observation vector (observed vector-computed vector).

A : Jacobean matrix.

ξ : Unknown parameters (corrections to exterior orientation, object coordinates, and the calibration elements).

e : Unknown true error.

Σ : dispersion matrix of the observations.

The estimation of the parameters by the least squares solution:

$\xi^{\sim} = (A^T P A)^{-1} A^T P Y$

P : the weight matrix.

$e^{\sim} = Y - A \xi^{\wedge} \qquad \sigma_o^{2\sim} = r^{-1} e^{\sim T} P e^{\sim}$

$\sigma_o^{2\sim}$: Estimated variance component.

$e^{\sim}$: residual vector.

r : is the redundancy of the system.

7 QUALITY CRITERIA

The quality control of calibration is assessed with theoretical and empirical accuracy measures [1]. Theoretical accuracy describes the statistical variability of the parameters estimated in the least squares adjustment. Empirical accuracy determines how close the estimated parameters match the true values. An empirical measure is obtained from a comparison to precise reference values.

8 TEST FIELD AND CALIBRATION

The digital camera images a ground test field at Madison county-Ohio. Eight images are selected to measure the coordinates of the control and tie points. The effect of additional parameters is evaluated with 39 control points, 15 checkpoints, and 206 image points observations. The effect of each parameter or a combination of parameters are listed in tables 1,1-a,2

Table (1) ____Theoretical Accuracy________ Empirical Accuracy_____

Ver	r	Ch	Co	$^{\sim}\sigma_o^2$	$^{\sim}\sigma_x$ m	$^{\sim}\sigma_y$ m	$^{\sim}\sigma_z$ m	μ_x m	μ_y m	μ_z m
0	93	15	39	20.1E-6	.374	.436	1.52	.406	.709	4.51
1	92	15	39	20.1E-6	.374	.436	1.52	.405	.705	4.51
2	92	15	39	20.1E-6	.374	.436	1.52	.407	.705	4.51
3	91	15	39	20.1E-6	.374	.436	1.52	.406	.709	4.51
4	92	15	39	20.1E-6	.374	.436	1.52	.405	.705	4.51
5	90	15	39	20.1E-6	.374	.436	1.52	.405	.705	4.51
6	92	15	39	4.5E-6	.080	.090	.333	.136	.256	.400
7	89	15	39	4.4E-6	.080	.092	.331	.136	.253	.395
8	91	15	39	4.4E-6	.080	.092	.331	.136	.252	.395
9	89	15	39	4.3E-6	.080	.093	.330	.128	.269	.416
10	91	15	39	20.7E-6	.374	.439	1.51	.395	.758	4.61
11	88	15	39	4.4E-6	.080	.092	.331	.136	.252	.395
12	91	15	39	20.4E-6	.388	.474	1.54	.571	.566	5.51
13	90	15	39	20.7E-6	.373	.436	1.51	.387	.767	4.58
14	87	15	39	4.3E-6	.080	.092	.328	.126	.267	.413
15	86	15	39	4.3E-6	.080	.092	.329	.127	.266	.412
16	84	15	39	4.0E-6	.080	.096	.323	.090	.183	.357
17	86	15	39	4.0E-6	.080	.096	.323	.090	.183	.357
18	85	15	39	4.2E-6	.075	.095	.320	.140	.158	.416
19	85	15	39	4.2E-6	.082	.092	.328	.083	.310	.498

Table (1-a)

Version	Additional Parameters(AP)
0	No AP
1	x_p
2	y_p
3	x_p, y_p
4	c
5	x_p,y_p,c
6	k_1
7	x_p,y_p,c, k_1
8	k_1,k_2
9	k_1,k_2,p_1,p_2
10	p_1,p_2
11	x_p,y_p,c,k_1,k_2
12	S_x, S_y
13	x_p,y_p,c,p_1
14	x_p,y_p,c,k_1,k_2,p_1
15	x_p,y_p,c,k_1,k_2,p_1,p_2
16	x_p,y_p,c,k_1,k_2,p_1,p_2,S_x,S_y
17	x_p,y_p,c,k_1,p_1,S_x,S_y
18	x_p,y_p,c,k_1,k_2,p_1,p_2,S_x
19	x_p,y_p,c,k_1,k_2,p_1,p_2,S_y

