INFLUENCE FACTORS EVALUATION ON HIGH-PRECISION PLANAR CALIBRATION OF NON-METRIC DIGITAL CAMERA

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ABSTRACT:

With the rapid development of three-dimensional (3D) modelling, camera calibration is paid more and more attention. In this article, we analyse the influence factors in the calibration: the camera and lens, the shape of control points, photography model and the scale between calibration object and measurement. Appropriate model can get the right result quickly, and the position of the model in the image effects the calibration result directly. The control points should cover the whole image evenly. The cross control point is better than circle points. The more similar the size of object model and the measurement object, the higher precision the calibration has. Actually, each of them plays an important part in calibration. We can get higher precision result based on considering those influence factors. And the experiments in the end show that the work is worthy. It means that we should take those factors into account.

1. INTRODUCTION

1.1 Background

With the rapid development of Photogrammetry and Electronic technology, the measurement, using the Close-range photogrammetry methods with stereo pair to identify and match the 3-Demensional coordinates of the objects in the scene, is more and more applied in the fields of the modeling of 3-Demensional city, computation vision, industry metrology, digital mapping and so on.

In the aerial photogrammetry, it is common to use the metric camera with pre-determined intrinsic parameters, and the geometric relationship in the image is specific. However, the metric camera is expensive, bulky equipment, inconvenience to be taken during photographing outside. Recently, the technology of digital camera develops fast, which capability has met the need of close-range photogrammetry. So, using non-metric digital camera in this field becomes more and more prevalent. Compared with the common metric camera, the intrinsic parameters of the usual non-metric digital camera are uncertain in advance. The digital camera has many advantages to obtain image: an error will be introduced when we flatten the film in common metric camera but not in digital camera; its images can be obtained fast and safely and needs no development; the camera is solid, small bulk and light-weighted, and it has strong adaptability and fine flexibility and maneuverability during the photography. On the other hand, disadvantages also exist in the digital camera, such as the distortion. The digital camera usually has larger lens distortion, which leads to the result that the principal points can't coincide with the geometric centre of image. The CCD array also has distortion and the image axes are not orthogonal sometimes. All those distortions must not be neglected, so the procedure of the camera calibration is complex and should take many factors into account.

Camera calibration is a critical part in 3-Demensional measurement, and its result will affect the measurement precision directly. The objective of stereo camera calibration is to estimate the internal and external parameters of each camera. For non-metric camera, the lens distortion plays an important part in calibration, so the corrected aberration cannot be ignored during the calibration. Therefore, another aspect of calibration is to compute the aberration coefficients.

What is Camera calibration? Camera calibration is to identify the camera's posture during the data acquisition process, including focal length f, as the principle point coordinate (u0, v0) and various aberration coefficients. Camera calibration is a critical part in 3D measurement. Measurement accuracy is based on calibration result directly.

After a period of development, the researchers have present a variety of calibration methods. Such as, the traditional calibration method which needs calibration object, and the self-calibration needs no calibration object.

At present, although self-calibration has its own superiority, its accuracy is not satisfactory. The traditional calibration has developed for a longer time, with higher precision, especially three-dimensional calibration, which accuracy has been able to meet a variety of needs. However, the traditional calibration requires high accuracy calibration object. It is difficult to use this method widely. So, the planar calibration comes into being. Generally speaking, compared with the accuracy based on three-dimensional calibration, the accuracy of two-dimensional calibration is lower slightly. There are several problems in three-dimensional calibration, such as expensive cost, inconvenience to carry. Because of the various deficiencies of the three-dimensional calibration, the camera calibration based on two-dimensional plate has been gain favor, and calibration algorithms in plate calibration have become a hot research in calibration area. Two-dimensional calibration is not only to be produced, but also provides high accuracy in measurement.

