On-the-Job Calibration of a Digital Camera for Industrial Photogrammetry

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Abstract

Digital frame cameras are increasingly accepted for close range applications of industrial metrology. The accuracy of a close-range photogrammetric measurement is a function of five basic factors: the geometric fidelity of the camera, the geometry of intersecting rays, the number of intersecting rays, the camera-object distance, and the accuracy of image coordinate measurement. The use of commercial digital cameras is an established and preferred trend for off-line measurements for their ease-of-use, easy availability and inexpensiveness. The commercial cameras do not come pre-calibrated, and hence, the essential pre-requisite is to calibrate the camera, preferably *in-situ.* Such a calibration process produces numerical values for the camera parameters representing the spatial relationships of the measuring system. The parameters include camera constant, principal point, and the coefficients of lens distortion. In a typical industrial environment, a Kodak 420C camera fitted with a 28 mm Nikon lens is used for shape calibration of an antenna of 7.5 m diameter. Stick-on targets of retro-reflective nature numbering about 200 are placed on the effective panel area of the die surface. In all, 12 convergent photographs; two of them with a roll-diversity of 90 degrees are used. A satisfactory calibration of the camera is accomplished as an integral part of the bundle adjustment. Further, the correlations of interior orientation parameters within themselves and with exterior orientation parameters are studied. The paper presents the process, and the systems (hardware, and software) adopted for the calibration of the camera.

Overview

1. Introduction

The development of the bundle adjustment allowed new techniques for camera calibration to be devised. One of these was termed ‘on-the-job’ calibration. This is a bundle adjustment with additional parameters to describe the parameters of lens distortion, focal length, offsets of the principal point and perhaps other unknowns such as CCD chip orthogonality. Control points are placed in the immediate vicinity or surrounding area of the object to be imaged for a constrained adjustment. It is the most common form of close-range camera calibration method presently being used; and is also applied by some for aerial calibration using test-fields [Clarke/Fryer, 1991]. Accuracies of 1 in 1 million are reported using high-end cameras [Fraser, 1997].

The term “on-the-job calibration” is sometimes confused with “self-calibration”, where there is, in fact, no need for control points at all. The criteria which need to be met for a successful self-calibration are: (1) A single camera must be used to take at least three images of the object; (2) both the interior geometry of the camera and the point to be measured on the object must remain stable during the measurement process; (3) the photogrammetric network must be strong and exercise a high degree of convergence; (4) at least one image must have a roll angle that is significantly different from the others; and (5) a relatively large number of well distributed points should be used [Brown, 1989]. It is observed by Brown that a satisfactory calibration of the camera can be accomplished as an integral part of the triangulation without the need for control of any kind. A difficulty with the aerial application of the self-calibrating bundle adjustment is obtaining images that have a sufficient diversity of camera angles.

1.1 International standards: ISPRS and ASPRS have setup panels to exclusively work on this important task of establishing standards for camera calibration. ISPRS recommends the procedures leading to the calibration of photogrammetric camera and related optical tests [Clarke/Fryer, 1991]. ASPRS classifies the calibration procedures as Component method, and System method [ASPRS, 1999].

In the Component method, camera manufacturers employ multi-collimators or goniometers to quantify the characteristics of components. For example, the accuracy potential and stability of the cameras are studied in ‘free-network’ and with external reference using 186 signalized points [Maas/Niederost, 1997]. Very high accuracies beyond 1:250,000 are reported in free network. In the System method, the complete operational system is evaluated.

In India, in-flight calibration of space borne sensors of IRS-1C/1D has been reported [Srivastava et al, 1999]. Digital cameras are applied for precision industrial measurements for validating an antenna die and a measurement accuracy of 1 in 100000 of the object size are reported [Murali Mohan/Raghunathan, 2002].

1.2 The camera: The Kodak DCS420, being discussed here, is of nominal focal length of 28 mm and focal plane accommodating 1524x1012 CCDs and approximately records 300 images per battery charge. A ring flash is desired to coincide the camera axis with the reflected light. In the four surveys presented in this paper, strobe flash or sometimes, ambient light is used while imaging. The retro-reflective targets of 0.1 mm thick and 25.4 mm diameter are used in both the surveys. The PC-based software, Australis [Fraser, 2001] is used for self-calibrating bundle adjustment.

