CAMERA CALIBRATION TECHNIQUE BY PAN-CLOSEUP EXPOSURES FOR INDUSTRIAL VISION METROLOGY

Harutaka Imoto [a], Susumu Hattori [b], Keiichi Akimoto [c], Yuzo Ohnishi [d]

[a] Dept. of Production Technology Development, Ishikawajima-Harima Heavy Industries Co.,Ltd., Yokohama, Japan
[b] Dept. of Computer Science, Fukuyama University, Fukuyama, Japan
[c] Dept. of Control Engineering, Shikoku Polytechnic-College, Marugame, Japan
[d] School of Urban and Environment Engineering, Kyoto University, Kyoto, Japan

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ABSTRACT:

A high precision and easy-to-use CCD camera calibration technique for industrial vision metrology is discussed. A well-known method is self-calibration by convergent camera configuration of a two- or three-dimensional target field. Only with this technique the central part of a sensor area is precisely calibrated, but off the centre the precision rapidly deteriorates. The presented technique is a simultaneous adjustment of both pan and close exposures, which compensates the lack of distortion data in the fringe area of the sensor and offers both uniform and high-precision calibration. Some patterns of camera configuration are compared in an experiment in terms of the precision and its uniformity over the sensor. And the combination of convergent pan exposures and vertical close exposures is proved the best.

1. INTRODUCTION

In industrial vision metrology with a single camera, high precision can be obtained by self-calibration, if a measurement configuration is good or in other words a measurement network is strong. But in many situations possible camera configuration is limited, targets are often not well distributed in space (even after supplement targets are added), and exposures might be reduced in number to save processing time.

If a network is weak, pre-calibrated interior orientation parameters are necessary, which are incorporated in bundle adjustment as weighted observations. Especially in the case of off-the-shelf cameras, the body is a bit fragile and therefore frequent camera calibration is required, and in practicability a cheap, time-effective and high precision technique is indispensable.

A conventional and reliable calibration method is a bundle adjustment of images of multi exposures over a field of 2D- or 3D control points (Hattori, 1995). Self-calibration of images taken in convergent camera configuration has been reported to be a good substitute in the case of no control points. But only with this technique, though the central area of a sensor is very well calibrated, the precision of parameters in the fringe of the sensor is deteriorated, since smaller number of common targets is captured in fringe areas. This causes the precision shortage not only industrial applications, but in conventional stereo measurement, where the entire sensor area is equally used.

This paper presents a self-calibration technique of simultaneous adjustment of images taken in different exposure distances. The basic idea is as follows: The object space coordinates can be measured from images of convergent exposures over the target field at remote stations. Images capture the field at the sensor centre. Then by use of these object coordinates the distortion functions can be precisely evaluated from images taken at close stations. The target images are uniformly distributed over the sensor area. These two pan and close sets of images are simultaneously adjusted. Thus it is expected that the same effect as the calibration using a 3D control field is obtained and distortions are uniformly compensated up to the fringe of the sensor.

In the following section, some combinations of camera configurations are compared by an experiment. As the result the self-calibration of images taken in a combined configuration of convergent pan exposures plus vertical close exposures shows the best precision.

2. THE PROPOSED CAMERA CALIBRATION METHOD

2.1 The distortion model

As a model of lens distortions, well-known Brown parameters (Brown, 1966) are used.

$$\begin{aligned}\Delta x &= -x_p + \left(K_1 r^2 + K_2 r^4 + K_3 r^6\right)\left(x - x_p\right)\\ &\quad + P_1\left\{r^2 + 2\left(x - x_p\right)^2\right\} + 2P_2\left(x - x_p\right)\left(y - y_p\right)\\ \Delta y &= -y_p + \left(K_1 r^2 + K_2 r^4 + K_3 r^6\right)\left(y - y_p\right)\\ &\quad + 2P_1\left(x - x_p\right)\left(y - y_p\right) + P_2\left\{r^2 + 2\left(y - y_p\right)^2\right\}\end{aligned} \tag{1}$$

where (x,y) are image coordinates of an object point, (x_p,y_p) are coordinates of the principal point, and $r^2=(x-x_p)^2+(y-y_p)^2$. K_1, K_2 and K_3 are coefficients of radial distortions and P_1 and P_2 are those of tangential distortions. It is assumed that the principal point coincides with the centre of lens distortion.

