A Survey of Calibration Methods for Traditional Cameras Based on Line Structure Light

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***Abstract*—The line structure light three-dimensional reconstruction system is a kind of three-dimensional non-contact measurement system, which has the advantages of high precision, high speed, small damage to objects and strong adaptability. Camera calibration is a major factor that constrains the accuracy of 3D measurement systems. The camera calibration is based on the pinhole imaging model, and through a series of complex calculations, the camera's internal parameters (focal length, distortion coefficient) and external parameters (rotation matrix and translation vector).The different calibration methods use different calibration targets, which can be divided into 3D calibration targets, 2D calibration targets, and one-dimensional calibration targets according to the characteristics of the calibration targets. This paper mainly discusses: calibration content and significance, calibration methods for different targets and evaluation methods for calibration of different targets. Firstly, the content and significance of calibration are expounded. Then, according to different calibration targets, the calibration algorithm is analyzed. Finally, the calibration algorithm is analyzed and summarized, and the development trends, advantages and disadvantages of different calibration methods are pointed out.**

Keywords-Calibration Target; Internal Reference; External Parameter

I. INTRODUCTION

Vision plays an important role in human understanding and transformation of the world. 80% of human information comes from vision[1].Three-dimensional measurement technology is of great significance in the fields of culture, film and television entertainment, medicine and cultural relics protection. With the continuous development of computer technology, the functions of computers are becoming more and more powerful. People use the camera to obtain the three-dimensional information of the object, and the obtained three-dimensional information is converted into data that can be processed by the computer through a series of calculations, and then the data is used to reconstruct the object. The method for measuring the line structure light is a technique of obtaining a three-dimensional point coordinate at the intersection of the plane and the surface of the object to be measured by projecting a line laser plane onto the surface of the object [2]. The three-dimensional measurement technology of line structure light has the advantages of fast measurement speed, high precision and low measurement environment requirements, and is widely welcomed [3].Camera calibration is the main factor that restricts the accuracy of 3D measurement, which has attracted wide attention from scholars and improved step by step.

II. CAMERA CALIBRATION CONTENT

Wherever Times is specified, Times Roman or Times New Rom The camera calibration method is different according to the way of solving the parameters (such as whether to use external reference objects, whether the camera needs precise motion, etc.). The camera calibration algorithm can be divided into three calibration methods: traditional calibration

DOI: 10.21307/ijanmc-2019-036

method, self-calibration method, active vision camera calibration method [4].As shown in Figure1 below, this article focuses on traditional camera calibration.

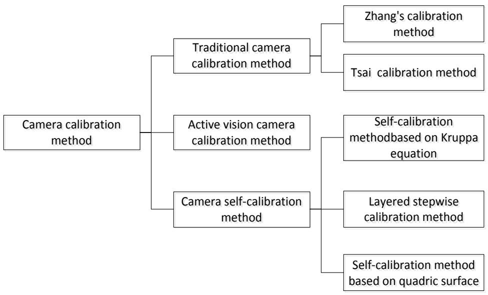

Figure 1. Classification method of calibration method

The camera calibration technology is mainly based on the linear model of small hole imaging, the geometric model established by the conversion between the two-dimensional image coordinate system of the known feature points and the three-dimensional world coordinate system. Using the optimal algorithm to derive the internal and external parameters of the camera model considering distortion, the process of solving the camera parameters is called camera calibration. Figure 2 below is the conversion diagram of the coordinate system. In the figure, $\{O-UV\}$, $\{O_o-XY\}$, $\{O_c-X_cY_cZ_c\}$ and $\{O_w-X_wY_wZ_w\}$ representing a pixel coordinate system, an image coordinate system, a camera coordinate system, and a world coordinate system, respectively. O_cO_o for the optical axis of the camera, f Indicates the focal length of the camera. Point P is a point on the object to be measured, and P' is the coordinate of P corresponding to the image coordinate system. Suppose the world coordinates of point P are (x_w, y_w, z_w) , Camera coordinates are (x_c, y_c, z_c) , Image coordinates are (x, y) , Pixel coordinates are (u, v) , Ideally, there is a certain conversion relationship between pixel coordinates and image coordinates, image coordinates and camera coordinates, camera coordinates, and world coordinates. If the world coordinates and image coordinates of some points are known, the internal and external parameters of the line structure light can be calculated using the conversion relationship.