In this paper, the System method is adopted to evaluate the camera, the software and the process.

2. The Functional Model

Consider the object to be measured is imaged from different plan and elevation positions all around (usually giving rise to as many image coordinates for each target as the number of exposures), it is referred to as convergent geometry. Then all the collinearity condition equations, taken together form a set of equations which is called the functional model of the photogrammetric system (Atkinson, 1996):

$$F(x,b,a) = 0 \quad \text{......(E-1)}$$

where

x = a vector representing the parameters to be estimated,
b = vector representing the m measured elements, and
a = vector representing elements whose values are known constants.

If cameras have been calibrated apriori, like the case in topographic mapping, the calibrated values are used to refine 'a'. If no prior calibration is available, the calibration elements can be included in 'x' only, a procedure known as self-calibration. The collinearity condition equations, after adding corrections for offset of the principal point (x_0, y_0) are:

$$x_a = x_0 - f\left[\frac{m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \quad \text{......(E-2)}$$

$$y_a = y_0 - f\left[\frac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \quad \text{......(E-3)}$$

where f is the camera focal length,

(x_a, y_a) are measured photo coordinates of image point a, related to principal point, m's are functions of the rotation angles omega (ω), phi (φ), kappa (κ),

(X_A, Y_A, Z_A) are the three object point coordinates of A, and

(X_L, Y_L, Z_L) are the three exposure station coordinates.

The photo coordinates measurements (x_a, y_a) are constant terms, and the calibration parameters x_0, y_0 and f are considered to be constant in most applications of collinearity [Wolf/Dewit, 2001]

The non-linear equations are linearized using Taylor's theorem. The equations E-2 and E-3 are rewritten as:

$$x_a = x_0 - f\frac{r}{q}$$

$$y_a = y_0 - f\frac{s}{q}$$

Augmenting the collinearity conditions E-2 and E-3 with the orientation parameters $k_1,\ k_2,\ k_3,\ p_1,\ p_2,\ p_3$:

$$x_a = x_0 - \bar{x}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3^2 r_a^2\right)\left[p_1\left(3\bar{x}_a^2 + \bar{y}_a^2\right) + 2p_2\bar{x}_a\bar{y}_a\right] - f\frac{r}{q} \quad \text{... (E-4)}$$

$$y_a = y_0 - \bar{y}_a\left(k_1 r_a^2 + k_2 r_a^4 + k_3 r_a^6\right) - \left(1 + p_3^2 r_a^2\right)\left[2p_1\bar{x}_a\bar{y}_a + p_2\left(\bar{x}_a^2 + 3\bar{y}_a^2\right)\right] - f\frac{s}{q} \quad \text{... (E-5)}$$

where

$$r = m_{11}(X_A - X_L) + m_{12}(Y_A - Y_L) + m_{13}(Z_A - Z_L)$$
$$q = m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)$$
$$s = m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)$$

$p_1, \; p_2, \; p_3$ are decentering distortion coefficients, and

$k_1, \; k_2, \; k_3$ are symmetric radial lens distortion coefficients.

$$\overline{x_a} = x_a - x_0$$
$$\overline{y_a} = y_a - y_0$$ and
$$r_a^2 = \overline{x}_a^2 + \overline{y}_a^2$$

With the inclusion of the extra unknowns, it follows that additional independent equations will be needed to obtain a solution. To solve the additional parameters (also referred to as 'added parameters' or 'self-calibration parameters') satisfactorily, it is necessary to have special constraints in the network design.

3. The Four Industrial Surveys

The details of the four surveys that are conducted in an industrial environment are listed in Table 1.