Ver: Version.
r : redundancy of the system.
Ch : check points.
Co : control points.
$\tilde{\sigma}_o^2$:variance component after the adjustment.
$\tilde{\sigma}_x$: standard deviation along the x- axis.
$\tilde{\sigma}_y$: standard deviation along the y- axis.
$\tilde{\sigma}_z$: standard deviation along the z- axis.
μ_x , μ_y , μ_z : Root Mean Square Error from comparison to check point coordinates in object space.

Estimated Calibration Parameters based on Version 16:

Table (2)

Parameter	Estimated value
x_p	3.72E-6 m
y_p	1.05E-6 m
c	50.0007 mm
k_1	-28.546E-6
k_2	0.001E-6
p_1	4.461E-6
p_2	2.265E-6
S_x	-201.24E-6
S_y	-256.40E-6

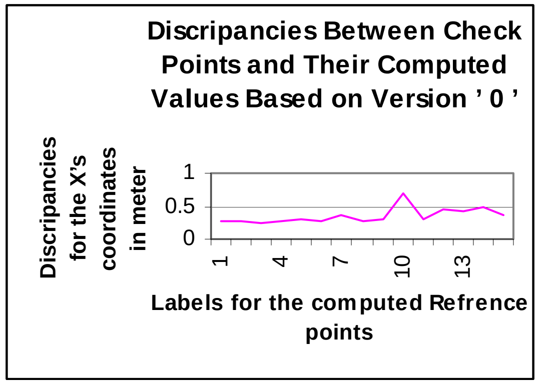


Chart 1

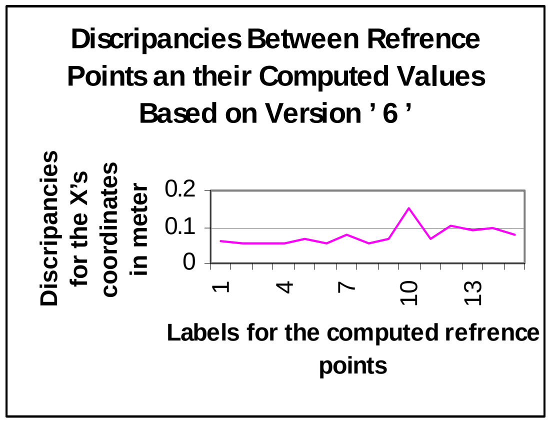


Chart 2

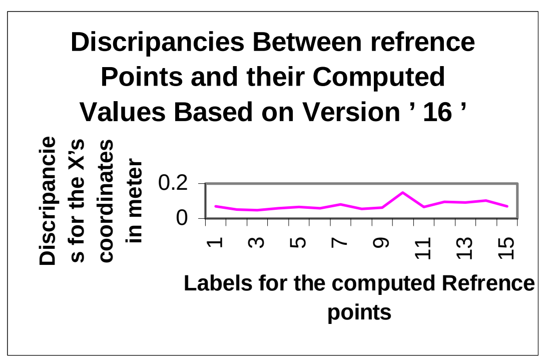


Chart 3

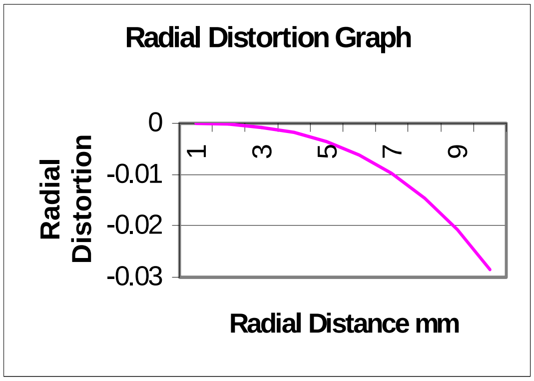


Chart 4

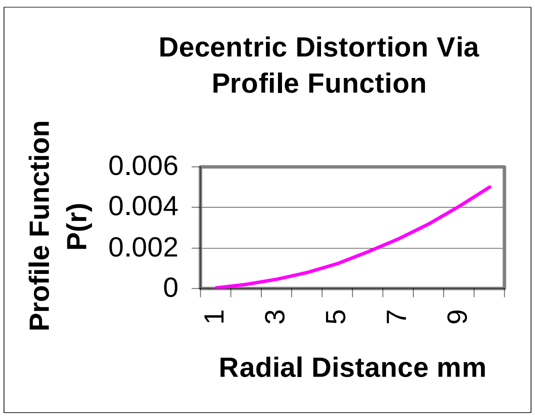


Chart 5

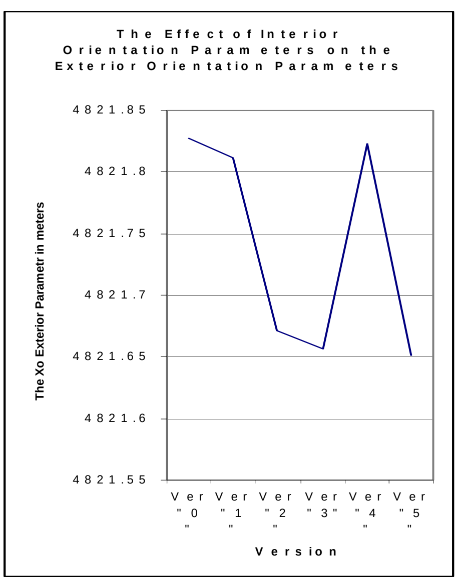


Chart 6

9 ANALYSIS AND DISCUSSION

- Without adding any additional parameters, version 0, we get an accuracy of 4/3 of a pixel in image space, and an accuracy of 3.8 and 4.4 pixels in the x and y directions in object space, see chart 1.
- Also we can observe disagreement between the accuracy and precision in version 0, and this is an indication to go further and model different kinds of image perturbations.
- This camera suffers from radial distortion problem and this is demonstrated by the comparison of version 6 with version 0, in which the variance component has a rapid drop from 20 micron to 4 micron. Thus the accuracy is improved to 1/3 of the pixel size in image space, see chart 2.
- After applying version 16 we got an accuracy of 1/3 of the pixel in the image space and less than a pixel in the x direction and two pixels in the y direction in object space.
- The estimated value of k_2 is highly correlated with k_1, almost 95% correlation.