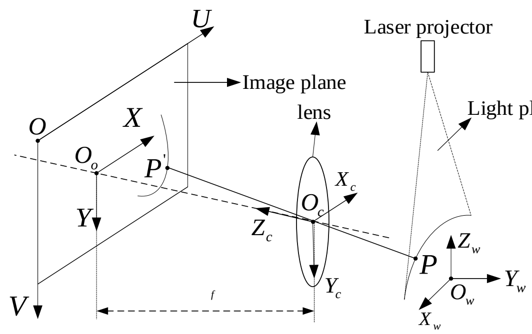

Figure 2. Coordinate system conversion diagram

After acquiring the three-dimensional coordinate point, the camera shifts the theoretical point P due to camera distortion and other factors[5], as shown in Figure 3 below.

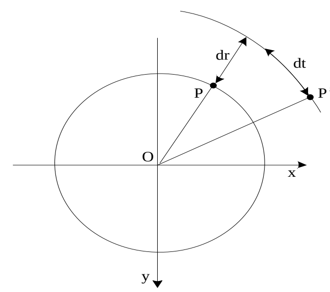

Figure 3. Distortion model diagram

The main factors affecting distortion are radial distortion and tangential distortion, as shown in Figures 4 and 5 below are common radial and tangential distortions.

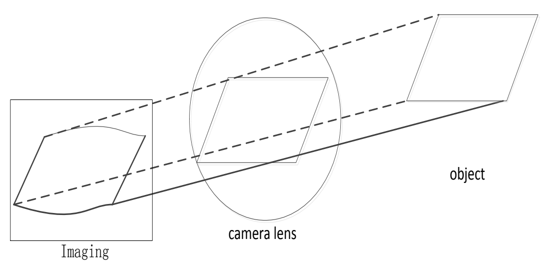

Figure 4. Radial distortion

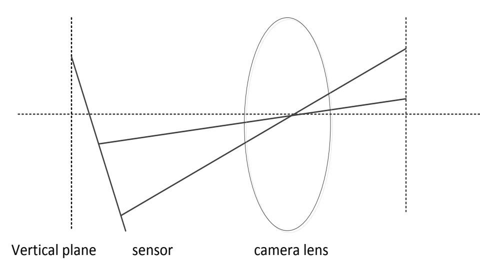

Figure 5. Tangential distortion

III. TRADITIONAL CALIBRATION METHOD

The calibration target is generally divided into a 3D calibration target, a 2D calibration target, and a one-dimensional calibration target[6].Common targets are shown in Figure 6 below:

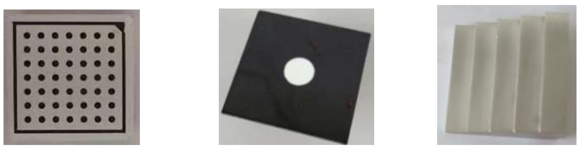

Figure 6. Schematic diagram of commonly used targets

A. *Camera model*

In this paper, the pinhole model is used as a camera model for research. The 2D calibration target is represented by $m=(u,v,1)^T$, the 3D calibration target is represented by $M=[X,Y,Z,1]^T$, and the corresponding homogeneous vectors are $\tilde{m}=[u,v,1]^T$, $\tilde{M}=[x,y,z,1]^T$, respectively. Then the relationship between the 3D point M and its projection point m is as follows[7]:

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

Where R is the rotation matrix, $t=\begin{bmatrix}t_x & t_y & t_z\end{bmatrix}^T$ for the translation vector,and describes the external parameters of the camera that the camera is calibrated. $f_u=a_x/d_x, f_v=a_y/d_y, d_x, d_y$ indicates the physical size of each pixel in the Y-axis Y-axis direction. f_u, f_v, u_0, v_0 is only related to the internal parameters of the camera, which is the internal parameters that the camera needs to calibrate.

B. *Camera calibration based on three-dimensional targets*

This paper introduces the calibration of 3D calibration targets, using the classic Tsai[8].two-step calibration algorithm. The Tsai two-step method is based on the calibration method of the radial correction constraint (RAC. Radial Alignment Constraint).