Table 1. Details of the surveys

Survey	Description	Aspect ratio
1.	Benchmarking on Precision granite surface (2.0 m *x* 1.0 m)	2.0
2.	Calibration of a mould for car top	1.5
3.	Calibration of a granite surface (1.0 *x* 1.0 m)	1.0
4.	Calibration of a die for antenna panel (3.75 m *x* 2.0 m)	1.8

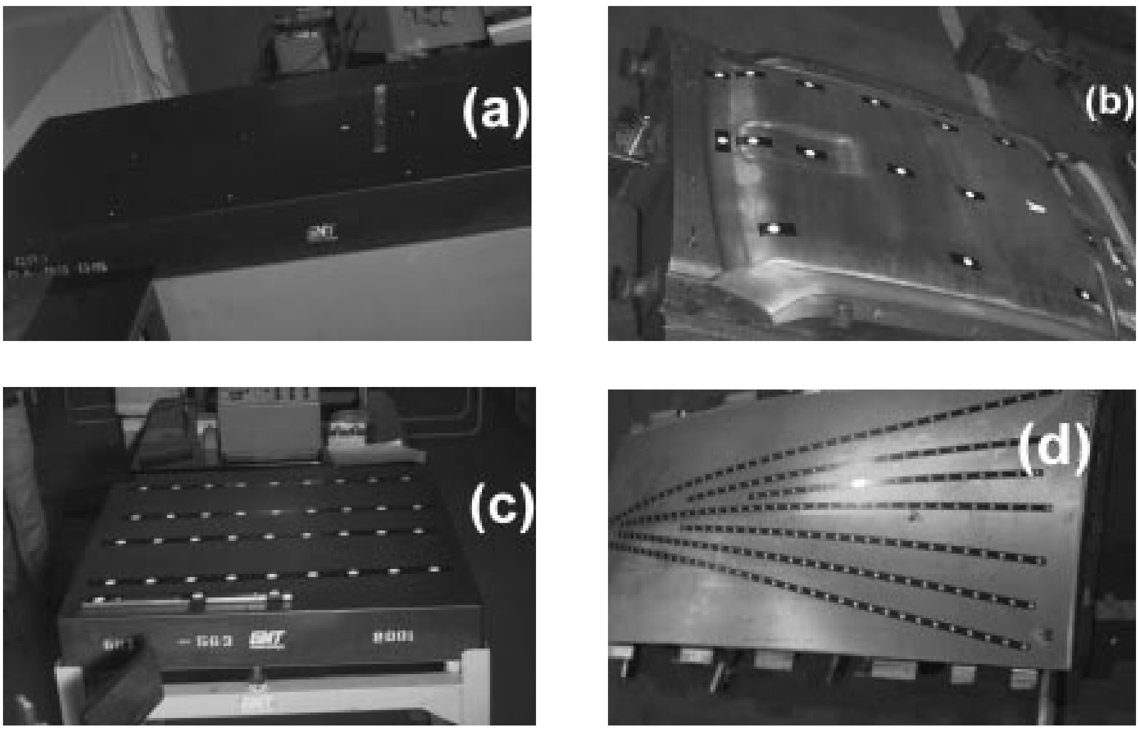

Figure 1: The images of four objects imaged with Kodak-420C and the retro-reflective target disposition in the effective areas: (a) high-aspect granite, (b) car top mould, (c) 1-metre square granite, and (d) antenna panel die

3.1 Measuring the texture-less surface: As all the four objects photographed are featureless homogeneous surfaces, it is required to texture them with high-contrast targets. One-inch diameter retro targets are glued to the surface as depicted in the above pictures. About 25, 30, 35, and 200 target points are pre-pointed on each object respectively.

The required number of photographs fully covering the dish is minimum eight. Twelve are desired. Except in survey no.1, good network geometry could be established.

4. Results and Discussion

The Camera has gone through the self-calibration in every exercise and the results are analyzed. Lens distortion curve and decentering curve of survey 3, are presented in Figure 2.