2.2 Target field and camera configurations

A 2-D target field is made of 500 x 500 x 5mm metal plate, 24 x 33 (792 in total) retro-targets with the diameter of 3mm are placed on a lattice of 15mm width.

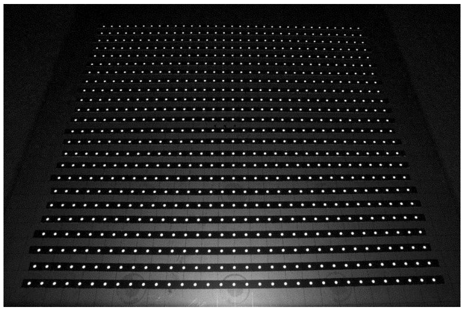

Figure 1. An image of close exposure over the target field

The camera used was Kodak DCS660m (Monochrome, 2008 x 3040 pixels CCD) with Nikkor 20mm lens. In order to stabilize the interior orientation parameters, working parts of the lens was fixed with silicone. In exposures shutter speed was set to 1/400, aperture to F/22, and a strobe light was used.
The following three basic camera configurations were considered.

(1) Panoramic convergent (Pan) configuration
(2) Close convergent (Close) configuration
(3) Close parallel or Block (Block) configuration

(1) Pan: Two images were taken at every eight camera stations with a convergent angle of 30degrees. The camera was rotated by 90degrees at each exposure. The distance to the field from the camera was 2,000mm. The object space was imaged to about 600 x 600 pixels in the CCD area. This configuration is expected to yield the high precisions of object space coordinates.

(2) Close: Sixteen images were exposed at eight camera stations just as in the same conditions as in (1), except for the distance from the camera to the field, which is set to 500mm. With this configuration a strong network is formed and the entire sensor area is uniformly covered with target images.

(3) Block: At the six camera stations of 1,000mm from the target field, two images per station were taken in the parallel camera configuration. Each two images covered a 1/6 target field as shown in Figure3 and were rotated with respect to the camera axis by 180degrees to the other.

This configuration is based on the following idea. For strengthening a network, convergent exposure is desirable. However, convergent exposure deforms a target to an ellipse form. And the close-up camera configuration may shift the image centre of the ellipse from the true centre of the target, which deteriorates image coordinates.
On the other hand, in a parallel exposure configuration, in spite of a weak network, target images become homogeneous. That is, this configuration has an advantage of the homogeneity to increase in coordinate quality. Taking it into consideration that the space coordinates of targets are already determined, it is expected that the weak network pose relatively little influence on coordinate quality. In order to keep target images homogeneous, it was necessary to avoid extreme close exposures and cover the target field by muli-exposures.

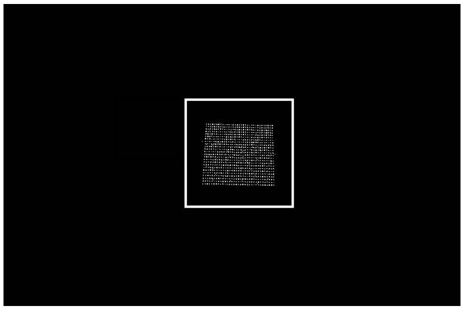

Figure 2. Panoramic and convergent exposure

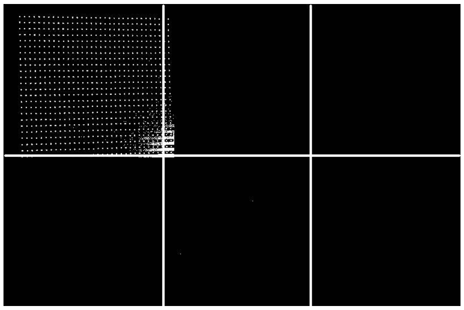

Figure3. Block exposure

Including these three camera configurations, their combinations were tested on calibration quality.

