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Solving the Camera Intrinsic Parameters with the Positive Tri-prism Based on the Circular Points

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Abstract: This study proposed a method of camera self-calibration with the positive tri-prism. The coordinates of circular points can be obtained through the properties of positive tri-prism. According to the theory of projective transformation, the coordinates of the vanishing points of each edges of positive tri-prism can be obtained. After that, combined with the corollary of Laguerre theorem (the infinity points of two mutually perpendicular lines and the circular points harmonic conjugate), one can obtain the image coordinates of the circular points. By computing coordinates of whole the circular points in an image, according to the constraints on the intrinsic parameters which are established through image of the absolute-conic, we can obtain the intrinsic parameters linearly. The method algorithm has been tested on both computer simulated data and real data. The technique only required single target image and the orientation of camera did not need to be known. The results gained considerable robustness.

Key words: Computer vision, positive tri-prism, camera self-calibration, circular points, harmonic conjugate

INTRODUCTION

Camera calibration is the basic of the computer vision and a key step of three-dimensional reconstruction (Park and Park, 2006; Arif *et al*., 2002). In recent twenty years, it has been researched widely by many people. In general, it can be divided into tradition calibration and self-calibration. Tradition calibration is used widely now. Using the known calibration object as the special reference and the homography which can be got through the relationship of space points and image points, the camera intrinsic parameters can be solved. A flexible new technique for calibration using a simple template of the planar lattice was proposed by Zhang (2000) but this algorithm needs six images at least. Meng and Hu (2003) and others have improved the algorithm provided by Zhang (2000) but in the process of measuring, the accuracy and stability can be influenced by the circle and its actual position. In order to overcome those faults, this study proposed a calibration method based on circular points. Through, this method, by extracting the perpendicular edges from positive tri-prism and using the harmonic conjugate of the midpoint, one could get the vanishing points of each edge, combining with the corollary of Laguerre theorem (Hartley and Zisserman, 2004; Xue-Cong *et al*., 2012). Then we obtained the circular points' image coordinates according to the constraint relationship of vanishing point and circular point. Then the constraint on the intrinsic parameters was established through images of the circular points. At last, all the intrinsic parameters could be determined linearly. In addition, calibration object in this method was simple and easy to implement and it needed only one image which had a good accuracy.

BASIC PRINCIPLES

Camera model: In this study, a camera is modeled by the usual pinhole (Ma and Zhang, 1998; Pu *et al*., 2011), P is any point in the space and its world coordinate is $M = (X_w, Y_w, Z_w, 1)$. The image coordinate p of p is $m = (u, v, 1)^T$. The relationship between M and m is:

$$\lambda\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}f_u & s & u_0\\0 & f_v & v_0\\0 & 0 & 1\end{bmatrix}[R\ \ T]\begin{bmatrix}x_w\\y_w\\z_w\\1\end{bmatrix}=K[R\ \ T]\begin{bmatrix}x_w\\y_w\\z_w\\1\end{bmatrix} \tag{1}$$

where, λ is an arbitrary scale factor, K is called the camera intrinsic matrix where (f_u, f_v) are the scale factors in image u and v axes, s is the skewness of the two axes and (u_0, v_0) is the coordinate of the principal point (R, T) is called the

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extrinsic parameter matrix, whose rotation and translation are relate the word coordinate system to the camera coordinate system (Fig. 1).

Basic knowledge of circular points: Let π be any of a finite plane in space, o-xy is called the Cartesian coordinate system through the coordinate origin o, z is vertical the plane of o-xy, then, establish the coordinate system of o-xyz. So the equation of the π is z = 0, p is any point in the space, of which homogeneous coordinate is $(x, y, z, w)^T$. The equation of the line at infinity on the plane π is as follows:

$$\begin{cases} w = 0 \\ z = 0 \end{cases} \tag{2}$$

Suppose, c is any circle in π, of which the center coordinate is $(x_0, y_0, 0, w)$ and the radius is R, then the circle can be described by the following equation:

$$\begin{cases} (x - x_0 w)^2 + (y - y_0 w)^2 = w^2 R^2 \\ z = 0 \end{cases} \tag{3}$$

It is easy to know, the circular points of the plane are the intersection between the line at infinity and any circle (Xue-Cong *et al.*, 2012; Zhao and Lv, 2012), so the coordinates of the circular points are $I = (1\ i\ 0\ 0)^T$, $J = (1\ \ -i\ 0\ 0)^T$ from the Eq. 2 and 3, where I, J are a pair of harmonic conjugate points in the absolute conic of the plane at infinity. According to the photography geometry, their images are denoted by the following equation:

$$\begin{cases} m_i = (x_1 + x_2 i, y_1 + y_2 i, 1)^T \\ m_j = (x_1 - x_2 i, y_1 - y_2 i, 1)^T \end{cases}$$