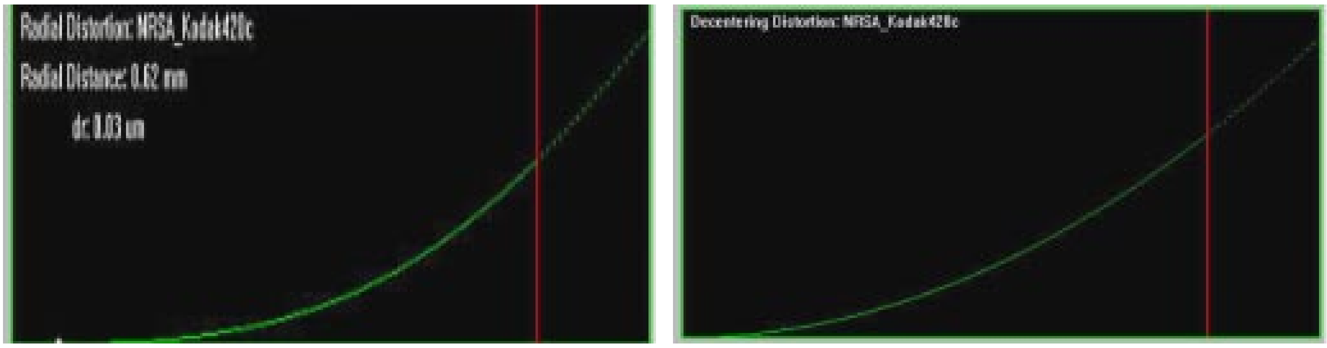

Figure 2. Radial lens distortion (left) and decentering distortion plots. Red vertical line limits the CCD format coverage

Observation 1. *Correlations within the Interior Orientation parameters*

The lens distortions coefficients k2 and k3 show large correlations with k1. This is a well-established fact, especially for medium angle, 'amateur' camera lenses. Basically, the distortion function in these cases is usually cubic; so all the distortion signal is modeled by the k1 term. This means that k2 and k3 are effectively unwarranted parameters, and they are nominally trying to model the same signal. In other words we have three parameters where only one is needed, which gives rise to the high correlations, between both k1 & k2 and k1 & k3. Similar observations are made in earlier studies [Fryer et al, 1994]. It is observed that polynomials are undesirable from a mathematical point of view because of high correlation among the different terms [Ziemann, 1986].

Table 2. Correlations among k-terms

Parameter1	Parameter2	Percent correlation Survey 1	Percent Correlation Survey 3
k_1	K_2	96.5	95.9
k_2	K_3	90.5	98.6
k_3	k_1	98.2	90.6

To see the small effect of k2 and k3 for the lens, their values are locked to zero in the bundle adjustment and as expectedly, only an ignorable change in the results is noticed (40 micron RMS became 41 microns, in one exercise). Generally, the high correlation between the k-terms does not affect solution stability and this phenomenon is usually ignored.

Observation 2: *Principal point (PP) is shifting its position for every survey.*

The principal point coordinates, as calibrated in the four surveys are tabulated below.

Table 3. Principal point coordinates

Survey	Principal point (units in mm)	
	x_p	y_p
1	0.1099	0.0624
2	0.0466	0.0482
3	-0.0439	-0.1292
4	0.0765	-0.0707

An unstable PP is also a quite common effect with non-photogrammetric cameras, often because the chip is not mounted in a stable position with respect to the housing. The fact that the PP moves between surveys is not such a problem if self-calibration is used, but it is a problem if it occurs in a survey between images. The lens-to-body and the CCD chip-to-body mountings for instability need to be checked.

Observation 3: *The camera yielded different f's in free network and a very different f when external control is introduced in the bundle.*

The changing focal lengths are recorded in Table 4.

Table 4. The focal length of the camera

Survey	Calibrated focal length (mm)	Remark
1	28.9145	Scale bar is used
2	28.9009	Free network
3	28.9646	Free network
4	28.7951	Constrained network

Depending on the strength of the network geometry, the principal distance value f, which of course changes with focus, may also vary a small amount with object space scale. The stronger the network, the less is the variation. Since the free-network adjustment implicitly sets its own scale (effectively that of the drive coordinates), it is expected to see small variations between this solution and the use of explicit, fixed control. If we have redundant 'fixed' control points (more than 3 points fixed, as is the case in survey 4), we have a different photogrammetric solution than the free-net solution, since the extra control can change the shape of the final network (in order to fit the control) and therefore change the calibration parameters.

