

Vision Sensor Calibration Method based on Flexible 3d Target and Invariance of Cross Ratio

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Abstract: A vision sensor calibration method based on flexible three-dimensional (3d) target and invariance of cross ratio is proposed. Flexible 3d target is obtained by moving planar target to different positions. According to the relative position relationship of planar targets in the different positions, unify target points to the base coordinate frame of the flexible 3d target. Using the invariance of cross ratio, the coordinates of the points in the light plane are obtained, then converted to sensor measurement coordinate system. Finally, vision sensor calibration parameters are obtained by the nonlinear optimization algorithm. The experimental results demonstrate that the proposed method can obtain higher calibration accuracy, reduce the calibration cost. In addition, the proposed method can adapt to field calibration for vision system.

1. Introduction

Recently, 3D vision measuring equipment is widely used in reverse engineering, autonomous navigation and visual reality [1][2]. Most of 3d vision sensor measure methods use active vision measure technology, which is the structured light sensor emits a certain mode of structure light on the profile of the object, structured light image information is transferred to a computer, and then image features are extracted by image processing. Eventually, a set of pixel-to-pixel matching correspondence between camera and projector is set up, resulting in three-dimension profile measurement. Based on the different pattern of optical projector, the mode of structure light is divided into line structure light, point structure light, multi-line structure light and so on. However, line structure light is widely applied to industrial vision measuring fields due to its simple structure, small volume, light weight, low cost, convenient calibration, and high accuracy of measurement [3].

Currently, different approaches for calibrating projector have been proposed in many literatures. A moving one-dimensional (1D) target arbitrarily placed in the field of view to simplify the calibration procedure [4]. In Robert Dewar's method [5], several thin non-coplanar threads are strained in the space illuminated by a light stripe, and then several bright light dots are obtained as the control points whose 3D coordinates can be measured by means of a theodolite. However, this method requires complicated and expensive equipment. Huynh [6] has proposed a method, in which the world points on the light stripe plane are generated based on the invariance of the cross-ratio. In the method, a 3D calibration target is difficult to be manufactured accurately. Besides the above methods, there are other methods of calibrating a structured light vision system being presented in the literature [7]. Wei [8] has proposed a novel 1D target-based calibration method for structured light vision sensors by randomly viewing a 1D target from different unknown orientations positioned within the field of view.

This paper proposes a new calibration approach of vision system based on flexible 3d target and invariance of cross ratio. Flexible 3d target is established. Then, control points in local coordinate frame are transferred to the base coordinate frame of the flexible 3d target by transformation matrix. Using the invariance of cross ratio, the coordinates of the points in the light planar are obtained, then converted to sensor measurement coordinate. Finally, vision system calibration parameters are obtained by the nonlinear optimization algorithm. The experimental results demonstrate that the proposed method can obtain higher calibration accuracy, reduce the calibration cost. In addition, the proposed method can adapt to field calibration for vision system.

2 Model of vision sensor

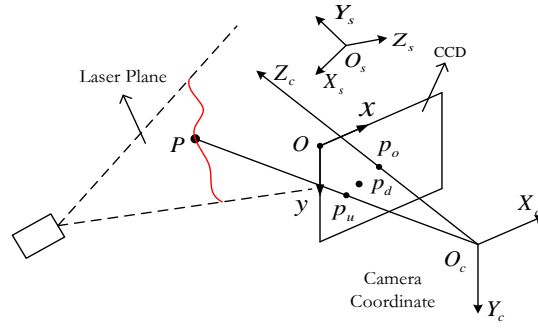


Figure1 Model of vision sensor

Figure 1 shows the line structured light model. $O_s-X_sY_sZ_s$ is the measuring-coordinate of vision sensor. The Origin O_s , the axis O_sX_s and O_sY_s are on the laser plane, O_sZ_s is normal to the laser plane. We set that the point P is on the laser stripe, $O_c-X_cY_cZ_c$ is camera coordinate. $O-xy$ is the image plane. p_o is the principal point of the camera. The point p_u is the ideal mapping point of P . p_d is the undistorted mapping point. $[x_d, y_d]$ is the coordinate of p_d , $[x_u, y_u]$ is the coordinate of p_u , $[x_0, y_0]$ is the coordinate of p_o . The relationship between p_u and p_d is computed as follows:

$$\begin{aligned} x_u &= x_d + \overline{x_d} (k_1 \cdot r_d^2 + k_2 \cdot r_d^4) + [p_1 \cdot (r_d^2 + 2 \cdot \overline{x_d}^2) + 2p_2 \overline{x_d} \overline{y_d}]; \\ y_u &= y_d + \overline{y_d} (k_1 \cdot r_d^2 + k_2 \cdot r_d^4) + [p_2 \cdot (r_d^2 + 2 \cdot \overline{y_d}^2) + 2p_1 \overline{x_d} \overline{y_d}]; \end{aligned} \quad (1)$$

where

$$\overline{x_d} = x_d - x_0, \quad \overline{y_d} = y_d - y_0; \quad r_d^2 = \overline{x_d}^2 + \overline{y_d}^2.$$

$[k_1, k_2, p_1, p_2]$ is the distortion coefficient of camera.

The relationship between P and p_u is as follows:

$$\lambda \cdot \tilde{p}_u = \mathbf{K}_c \cdot [\mathbf{R} \quad \mathbf{T}] \cdot \tilde{P} \quad (2)$$

where λ is a scale factor, \tilde{p}_u is the homogeneous coordinate of p_u , \mathbf{R} is unitary orthogonal matrix, \mathbf{T} is the translation vector, \mathbf{K}_c is the internal matrix of the camera.

By developing the formula (2), the following formula is obtained:

$$\lambda \cdot \begin{bmatrix} x_u \\ y_u \\ 1 \end{bmatrix} = \mathbf{H} \cdot \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \cdot \begin{bmatrix} x_s \\ y_s \\ 1 \end{bmatrix} \quad (3)$$

where λ is a scale factor, \mathbf{H} is the parameter of the line structured-light.

3 Flexible 3d Target theory

3.1 Flexible 3d Target model

Figure 2 describes the established process of flexible 3d target.

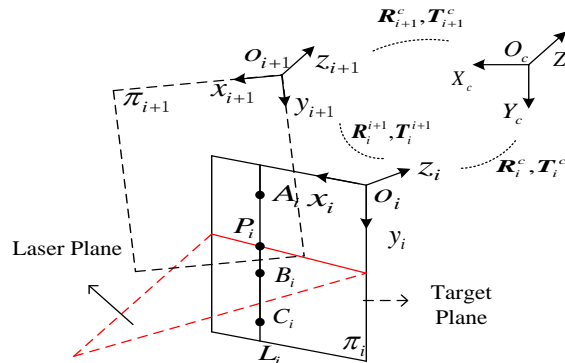


Figure 2 Flexible 3d target

In order to determine the structure light plane, a flexible planar target method is given. Flexible 3d target is formed by moving planar calibration board to different orientations, and the light stripe is projected onto the planar calibration board. We assume that the first target plane is the reference coordinate frame, then establish local coordinate system in every position of the target plane. The point P_i is the intersection of the co-line point and the stripe line in target plane. Then, the point P_i coordinate in local coordinate system is solved based on the invariance of cross ratio [9].

At different position of the target plane, we can resolve the relationship between the camera coordinate frame and the local coordinate frame of the target plane by the world to image co-ordinates, i.e. the camera external parameters. At the i th position of the target plane, the camera external parameters is rotation R_i^c and translation T_i^c . However, the rotation R_i^{i+1} and translation T_i^{i+1} among the adjacent planar target are as follows:

$$\begin{aligned} R_i^{i+1} &= R_{i+1}^c \cdot R_i^c; \\ T_i^{i+1} &= T_{i+1}^c - R_{i+1}^c \cdot R_i^c \cdot T_i^c; \end{aligned} \quad (4)$$

The control point coordinates in local coordinate system are switched to reference coordinate frame via equation (4). So the established process of flexible 3d target is done.