(1) Adjustment of only Pan images
(2) Adjustment of only Close images
(3) Simultaneous adjustment of Pan and Close images
(4) Simultaneous adjustment of Pan and Block exposure images
(5) Simultaneous adjustment of all the images

2.3 Coordinates measurement and adjustment

Since the target field is of a form of a lattice, it is easy to identify image points using the 2D projective transformation equation once the image points are extracted. Namely they can be identified by manual labelling of four or more points of the corners of the lattice. Hence the difficulty lies in measurement of target images coordinates.
For this measurement, target images are first recognized by binarization of images, and then coordinates are measured by simple centroid calculation in Pan and Block images, while this technique is hard to adapt to Close images, since the size and brightness of target images vary drastically over an image plane. The farthest target image is dark and its diameter is about only three pixels, while the nearest target image is very bright with a diameter of about 20 pixels. For this reason, simple binalization does not work well. To conquer this difficulty, the Laplacian of Gaussian filter in equation 2 was applied to the image, and the target images were extracted using zero-crossing information.

$$f(x, y) = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \exp\left(-\frac{x^2 + y^2}{2\mu^2} \right) \qquad (2)$$

where *(x,y)* are image coordinates, and μ is a scale factor.

An example is shown in Fig. 4. A target image of the central part was truncated and extracted (right side) from the image (left side).

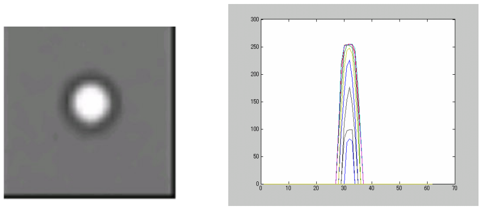

Figure4. Extraction of a target image

When μ is a small value, a zero crossing tends to appear inside a target image according to small in-homogeneity of intensity of a target image. On the other hand, for large value of μ , the circumference of a target image becomes blurring and the target image can't be extracted correctly.

According to preliminary experiments, the proper value of μ for the diameter of a target image of 3-10 pixels is μ =1 , μ =2 in for the diameter of 15-30 pixels, and μ =3 for the diameter of 5-20 pixels. In general most of targets were correctly measured for μ = 2 .

Table1 shows interior orientation parameters and standard deviations evaluated for the five camera configurations. Because of adjusting only in the central part of a sensor area with little lens distortion, the value of standard deviation of Pan exposure is the best.

3. AN EXPERIMENT ON ACCURACY CHECK

The accuracy of interior orientation parameters by the above five calibrations was checked.

Figure5 shows a target field for the accuracy check. Twelve scale bars (called Scale 1,2…12 hereafter) of one meter long have been arranged squarely. The scales were made of steel.

For Scale 1, 4, 7, and 10 two retro-targets with a diameter of 15mm were applied to the ends of each bar.

For the other scales, retro-targets of 5mm in diameter were applied. This is to compare the influence of target size.

All the scales were precisely pre-calibrated with UMM (Universal Measuring Microscope, Leitz). The nominal accuracy is 0.01mm.

Three images were taken in a convergent configuration at camera stations along the centre line of the object space. The distance to the object space is about 1,000mm and the convergent angle was 45degrees. The three images were bundle-adjusted as free-network with interior orientation parameters fixed with values shown in Table1. For a reference the result of self-calibration is added to the table.

Then the scale of the object space was adjusted to the Scale3 and 12. The residuals of the adjusted scale values from true values were shown in Table2.

The size of a scale was calculated from object coordinates of the target computed as a result of bundle adjustment, and the result, which performed comparison with true value, was shown in Table2.

Figure5. Test Field.

The major results obtained by the experiment are as follows.

a) The accuracy of (3) the combination of Pan exposure and Block exposure is proved the best, and it exceeds the precision of self-calibration.

The accuracy of measurements with 15mm targets, which were imaged up to 40 pixels, is always degraded than the measurements with 5mm targets.

b) The accuracy of (1) Pan exposure is the worst, since no information of lens deformations in the fringe of the sensor.

c) The precision of (2) Close exposure is second worse to (1) Pan exposure. Especially the cases for use of 15mm targets get even worse. This shows that the fact the centroid of a target images does not coincide with the true centre is strongly influenced.

It is possible to compensate for this error by fitting an elliptic curve to each target image. But considering additive measurement time beside the time for the above-mentioned processing, it may not make sense.

4. CONCLUTION

A calibration technique, which is simple and easy and produces homogenous and high precision over the sensor area, is discussed. Some combinations of camera configurations are compared by an experiment using 2-D target field. As the result the self-calibration of images taken in a combined configuration of convergent pan exposures plus vertical close exposures shows the best precision. By using this result, restrictions conditions, such as camera configuration, decrease and the range of practical use of photogrammetry can be extended.