The best course of action here is to mechanically ensure the CCD chip is indeed stable. Basically, the stability can be assessed in a strong network by confirming that photo coordinate residuals are as small as anticipated (e.g. about 1/30th pixel for good retro-targets).

Observation 5: *Decentering parameters highly correlated with principal point offsets.*

Decentering defined as the misalignment of lens components relative to the optical axis, estimated in the surveys is listed in Table 5.

Table 5. Correlations of principal point offsets with decentering

Parameter1	Parameter2	Percent correlation Survey 1	Percent Correlation Survey 3
x_p	p_1	93.8	93.2
y_p	p_2	91.01	80.7

The parameters of the decentering distortion and principal point offsets indicate high correlations. Fryer/ Fraser, 1986 noted that the actual effect of applying decentering distortion is the same as knowing and applying the offsets of the principal point from the fiducial axes [Fryer/Fraser, 1986].

Observation 6: *Correlation of f with exterior orientation parameters.*

The correlations between the calibrated focal length and camera's standoff from the object are plotted in Figure 3. In the first case, camera's elevation is analyzed. When no correlation is noticed, the maximum standoff distance among X, Y, Z is considered. Surprisingly, focal length appears to be uncorrelated with the camera distance.

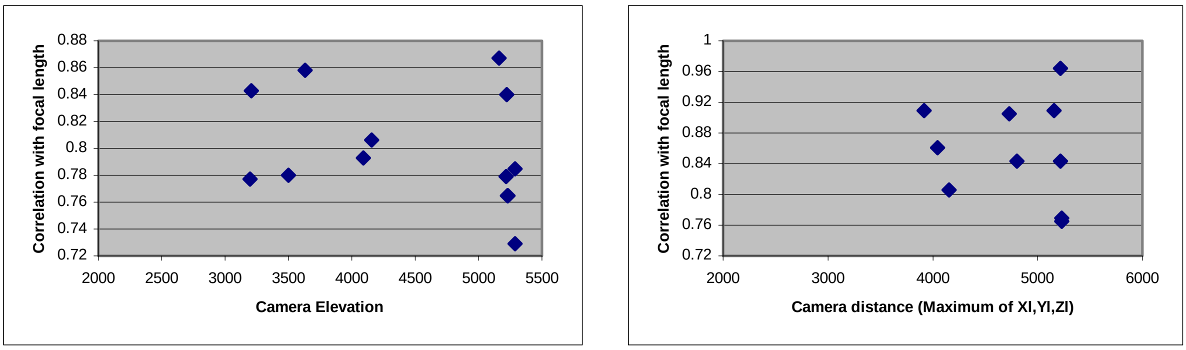

***Figure 3. Correlation of focal length with (a) camera elevation and (b) maximum of* X,Y, Z**

Observation 7: *The camera parameters b_1, b_2 are not relevant for CCD cameras.*

The terms b_1 and b_2 provide a correction to the x coordinate in the form: $dx = b_1 x + b_2 y$. Thus, b_1 is an affinity term to compensate for different scales between the x & y image coordinates. b_2 is a term to model any non-orthogonality or skew between the x & y axes. For direct CCD cameras such as the DCS420, these two terms can be suppressed. For video imagery with A/D signal conversion or scanned film they may assume significance [Fraser, 2002].

5. Conclusions

A digital camera has been calibrated fully. The calibration parameters obtained from four industrial surveys have been analyzed. The correlations among the interior orientation parameters have been studied and the fundamental digital camera parameters are identified. The camera focal length, the principal point offsets, the first term in radial lens distortion are observed to be the fundamental parameters. The remaining parameters are highly correlated with these fundamental parameters and hence, their effect can be absorbed by these by modifying the collinearity condition equations. It may be necessary to model the interior orientation on an image-by-image basis, rather than on block basis, considering the variations in camera parameters for every exposure. It is necessary to analyze its impact on the geometric strength of the solution. Hence, till such enhancements are made in the block adjustment software, it is appropriate to employ a camera with a stable chip.

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