Tsai.[1] proposed the two-step method based on the RAC (radial alignment constraint), which can get the calibration result by linear equations. Triggs[2] use the absolute quadratic curve principle to calibrate. Zhang zhengyou[3] calibrates the camera by the orthogonal rotation matrix of conditions and nonlinear optimization in China, Zhang Yongjun[4] proposed the 2-D DLT (direct linear transformation) with a bundle adjustment of the camera calibration algorithm, and so on. The purpose of all those methods is to calibrate non-metric camera. Thus, what are the influence factors in camera calibration?

2. THE ANALYSIS OF INFLUENCE FACTORS

There are several influence factors in calibration. In this section, we try to analysis each influence factor in theoretic.

2.1 Camera and lens

In non-metric camera, the scales in u, v directions are often inconsistent, so focal length f is accustomed to be decomposed into two directions, expressed as f_u, f_v respectively. f_u stands for the focal length in u axis and f_v in v axis. And sometimes, we need to take the skewness of the two image axes into account. So the camera intrinsic matrix is often expressed by A:

$$A = \begin{bmatrix} f_u & \gamma & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2\text{-}1)$$

Where, γ is the skewness of the two image axes, and (u_0 , v_0) is the principle point coordinate in image plane.

For ordinary digital camera, lens distortion can't be ignored. In weng's article, the lens distortion is departed into three parts: radial distortion, decentering distortion and thin prism distortion. Radial distortion causes an inward or outward displacement of a given image point from its ideal location. The radial distortion of a perfectly centred lens is governed by an expression of the following form:

$$\delta_{\rho r} = k_1\rho^3 + k_2\rho^5 + k_3\rho^7 + \ldots \quad (2\text{-}2)$$

Where ρ is the radial distance from the principal point of the image plane, and k_1, k_2, k_3... are the coefficients of radial distortion.

The optical centres of lens elements are not strictly collinear. This defect introduces what is called decentering distortion, which can be described by the following expressions:

$$\begin{aligned} \delta_{ud} &= p_1(3u^2 + v^2) + 2p_2uv + O[(u,v)^4] \\ \delta_{vd} &= 2p_1uv + p_2(u^2 + 3v^2) + O[(u,v)^4] \end{aligned} \quad (2\text{-}3)$$

Thin prism distortion arises from imperfection in lens design and manufacturing as well as camera assembly. This type of distortion can be adequately amended by the adjunction of a thin prism to the optical system, causing additional amounts of radial and tangential distortions. It can be expressed as:

$$\begin{aligned} \delta_{up} &= s_1(u^2 + v^2) + O[(u,v)^4] \\ \delta_{vp} &= s_2(u^2 + v^2) + O[(u,v)^4] \end{aligned} \quad (2\text{-}4)$$

So, the total amount of lens distortion can be expressed as:

$$\begin{aligned} \delta_u(u,v) &= s_1(u^2 + v^2) + p_1(3u^2 + v^2) \\ &\quad + 2p_2uv + k_1u(u^2 + v^2) \\ \delta_v(u,v) &= s_2(u^2 + v^2) + p_2(u^2 + 3v^2) \\ &\quad + 2p_1uv + k_1v(u^2 + v^2) \end{aligned} \quad (2\text{-}5)$$

2.2 The shape of control points

In Photogrammetry, the object space translates into image plane through perspective projection. After projection, line is still line, but other objects can't keep the shape. For instance, the object is a circle before projection, but the shape is not a circle any more after projection. So, the centres of the shape are not consistence with each before and after projection. Many researchers ignore the error in their study. When we use the circular control points, it will cause error to extract point coordinates. So cross control points is better than circular control points for calibration. If we want to avoid the bias caused by extracting points, we can rectify the error through some method [5].

