An Improved Flexible Camera Calibration Technique for Rock Three Dimensional Shape Measurement System

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ABSTRACT

With these advantages such as no phase shift error, measured fast, portable, high accuracy, the three-dimensional measurement system which is based on the heterodyne principle and digital grating phase-shift technology has been widely used in rock three-dimensional shape measurement. The precision of camera calibration determines the measurement accuracy of the system. In this paper, the Zhang Zhengyou planar flexible calibration method is improved and an improved flexible camera calibration means is presented. This method adopts a lens distortion model based on second-order radial distortion and second-order tangential distortion and uses a high precision planar calibration target printed with circular targets. First, getting the initial values of camera model through image points near the center, the initial values can be a good approximation of the exact values because the distortion of these points near the center is small. Then, using the entire calibration board images, all parameters can be acquired by applying maximum likelihood estimation. The experimental results show that this approach is superior to Zhang's in precision and robustness.

KEYWORDS: Camera Calibration; Radial Distortion; Tangential Distortion; Maximum Likelihood Estimation; Rock 3D Shape Measurement

INTRODUCTION

Rock mechanics and rock engineering is an applied science discipline which is extremely closely related to the national economic construction and defense construction. Jointed surface factors have great influence on various properties of rock, while the important features of joint surface such as mechanics and seepage properties is closely related to the joint surface morphology. Only accurately to obtain the joint surface morphological parameters and then to combine with joint closure, shear related theoretical models and empirical formulas can correctly reflect the actual mechanical behavior of joint. Therefore, accurate determination of the joint surface morphology is a prerequisite to study deformation and the mechanical mechanism of strength, then to further establish the appropriate model [1].

How to access to the rock surface 3D information conveniently, fast and accurately is a very important basic issue. Based on the heterodyne principle and digital grating phase-shift technology, the three-dimensional measurement system has many features such as no phase shift error, measured fast, portable, high accuracy [2-3]. Moreover, it has been widely used in rock 3D shape measurement [2].

Camera calibration accuracy determines the precision of three-dimensional measuring system [3-4]. Up to now, the domestic and foreign scholars have proposed many calibration methods. Brown [5] raised a fully nonlinear calibration model of camera, and it required three-dimensional calibration object in the calibration process. As a result of the full non-linear model, the solution is instable. At the same time, the calibration is expensive because it needs a 3D calibration object with high accuracy. Tsai [6] presented a classic two-step calibration means, which makes the solving process be simple and stable. However, only the first-order radial distortion is considered, and 3D calibration object is also necessary. Based on the methods Triggs and Zisserman proposed, Zhang Zhengyou [7] put forward an approach that entirely relied on planar grid calibration target, yet it also only considered the first-order radial distortion and the model is not very fine. It has certain drawbacks to improve the accuracy for the calibration targets used in these ways above. Consequently, this paper presents an improved flexible camera calibration algorithm which has been applied to the digital grating three-dimensional measurement system.

CAMERA CALIBRATION MODEL

Pinhole Camera Model

According to pinhole model imaging theory, establish coordinate transformation relation between the homogeneous coordinates $\widetilde{M}$ of point P represented in the world coordinate system and the homogeneous coordinates $\widetilde{m}$ of its projection point p. As follows:

$$s\widetilde{m} = A[R\ t]\widetilde{M} \tag{1}$$

where $A = \begin{bmatrix} f_c(1) & c & u_0 \\ 0 & f_c(2) & v_0 \\ 0 & 0 & 1 \end{bmatrix}$, s is an arbitrary scale factor, containing the depth information of the image point m. R and t are respective the rotation matrix and translation matrix from camera coordinate system to the three-dimensional world coordinate system, and (R, t) is the camera external parameters. The camera extrinsic parameters are used to determine the position and orientation of a beam in a given world coordinate system, namely, the camera beam position in the global coordinate system (defined by the translation matrix t) and posture (defined by R). A represent the camera internal parameters, which are the key elements to determine the relative positional relationship between camera projection center and images. By means of the internal parameters, the relationship can be uniquely identified, i.e. to restore the shape of the beam in photography. (u_0, v_0) is the principal point coordinate, $f_c(1)$ and $f_c(2)$ denote the camera's focal length, c means the skew angle between the x and y pixel axes.