As can be seen above, the established process of flexible 3d target is flexibility, reduces the cost of the calibration equipment and simplifies the calibrating procedure.

3.2 Uniqueness sorting

As shown in Figure 3(a), we use a specifically designed calibration board. In which, the center of every circle is the landmark point. In addition, there are five bigger circles to ensure the uniqueness of landmark order. According to the following principles, the five control points are determined. The first one is that the distance of landmark point between number 2 and number 3 is the minimum, while the distance of control point between number 4 and number 5 is maximal. The second one is that the distance of control point between number 1 and number 3 is greater than that between number 1 and number 2. The last one is the distance of control point between number 3 and number 4 is less than that between number 3 and number 5.

After determining the order of the five control points, we can compute the homography matrix between pixel coordinate system and world coordinate system of calibration board. Then, the centers of other circles are detected using edge detection and ellipse fitting. The homography matrix is used to compute the image coordinate of control point. Finally, the real mapping points are calculated by minimizing the distance between the projective points and the ellipse center coordinates. Figure 3(b) shows the result of coded target points under an arbitrary position of the calibration board.

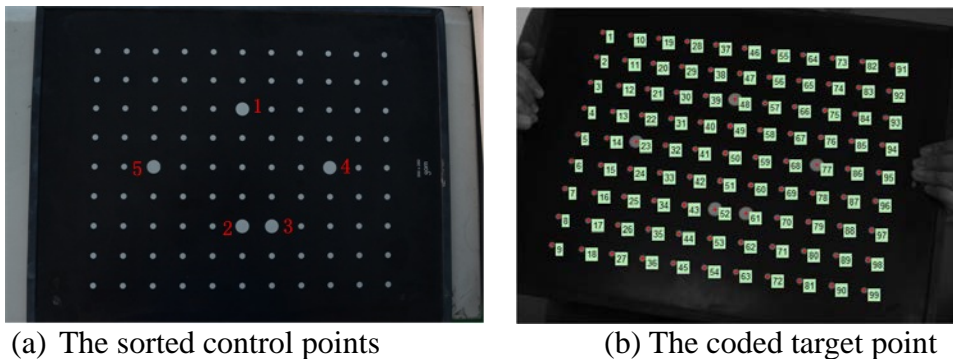


Figure 3 The calibration board

4 Calibration for structure light parameters

4.1 Transformation matrix among coordinate frames

The mapping matrix H of the structure light is the transformation matrix from measuring coordinate to image plane. The transformation relation between the reference coordinate frame and the measuring coordinate frame is as follows:

$$\tilde{P}_s = T_w^s \cdot \tilde{P}_w \quad (5)$$

Where the points \tilde{P}_s and \tilde{P}_w are respectively the homogeneous coordinates of measuring coordinate and the reference coordinate, the transform matrix T_w^c is as follows:

$$T_w^s = \begin{bmatrix} R_w^s & -R_w^s \cdot \tilde{P}_0 \\ 0^T & 1 \end{bmatrix}$$

Let us suppose that the normal vector of the light plane is $n = [n_1, n_2, n_3]^T$, The direction vector of the measuring coordinate system is $z_w = [0, 0, 1]^T$. The rotation axis and rotation angle of the vector n and z_w are respectively:

$$a = (n \times z_w) / \|n \times z_w\|;$$

$$\varphi = \arccos(n \cdot z_w);$$

The rotation matrix R_w^s is expressed by as follows:

$$R_w^s = a \cdot a^T + \cos \varphi (I - a \cdot a^T) + \sin \varphi (I \times a) \quad (6)$$

Where I is an unit matrix, $I \times a$ is the antisymmetric matrix.

4.2 Optimizing the mapping matrix

According to the control points in the light plane and image coordinates, the mapping matrix H is solved by formula (3).