It is easy to prove that the circular points m_i, m_j are a pair of harmonic conjugate points in the absolute conic ω of plane at infinity. Because the circular points are the points on the absolute conic ω and the image of ω is $K^{-T} K^{-1}$, m_i, m_j are a pair of points in $K^{-T} K^{-1}$ and satisfy the constraint as follows:

$$\begin{cases} m_i^T K^{-T} K^{-1} m_i = 0 \\ m_j^T K^{-T} K^{-1} m_j = 0 \end{cases} \tag{4}$$

SOLVING INTRINSIC PARAMETERS WITH CIRCULAR POINTS

Computing the vanishing points of each edges: The positive tri-prism is composed of two triangles and three squares, which is shown in Fig. 2.

As is shown in Fig. 2, ABC and A_1 B_1 C_1 are positive triangles, the sides of the positive tri-prism are squares, D, E, F, G, are the midpoints of BC, AD, AC, BF, CC_1. The and are the center of BCC_1 and ACC_1A_1. Let a, b, c, d, e, f, g be the image points of A, B, C, D, E, F, G and p_1, p_2, p_3, p_4 be the vanishing points of ad, bc, bf, ac.

According to the projective transformation and the invariance of cross-ration, we have:

$$\begin{cases} (AD, EP_{1\infty}) = (ad, ep_1) = -1 \\ (BC, DP_{2\infty}) = (bc, dp_2) = -1 \\ (BF, GP_{3\infty}) = (bf, dp) = -1 \\ (AC, FP_{4\infty}) = (ac, fp_4) = -1 \end{cases} \tag{5}$$

Let the coordinate of a, b, c, d, e, f, g be (u_0, v_a), (u_b, v_b), (u_c, v_c), (u_d, v_d), (u_e, v_e), (u_f, v_f) (u_g, v_g) and the coordinate of p_1, p_2, p_3, p_3 be (u_{p1}, v_{p1}), $u_{p2}, v_{p2})$, (u_{p3}, v_{p3}), (u_{p4}, v_{p4}). According to Eq. 5, the coordinates of p_1, p_2, p_3 and p_4 can be obtained. In BCC_1B_1, $p_{2\infty}$, $p_{3\infty}$, $p_{3\infty}$, $p_{4\infty}$ are the vanishing point coordinates of BC, CC_1, B_1C. Similarly, the coordinate of p_2, p_5, P_8, p_9 can be obtained. In ACC_1 A_1, $p_{4\infty}$, $p_{5\infty}$, $p_{6\infty}$, $p_{7\infty}$ are the vanishing point coordinates of AC, CC_1, AC_1, A_1C. Similarly, the coordinate of p_4, p_5, p_6, p_7 can be obtained.

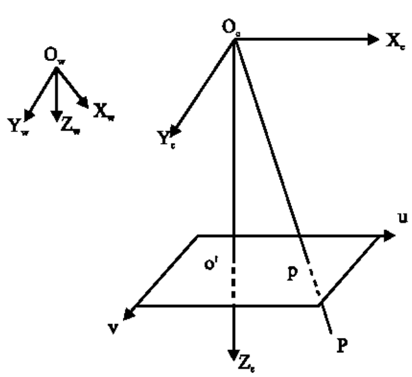

Fig. 1: Camera model

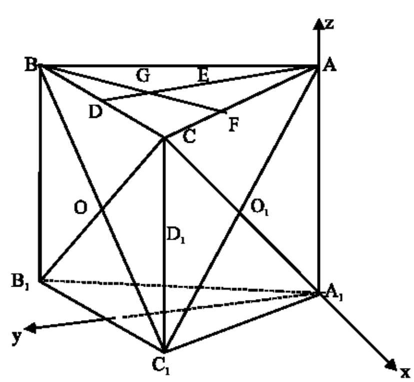

Fig. 2: The positive tri-prism

Solving the image coordinates of circular points: Suppose the coordinates of circular points on the plane of triangle are:

$$\begin{cases} m_{i1} = (x_1 + x_2 + x_2 i,\ y_1 + y_2 i) \\ m_{j1} = (x_1 - x_2 i, y_1 - y_2 i) \end{cases} \quad (6)$$

In Fig. 2, ABC is triangle, D and F are the midpoint of edge and BC, and AC, are the midpoints of edge AD and BF, AD⊥BC, BF⊥AC. According to the corollary of Laguerre theorem (The points at infinity of two mutually perpendicular lines and the circular points harmonic conjugate), we have:

$$\begin{cases} (p_1 p_2, m_{i1}, m_{j1}) = -1 \\ (p_3 p_4, m_{i1}, m_{j1}) = -1 \end{cases} \quad (7)$$