The Actual Imaging Model

Since various distortions being for actual optical lens, there is an error between the image point position of an object point in the actual case and ideal (on the base of pinhole imaging). Zhang mainly take radial distortion into account but not the tangential distortion. To further improve the calibration precision, this paper considers both the radial and tangential distortion.

Radial distortion is usually caused by a lens with defective shape, which is divided into barrel distortion and pincushion distortion. The model of radial distortion can be expressed as:

$$\begin{cases} \mathrm{dx_r} = \mathrm{x}[\mathrm{k_1 r^2} + \mathrm{k_2 r^4}] \\ \mathrm{dy_r} = \mathrm{y}[\mathrm{k_1 r^2} + \mathrm{k_2 r^4}] \end{cases} \tag{2}$$

where k_1 and k_2 are radial distortion coefficients, $r^2 = (x^2 + y^2)$, (x, y) is the ideal image coordinates without distortion acquired on the base of pinhole imaging principle.

The model of tangential distortion is:

$$\begin{cases} dx_d = p_1(r^2 + 2x^2) + 2p_2xy \\ dy_d = p_2(r^2 + 2y^2) + 2p_1xy \end{cases} \tag{3}$$

where p_1 and p_2 are tangential distortion coefficients, r, x, y is the same as shown above.

CAMERA CALIBRATION

In order to enhance calibration accuracy, an elaborate calibration target is needed. Hereinafter, this paper will introduce the used calibration target and calibration algorithm briefly.

Calibration Target

The quality of camera calibration result has a direct impact on the accuracy of the final measurement result. While during the camera calibration process, the selection of image mark point pattern and extraction of feature point directly affect the accuracy of the eventual calibration. Not only do circular targets have radial symmetry, but also the confirmation of circular marking point centers possesses rotation invariant. Simultaneously, in a wide range of image magnification, they also have scale invariance, and previous literatures have reported that circular pattern features are better than other geometric patterns [8].

The used calibration board is shown in Figure 1, which consists of five great circles and 94 small rounds. It mainly has two advantages: First, ellipse fitting algorithm could provide a stable and high-precision coordinates of the centers. Furthermore, via the positional relations of the 5 great circles, it can automatically number all the rounds, and then achieve automation of the calibration process [9].

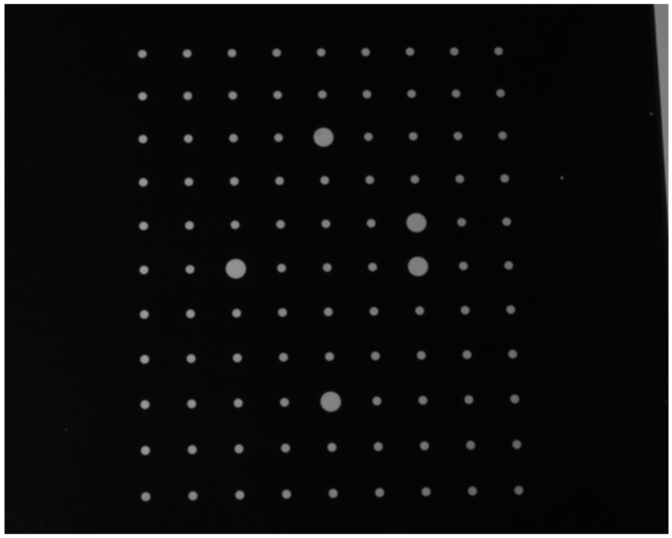

Figure 1: Calibration target

Calibration Algorithm

Firstly, applying the image coordinates and the corresponding three-dimensional coordinate of the middle 35 centers in each calibration image, the initial value of external and internal parameters without distortion can be obtained by the following formula.

$$\mathrm{MIN} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left\| m_{ij} - \widehat{m}\left(A, R_i, t_i, M_j\right)\right\|^2 \qquad (4)$$

where i represent the number of images, j is the number j point in image i, $\widehat{m}\left(A, R_i, t_i, M_j\right)$ mean the projection points of image i corresponding to space plane 3D points M_j. Generally, using the Levenberg-Marquardt algorithm to conduct optimization can get the final external and internal parameters.