- The radial distortion parameter k_1 is invariant quantity in all of the above versions; i.e we can build the radial distortion graph independently of the other calibration parameters, see chart 4.
- The highly accurate reference points do influence the accuracy and are only required to verify the accuracy.
- The comparison of version 0, computed without calibration parameters, and version 1, 2, 3, 4, 5, computed with the first three additional parameters (xp,yp,c) indicate that the effects of these parameters are to a large extent absorbed by exterior orientation elements, see chart 6.
- A quick comparison between version 6 and 16, we can observe that there is no considerable gain in the accuracy, but we have a gain in precession, or in other words, in version 16 more systematic errors are modeled.
- There is a shift problem in the recording process, and this is well demonstrated by version 18 and 19 when S_x and S_y turned off respectively, and this shift is systematic because when S_x, and S_y are on or off we did not have any gain in accuracy but we have a gain in precession.

  Still we observe a difference between the theoretical accuracy and the empirical measures in version 16, and this is an indication to systematic errors or some factors limiting the accuracy.

10 CONCLUSION AND RECOMMENDATIONS

The traditional calibration of analog camera is not suitable for the CCD camera, but it has to be modified to include electronic calibration model.

The radial and decentric distortion parameters can be separated from the above carried calibration, and their estimation can be done by the plumb line method (Brown method). In this way these parameters can be decorrelated.

More tests will be run in the near future in order to investigate the calibration behavior of different CCD cameras .

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