The camera distortion model shown in Figure 7 below, The following model includes five coordinate systems, which are camera coordinate system O_C, image pixel coordinate system O_i, world coordinate system O_W actual image physical coordinate system O_d, and ideal image physical coordinate system O_u . The solution process assumes that u0, v0 is known to only consider second-order radial distortion. The main point is both the center of the image and the center of the radial distortion.

The first step ： uses a radial alignment constraint (RAC) linear solution.

Step 2: Find the remaining parameters for nonlinear optimization.

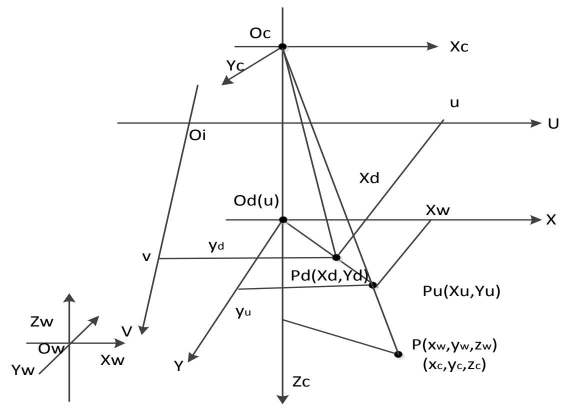

Figure 7. Camera distortion model diagram

Advantages: Applicable to any camera model, high calibration accuracy.

Insufficient: calibration needs to calibrate targets, which is difficult to achieve in some applications.

C. *Camera calibration based on two-dimensional targets*

In this paper, the research method of two-dimensional calibration target is explained by Zhang Zhengyou calibration method[9][10].To facilitate the operation, the template is defined on a plane parallel to the X-Yplane (Z = 0) in the world coordinate system..

From the above formula (1):

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}\alpha & \gamma & u_0 & 0\\0 & \beta & v_0 & 0\\0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}R & t\\0^T & 1\end{bmatrix}\begin{bmatrix}x_w\\y_w\\z_w\\1\end{bmatrix} \tag{2}$$

$$R=\begin{bmatrix}r_1 & r_2 & r_3\\r_4 & r_5 & r_6\\r_7 & r_8 & r_9\end{bmatrix} \tag{3}$$

Where is the u_0、v_0 principal point coordinate, α、β is the vector of the (u,v) , the coordinate axis in the image, and γ is the perpendicularity of the two coordinate axes. Let the template plane $Z_W = 0$ be in the world coordinate system, you can get:

$$s\tilde{m} = H\tilde{M} \tag{4}$$

Where $H = [h_1 \quad h_2 \quad h_3] = \lambda A[r_1 \quad r_2 \quad r_3]$, λ is the scaling factor scalar, r_1, r_2 is the two column vectors of the rotation matrix, and t is the translation matrix.

By the nature of the rotation matrix, a constraint matrix is available for each image:

$$\begin{Bmatrix} h_1^T A^{-T} A^{-1} h_2 = 0 \\ h_1^T A^{-T} A^{-1} h_1 = h_2^T A^{-T} A^{-1} h_2 \end{Bmatrix} \tag{5}$$

make:

$$B = A^{-T} A^{-1} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} = \begin{bmatrix} \frac{1}{\alpha 2} & -\frac{\gamma}{\alpha^2 \beta} & \frac{v_0\gamma - u_0\beta}{\alpha^2\beta} \\ -\frac{\gamma}{\alpha^2\beta} & \frac{\gamma^2}{\alpha^2\beta^2} + \frac{1}{\beta^2} & -\frac{\gamma(v_0\gamma - u_0\beta)}{\alpha^2\beta^2} - \frac{v_0}{\beta^2} \\ \frac{v_0\gamma - u_0\beta}{\alpha^2\beta} & -\frac{\gamma(v_0\gamma - u_0\beta)}{\alpha^2\beta^2} - \frac{v_0}{\beta^2} & \frac{\gamma(v_0\gamma - u_0\beta)^2}{\alpha^2\beta^2} + \frac{v_0{}^2}{\beta^2} + 1 \end{bmatrix} \tag{6}$$

From (6): B is a symmetric matrix, which can be represented by the following 6D vector:

$$b = [B_{11} \quad B_{12} \quad B_{13} \quad B_{22} \quad B_{23} \quad B_{33}]^T \tag{7}$$

Let the ith column vector $h_i = [h_{i1} \quad h_{i2} \quad h_{i3}]$ in H be obtained:

$$hi^T B h_j = v_{ij} T b \tag{8}$$

Then you can write (5)as:

$$\begin{bmatrix} v_{12}{}^T \\ [v_{11} - v_{12}]^T \end{bmatrix} b = 0 \tag{9}$$

Suppose you take n images of the template plane and get n images.