The mapping matrix H is optimized by the nonlinear optimization method. Optimizing the object function is defined as follows:

$$f(H) = \sum_i^{num} (m_i - \hat{m}_i)^T (m_i - \hat{m}_i) \quad (7)$$

Where num is the number of control point, m_i is image point. \hat{m}_i is image point by mapping matrix H with the following expression:

$$\hat{m}_i = \frac{1}{h_3^T} \cdot \begin{bmatrix} h_1^T M_i \\ h_2^T M_i \end{bmatrix} \quad (8)$$

Where $\hat{h}_i (i=1,2,3)$ is the i th row of the matrix H , M_i is the point coordinate in measuring-coordinate.

Then, a nonlinear optimization function is established when the radial distortions are taken into consideration. Finally, the calibration is finished by using the Levenberg-Marquardt (LM) algorithm.

5 Experiment

5.1 Vision sensor calibration

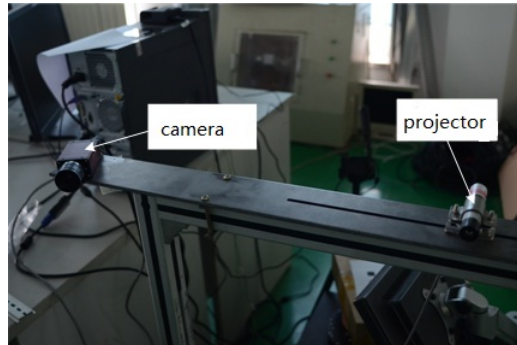


Figure 5 Vision sensor equipment

As shown in Fig 5, the vision sensor experiment equipment consists of a camera with an 8mm

lens and a projector.

Firstly, camera calibration parameter, i.e. intrinsic matrix K_C and distortion matrix k_c are obtained by Zhang[10] method. The result shows that the reprojection error is 0.1522 pixel, with higher accuracy. Figure 6 shows image set for vision sensor calibration.

Then, we set the first image of the image set as a benchmark, then unify target landmark to the base coordinate frame of the flexible 3D target according to the relative position relationship of planar targets in the different positions.

$$K_C = \begin{bmatrix} 2231.076 & 0 & 661.605 \\ 0 & 2232.727 & 494.593 \\ 0 & 0 & 1 \end{bmatrix};$$

$$k_c = [-0.08470 \quad 0.04826 \quad -0.00050 \quad 0.00083];$$

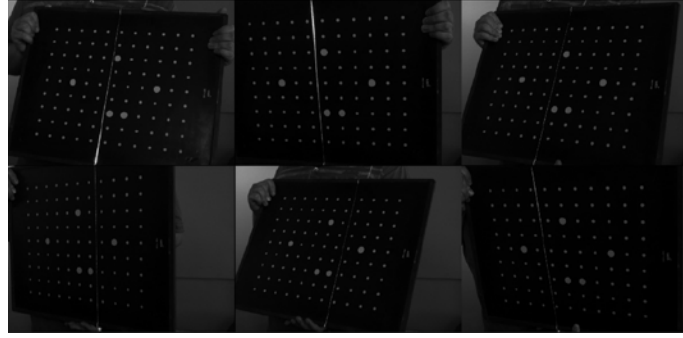


Figure 6 Image set for vision sensor calibration

Fig.7(a) shows the target points in reference coordinate, Fig.7(b) shows the Target points in measuring coordinate, Fig.7(a) shows the normalized image coordinate.