Let us assume that a circular control point *R* with radius *r* is located on the image plane so that its centre is at the origin of the planar coordinate frame *H*. circles are quadratic curves that can be expressed in the following manner:

$$AX_H^2 + 2BX_HY_H + CY_H^2 + 2DX_H + 2EY_H + F = 0 \quad (2\text{-}6)$$

Where *A, B, C, D, E* and *F* are coefficients that define the shape and location of the curve. In homogeneous coordinates, this curve can be written as:

$$\begin{bmatrix} x_H \\ 1 \end{bmatrix}^T Q \begin{bmatrix} x_H \\ 1 \end{bmatrix} = 0 \quad (2\text{-}7)$$

Where

$$Q = \begin{bmatrix} A & B & D \\ B & C & E \\ D & E & F \end{bmatrix}$$

For the circle *R*,

$$Q = \begin{bmatrix} -\frac{1}{r^2} & 0 & 0 \\ 0 & -\frac{1}{r^2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

According to the relationship between object points and corresponding points, R can be projected on the image plane, and the resulting curve becomes:

$$\begin{bmatrix} a_c \\ 1 \end{bmatrix}^T ((FH)^{-1})^T Q (FH)^{-1} \begin{bmatrix} a_c \\ 1 \end{bmatrix} = 0 \qquad (2\text{-}8)$$

We can see that the result is a quadratic curve, whose geometric interpretation is a circle, hyperbola, parabola or ellipse. As a result, we can obtain an unbiased relationship between the observed centres of the ellipse and the camera model.

The image coordinates precision is very important to calibration. In a word, when we extracting control points coordinate from image plane, it is not necessary to correct the bias for the cross control points, but for the circle control points.

2.3 Photography Model

The calibration precision is not only related to the camera lens, the shape of the control points, but also the photography model.

In other words, the camera attitude, the position of the control points in the image and longitudinal tilt all can affect the precision of calibration. Next, we will introduce in detail.

Focal length is often fixed in calibration. And the objective distances are similar (because it needs to take several images to calibrate camera at a time). In order to demarcate the focal length and the distortion coefficients, we should photograph in different objective distances so that the same object can image in different sizes. Because the calibration model images in the centre of the image, so we can solve the focal length and the distortion coefficients more accurately. It means that the relevance between the focal length and distortion coefficients can be eliminated in a large extent in this way.

Lens distortion is mainly composed with the radial distortion and tangential distortion. Rotating camera can differentiate the radial distortion coefficients and tangential distortion coefficients. So it is a good method for calibration to rotate camera in photography.

In aerial photogrammetry, it is often required that the control points distribute evenly in the image plane. It is as the same in the close range photogrammetry, in the calibration. Control points in the image must be even and covered the whole image. If the control points can't cover the whole image plane, they must be around the image centre, the wilder the better.

The longitudinal tilt of camera is an influence factor too. The more atilt the camera is, the more the control points crowed together in the direction far away from the camera.

2.4 The scale between calibration object and measurement object

The purpose of calibration is measurement. Only the calibration is good which contributes to the measurement accuracy. Therefore, we should not only consider calibration itself, but also the contribution that the camera calibration does to the measurement accuracy.

As all know, Camera has a certain depth of field, that is, if the focal length is fixed, there is a clear image when the objective distance changes in certain range. If we use smaller plane to calibrate camera, when we plan to measure larger object, we can't achieve high accuracy, even get wrong result at last. On the contrary, if we measure a smaller object with a larger plane to calibrate, we can not be satisfied with the accuracy, too. In order to assess such factor's effect on the measurement accuracy, we used a series of plane with different size to measure the same object. So that we accessed the sensitivity of the measurement accuracy to the calibration plane size.

3. EXPERIMENT

3.1 Real data

In experiment, we use Olympus E-500 single-lens reflex (SLR) camera, with the 14-45 mm lens. This camera has 800 million valid pixels. The CCD (Charge Coupled Device) physical size of 17.3 mm * 13mm. Manual focus is used in photograph and image resolution is set to 3264 x 2448.

Next, the images used in the experiments are listed. They are photographed at the same focal length.