Similarly, because the distortion in the middle part of images is very small, the initial internal and external camera parameters, distortion parameters can also be got by applying Levenberg-Marquardt algorithm. The optimization algorithm formula as follows:

$$\mathrm{MIN} = \sum_{i=1}^{n}\sum_{j=1}^{m}\left\| \mathrm{m}_{ij} - \widehat{\mathrm{m}}\left(\mathrm{k}_1, \mathrm{k}_2, \mathrm{p}_1, \mathrm{p}_2, \mathrm{A}, \mathrm{R}_i, \mathrm{t}_i, \mathrm{M}_j\right)\right\|^2 \qquad (5)$$

where k_1, k_2, p_1 and p_2 are respective radial and tangential distortion coefficients. Using the result optimized by (5) as a starter, and then plugging all center coordinates of each calibration image into equation (5) to refine parameters, finally, the final internal and external camera parameters and distortion parameters can be calculated.

EXPERIMENTAL RESULT

In order to validate if the proposed algorithm can improve the accuracy of camera calibration, this paper exploits 13 collected images to complete camera calibration. Calibration results are shown in Table 1. Figure 2 shows the distribution of projection errors.

The standard deviation of calibration results is [0.02479, 0.02167]. However, Zhang used calibration board with checkerboard pattern is [0.11689, 0.11500]. The calibration accuracy of this method is superior to Zhang, and robustness is better.

Table 1 Calibration result

Name	Value(pixel)	Error(pixel)
$fc(1)$	1691.50289	0.09765
$fc(2)$	1691.50289	0.011634
u_0	334.63985	0.126831
v_0	252.73961	0.130254
c	0.00037	0.00009
k_1	- 0.22933	0.00121
k_2	- 0.16297	0.00095
p_1	- 0.00025	0.00004
p_2	0.00008	0.00012

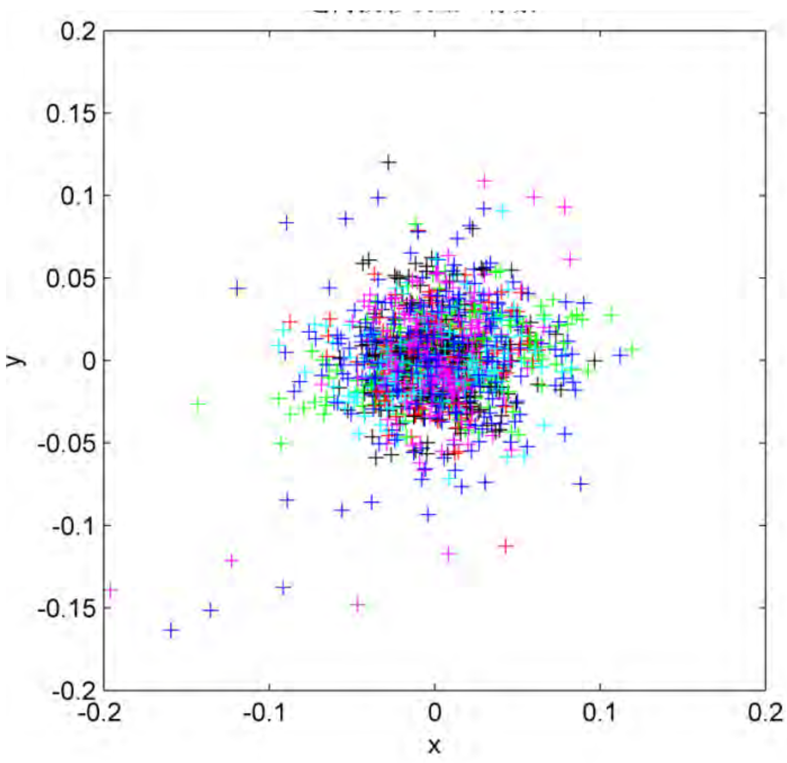

Figure 2: Distribution of projection errors

CONCLUSION

Digital raster three-dimensional measurement system has been widely used in rock three-dimensional shape measurement due to its characteristics as non-contact, high speed and high precision. Based on the camera calibration algorithm proposed by predecessors, an improved flexible camera calibration method is presented. The algorithm is simple to implement, furthermore, with high accuracy and robustness.

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