REFERENCES

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Table1. Comparison of precision and estimated interior orientation parameters for combinations of images.

	pan	closeup	pan+closeup	pan+block	all
Number of Images	16	16	32	28	44
Total of target images	12928	12544	25088	22336	34880
umber of observation eqs.	25856	25088	50176	44672	69760
Number of unknowns	2530	2458	2554	2602	2698
Internal precision X[mm]	0.0053	0.0026	0.0021	0.003	0.0032
Y[mm]	0.0052	0.0026	0.0021	0.003	0.0032
Z[mm]	0.0113	0.004	0.0032	0.0077	0.006
Average[mm]	0.0078	0.0031	0.0025	0.0051	0.0043
Int.ori.prms.(M.p.v)					
c[mm]	20.38436278	20.38354628	20.38503735	20.40128968	20.39270232
xp[mm]	0.23796479	0.23926544	0.23926871	0.23916313	0.23865449
yp[mm]	-0.32257554	-0.32349058	-0.32338634	-0.32164937	-0.32341831
k1[mm^{-2}]	2.711189e-04	2.817909e-04	2.805789e-04	2.738291e-04	2.813398e-04
k2[mm^{-4}]	-1.892748e-07	-4.580886e-07	-4.539315e-07	-4.590845e-07	-4.314074e-07
k3[mm^{-6}]	-1.905598e-09	5.696333e-11	4.995959e-11	-7.935552e-11	-1.553431e-10
p1[mm^{-1}]	2.401548e-06	1.001229e-06	1.024310e-06	7.849463e-07	1.272433e-06
p2[mm^{-1}]	9.229950e-06	9.245568e-06	9.444295e-06	8.315674e-06	9.519769e-06
Int.ori.prms.(Std. Dev.)					
c[mm]	2.5230e-03	1.2930e-03	9.2530e-04	1.0820e-03	3.1060e-04
xp[mm]	7.4030e-04	1.4760e-04	1.1990e-04	3.3780e-04	1.4020e-04
yp[mm]	6.5840e-04	1.2220e-04	9.9140e-05	3.5050e-04	1.2160e-04
k1[mm^{-2}]	1.4270e-06	1.9680e-07	1.4900e-07	9.4160e-08	1.0700e-07
k2[mm^{-4}]	1.0250e-07	1.8830e-09	1.4830e-09	7.1950e-10	9.6080e-10
k3[mm^{-6}]	2.1450e-09	6.0690e-12	4.8220e-12	1.9690e-12	2.7560e-12
p1[mm^{-1}]	6.4750e-07	1.4320e-07	1.1640e-07	1.5390e-07	1.3290e-07
p2[mm^{-1}]	6.2230e-07	1.1540e-07	9.3540e-08	1.4700e-07	1.1010e-07

nt.ori.parms = interior orientation parameters   M.p.v = most probable value   Std. Dev. = standard deviatio

Table2. Comparison of error for calibration data.(unit: mm)

	self-calibration	pan	closeup	pan+closeup	pan+block	all
scale1 *1)	0.086	-0.664	0.529	0.535	0.042	0.374
scale2	-0.059	0.200	-0.068	-0.053	-0.001	-0.018
scale3	-0.083	0.132	-0.122	-0.107	-0.008	-0.074
scale4 *1)	0.127	-1.038	0.529	0.551	0.047	0.355
scale5	-0.017	0.068	-0.077	-0.050	0.017	-0.024
scale6	-0.031	0.054	-0.110	-0.087	0.024	-0.060
scale7 *1)	0.396	-3.432	1.220	1.155	-0.040	0.572
scale8	0.177	-0.820	0.387	0.352	-0.020	0.198
scale9	0.109	-0.555	0.227	0.201	-0.021	0.103
scale10 *1)	0.358	-0.875	0.694	0.649	0.120	0.445
scale11	0.184	-0.353	0.321	0.289	0.028	0.201
scale12	0.111	-0.178	0.164	0.143	0.011	0.098
Std. Dev.	0.153	0.983	0.400	0.378	0.042	0.215

Std. Dev. = standard deviation   *1) = 15mm target