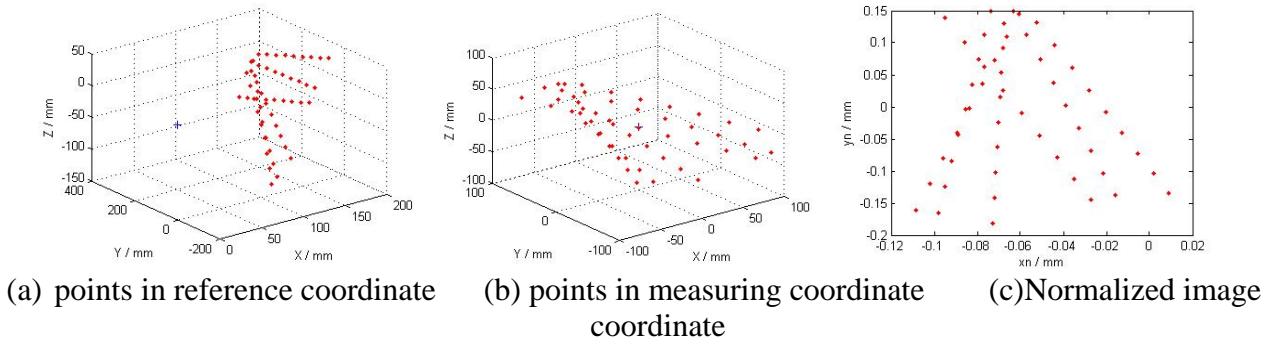


Figure 7 3d coordinate of target points

Finally, the homography matrix H between the light plane and image plane is obtained by equation (7).

$$H = \begin{bmatrix} 1825.3201 & 220.4005 & 94.8310 \\ -349.1362 & 981.9752 & -12.6930 \\ -1.7224 & -0.04176 & 1 \end{bmatrix};$$

Accuracy assessment

The absolute and relative error between the reference values and measured values are employed to evaluate vision sensor calibration accuracy. As is shown in Figure 1, normalized image coordinate, target coordinate and measuring coordinate are given. The absolute and relative errors of distance between the reference values and measured values are shown in Table 2, Sequence pairs represent the first target point and other target point.

Table 1: Target point coordinate values

Sequence	Normalized image coordinate /mm		Target coordinate /mm		Measuring coordinate /mm	
	x_n	y_n	X_s	Y_s	X_s	Y_s
1	-0.0589	-0.1621	158.5291	0	-43.7035	-136.5319
2	-0.0605	-0.1237	158.1646	35	-38.5623	-101.8770
3	-0.0620	-0.0851	157.8626	70	-33.4224	-67.2313
4	-0.0636	-0.0466	157.5114	105	-28.2838	-32.5938
5	-0.0651	-0.0079	157.1460	140	-23.1455	2.0413
6	-0.0667	0.0308	156.7978	175	-18.0067	36.6802
7	-0.0682	0.0696	156.3863	210	-12.8737	71.2793
8	-0.0698	0.1084	155.9595	245	-7.7388	105.8918
9	-0.0713	0.1473	155.5889	280	-2.6090	140.4699

As shown in Table 2, the absolute error is less than 0.1mm. Meanwhile, relative error is less than 0.1%. The experimental results demonstrate the proposed method can obtain higher calibration accuracy to meet detection requirements.

Table2: The error comparison between the reference values and measured values

Sequence pair	Reference value / mm	Measured value / mm	Absolute error	Relative error /%
			/ mm	
(1,2)	35.0019	35.0341	0.0322	0.0920
(1,3)	70.0032	70.0591	0.0559	0.0798
(1,4)	105.0049	105.0756	0.0707	0.0673
(1,5)	140.0068	140.0898	0.0830	0.0592
(1,6)	175.0086	175.1078	0.0992	0.0567
(1,7)	210.0109	210.0856	0.0747	0.0356
(1,8)	245.0135	245.0769	0.0635	0.0259
(1,9)	280.0154	280.0334	0.0180	0.0064

5 Conclusions

A new calibration approach of vision system based on flexible 3d target and invariance of cross ratio is proposed. In the method, flexible 3d target is established. The point coordinates in the light planar are obtained by using the invariance of cross ratio, then converted to sensor measuring coordinate. Finally, vision system calibration parameters are obtained by the nonlinear optimization function. The method generated large number of control points for vision sensor. The experimental results demonstrate that the proposed method can obtain higher calibration accuracy and reduce the calibration cost to adapt to field calibration.

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