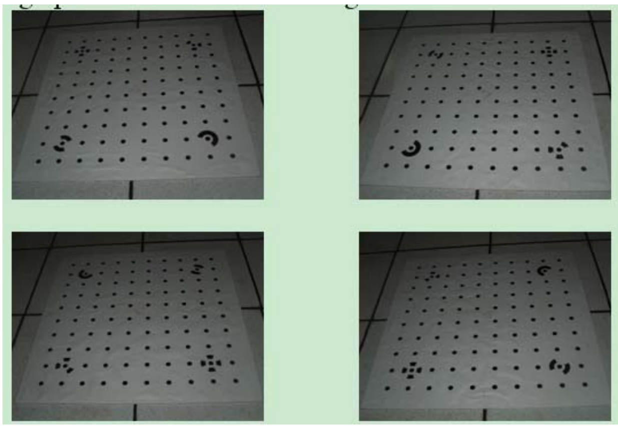

Fig.1 The first four images of the model plane.
They are photographed from 4 different directions.

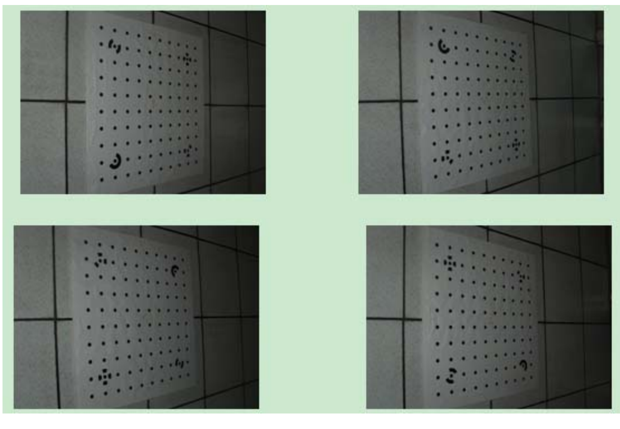

Fig.2 The second four images of the model plane.
They are photographed with the camera rotated 90 degrees anti-clockwise.

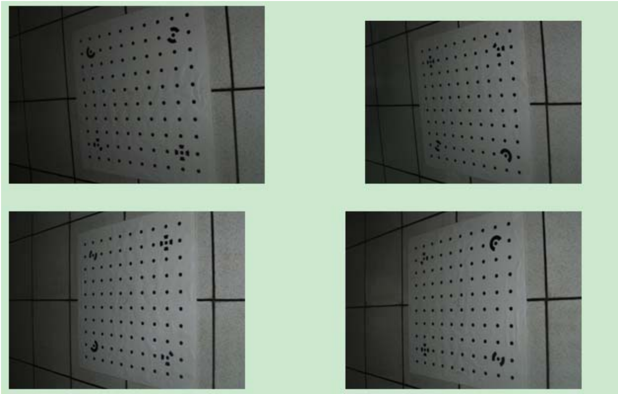

Fig.3 The third four images of the model plane.
They are photographed with the camera rotated 90 degrees clockwise.

Fig.4 The forth four images of the model plane.
They are photographed with the object distance
further than the former.

At the same time, we photographed a 3D control field with the same focal length so than we can compare the calibration precision of the plane calibration and the 3D calibration. And we make three-dimensional calibration result as a reference standard.

Fig.5 one image of the model plane,
where the model is not in the centre of the image.

Fig.6 The image of cross control points

Fig.7 the small object model

Fig.8 One high precision 3D control field

3.2 Experiments

In order to analyze the influence factors, we designed several experiments.

First, in order to analyze the influence of the camera model, we take three coefficients into account: the skewness, the ratio of focal length in the two axises and the distortion coefficients. In this experiment, we use the images in fig.1. There is a table which can descript the result.