Vb=0 n is the matrix of $2n \times 6$ (10)

If $n \geq 3$,you can get the unique solution b and matrix B, you can get:

$$\begin{aligned} r_1 &= \lambda A^{-1} h_1 \\ r_2 &= \lambda A^{-1} h_2 \\ r_3 &= r_1 r_2 \\ t &= \lambda A^{-1} h_3 \end{aligned} \tag{11}$$

Get the internal and external parameters of the camera for optimization:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} \| m_{ij} - \hat{m}(A, R_i, t_i, M_j) \|^2 \tag{12}$$

Where $m(A, k_1, k_2, k_3, R_i, T_i, M_j)$ represents the coordinate point at which the jth point is projected onto the i-th image according to equation (4).

D. Camera calibration based on one-dimensional target

As shown in Figure 8, AB is a one-dimensional calibration with a length of L[11].

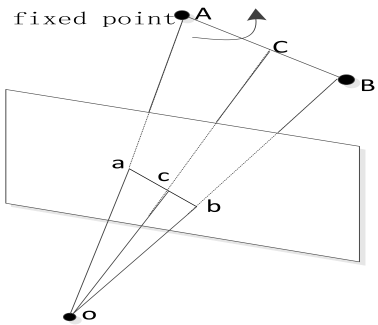

Figure 8. One-dimensional calibration target

$$\| A-B \|= L \tag{13}$$

Since the ratio of the line segments is known, B points can be calculated in the case where points A and C are known.

Then, according to the formula (2-1), there is a following formula, where Z_A, Z_B, Z_C is the depth of the corresponding point on the one-dimensional calibration object.

$$Z_C = \mathrm{Z_A} \lambda_\mathrm{A} \mathrm{a} + \mathrm{Z_B} \lambda_\mathrm{B} \mathrm{b} \tag{14}$$

Where $\lambda_B = BC / AB$, $\lambda_B = AC / AB$ Representation ratio.

According to (13):

$$\| K-1(Z_B b - Z_A a) \| = L \tag{15}$$

According to (14):

$${Z_A}^2 h^T K^{-T} K^{-1} h = L^2 \tag{16}$$

The parameters of the camera can be obtained by (16). According to the theory of higher geometry, the projection of the absolute quadratic curve on the image plane is actually described.

IV. EVALUATION OF CALIBRATION RESULTS

At present, the standard for calibration evaluation is mainly calibration accuracy and speed. The calibration target has a slight influence on the accuracy of the calibration. The commonly used calibration target materials are ceramic and metal and glass. The calibration target of the strong reflective material is easy to introduce noise, and the accuracy of the diffuse reflection calibration is better.

According to the above analysis of the algorithm, the advantage of the one-dimensional calibration target is that the construction of the calibration target is relatively simple and easy to implement; the disadvantage is that the number of points on the calibration object is small, the coordinates are unknown, and the calibration accuracy for the nonlinear distortion coefficient is not high. Based on the calibration method of two-dimensional and three-dimensional calibration targets, a large number of known coordinate systems on the calibration target can be used for calibration. The calibration accuracy is high and the speed is fast, but it is easy to appear blind spots due to its own characteristics. The three-dimensional calibration target is expensive to manufacture, and the commonly used fabrication methods mainly include photolithography, grinding, printing, and the like.

Different calibration targets are suitable for different calibration systems, and one-dimensional calibration targets are suitable for systems with less budget and less demanding calibration accuracy. The production of three-dimensional calibration targets is difficult, mainly machine processing, suitable for high precision requirements and sufficient funds. The calibration algorithm of the two-dimensional calibration target is easy to extract features, and the reconstruction effect is worse than the three-dimensional calibration target.

ACKNOWLEDGMENT

This work is partially supported by Science & Technology Program of Weiyang District of Xi'an City with project “201836".

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