In the table 1, we can get that: the coefficients: γ, k3 and the ratio of the two focal length, effect on the calibration result slightly in the camera, and the appropriate model can get the right result quickly. In fact, we can choose approximate camera model without experiment one by one. We can choose the coefficient by significant analysis, which we won't introduce here.

	experiment 1	experiment 2	experiment 3	experiment 4	experiment 3
	$f_x = f_y$, $\gamma=0$	$f_x = f_y$, $\gamma \neq 0$	$f_x \neq f_y$, $\gamma=0$	$f_x=f_y$, $\gamma=0$	$f_x \neq f_y$, $\gamma=0$
	$k_3=0$	$k_3=0$	$k_3=0$	$k_3 \neq 0$	$k_3=0$
f_x	4093.1739	4094.4707	4093. 5196	4093.2611	4093.2611
f_y	4093.1739	4094.4707	4093. 1395	4093.3723	4093.3723
u_0	1593.6447	1624.5627	1624.2831	1593.4418	1593.4418
v_0	1199.3241	1193.4379	1193.2168	1199.5787	1199.5787
k_1	-0.1196	-0.1428	-0.1276	-0.1211	-0.1211
k_2	0.0233	0.3238	0.0667	0.0347	0.0347
k_3	0	0	0	0	0
p_1	-0.0011	-0.1273	-0.0011	-0.0021	-0.0021

p_2	-0.005	0.0647	-0.0006	-0.0034	-0.0034
γ	0	0	0	0.0046	0

Table.1 the coefficient of the camera model and the calibration results

	experiment 1 image： fig.1, fig.2	experiment 2 image： fig.1, fig.2, fig.3	experiment 3 image： fig.3, fig.4	experiment 4 image： fig.3, fig.4, fig.5	experiment 5 3D calibration result
f_x	4093.1739	4092.8528	4093.4573	4091.1457	4092.9533
f_y	4093.1739	4092.8528	4093. 4573	4091.1457	4092.9533
u_0	1613.6447	1613.5213	1599.6447	1593.4342	1612.9712
v_0	1203.3241	1209.7321	1201.3241	1200.8646	1210.3524
k_1	-0.1196	-0.0232	-0.1196	-0.1260	-0.0231
k_2	0.0233	0.0183	-0.1196	0.0901	0.0045
k_3	0	0	0	0	0
p_1	-0.0011	-0.0009	-0.0011	-0.0009	0.0005
p_2	-0.0012	-0.0001	-0.0012	-0.0011	0.0003
γ	0	0	0	0	0

Table.2 Photography model and the calibration results

The shape of the control points effect the results actually. Because the centre of the shape is not the circle centre any more.

The photography model influent the results, too. In table 2, we use the images in different photography ways.

When the model doesn't cover the whole image, the result is bad. When the model image is not in the centre of the image (fig.5), the result is wrong!

At last, when the size of the object model is similar to the size of the measurement object, the measurement precision is the highest. You can see, fixed focal length, camera within a certain distance of imaging is clear, because the cameras have a certain depth of field.

Fig. 9 the modelling object

4. CONCLUSION

By experiments, we analyse the influence factors in the calibration: the camera and lens, the shape of control points, photography model and the scale between calibration object and measurement. Appropriate model can get the right result quickly, and the position of the model in the image effects the calibration result directly. The control points should cover the whole image evenly. The cross control point is better than circle points. The more similar the size of object model and the measurement object, the higher precision the calibration has. Actually, each of them plays an important part in calibration. We can get higher precision result based on considering those influence factors. And the experiments in the end show that the work is worthy. It means that we should take those factors into account.

REFERENCES

Janne heikkila. Geometric Camera Calibration Using Circular Control Points. IEEE Transactions on pattern analysis and machine intelligence. Vol.22. No.10. October 2000.

Triggs B. 1998. *Auto-calibration from planar scenes*. [A]. In: Proceedings of 5th European Conference on Computer Vision [C], Freiburg Germany: 89~105.

Tsai RY. 1987, *A versatile camera calibration technique for high-accuracy 3-D machine metrology using off-the-shelf TV cameras and lens*. IEEE Journal on Robotics and Automation, RA-3(4): 323-344. [J]

Yongjun Zhang, 2002. Camera Calibration Using 2D_DLT and Bundle Adjustment with Planar Scenes, Geomatics and Information Science of Wuhan University, Vol.27 No.6.

Zhengyou Zhang, *A Flexible New Technique for Camera calibration*. December 2, 1998.