In ACC_1A_1, F and D_1 are the midpoints of AC and CC_1, suppose the coordinates of circular points on the plane of square ACC_1A_1 are m_{i2}, m_{j2}, according to $AC \perp CC_1$ and $AC_1 \perp A_1C$, we have:

$$\begin{cases} (p_4 p_5, m_{i2}, m_{j2}) = -1 \\ (p_6 p_7, m_{i2}, m_{j2}) = -1 \end{cases} \quad (8)$$

Repeat the above steps, suppose the coordinates of circular points on the plane of square BCC_1B_1 are m_{i3}, m_{j3}, similarly, we have:

$$\begin{cases} (p_2 p_5, m_{i3} m_{j3}) = -1 \\ (p_8 p_9, m_{i3} m_{j3}) = -1 \end{cases} \quad (9)$$

The coordinates of circular points, m_{i1}, m_{j1}, m_{i2}, m_{j2}, m_{i3}, m_{j3}, can be solved from Eq. 7-9.

Solving the intrinsic parameters: The circular points are the points on the absolute conic ω and the image of the ω $K^{-T}K^{-1}$ is , we have:

$$m^T_{i1} K^{-T} K^{-1} m_{i1} = 0,\ m^T_{j1} K^{-T} K^{-1} m_{j1} = 0 \quad (10)$$

$$m^T_{i2} K^{-T} K^{-1} m_{i2} = 0,\ m^T_{j2} K^{-T} K^{-1} m_{j2} = 0 \quad (11)$$

$$m^T_{i3} K^{-T} K^{-1} m_{i3} = 0,\ m^T_{j3} K^{-T} K^{-1} m_{j3} = 0 \quad (12)$$

From Eq. 10-12, according to the property of circular points, we have:

$$\mathrm{Re}\,(m^T_{i1} K^{-T} K^{-1} m_{i1}) = 0,\ \mathrm{Im}\,(m^T_{i1} K^{-T} K^{-1} m_{i1}) = 0 \quad (13)$$

$$\mathrm{Re}\,(m^T_{i2} K^{-T} K^{-1} m_{i2}) = 0,\ \mathrm{Im}\,(m^T_{i2} K^{-T} K^{-1} m_{i2}) = 0 \quad (14)$$

$$\mathrm{Re}\,(m^T_{i3} K^{-T} K^{-1} m_{i3}) = 0,\ \mathrm{Im}\,(m^T_{i3} K^{-T} K^{-1} m_{i3}) = 0 \quad (15)$$

Suppose:

$$C = K^{-T} K^{-1} = \begin{pmatrix} c_1 & c_2 & c_3 \\ c_2 & c_4 & c_5 \\ c_3 & c_5 & c_6 \end{pmatrix}$$

can be obtained according to Eq. 13-15, then using the method of Zhang (2000), we can get all of the intrinsic parameters.

EXPERIMENTAL RESULTS

The steps of algorithm:

Step 1: Make a positive tri-prism and take a few images of it under different orientations by moving either the camera or the positive tri-prism (Song *et al*., 2011)

Step 2: Detect the feather points (Harris and Stephens, 1988; Amirani *et al*., 2008; Vyawahare and Rao, 2011; Ahmadi *et al*., 2008)

Step 3: Get the vanishing points of each edge through Eq. 5

Step 4: Solve the circular points of each plane through Eq. 6-9

Step 5: Solve the image of the using the Eq. 13-15

Step 6: Solve the five intrinsic parameters using the method of Zhang (2000)

Computer simulation: The simulated camera had the following property: f_u = 1000, f_v = 800, s = 0.2, u_0 = 640, v_0 = 480 and T1 = [20, 80, 50], R1 = [-0.23565977164177; 0.76782262015126; -0.59574566386488; -0.65963965913261 -0.57654953735323 -0.48214743707417; -0.71368059531499 0.27935471172299]. We varied the noise level from pixels to pixels. For each noise level, independent trials were performed and the results showed the average, as we can see from Table 1. And the standard deviations of the five

Table 1: The results under each noise level

σ	f_u	f_v	s	u_0	v_0
0	1000.0000	800.0000	0.2000	639.9759	480.0000
0.1	999.9999	799.9999	0.1999	639.9750	479.9990
0.2	999.9999	799.9999	0.1999	639.9676	479.9917
0.3	1000.0000	800.0000	0.2000	639.9678	479.9918
0.4	999.9999	799.9999	0.1999	639.9593	479.9833
0.5	1000.0000	800.0000	0.2000	639.9551	479.9792
0.6	1000.0000	800.0000	0.2000	639.9531	479.9771
0.7	999.9999	799.9999	0.1999	639.9468	479.9708
0.8	1000.0000	800.0000	0.2000	639.9426	479.9666
0.9	999.9999	800.0000	0.2000	639.9484	479.8899
1.0	999.9999	799.9999	0.1999	639.9807	480.0048

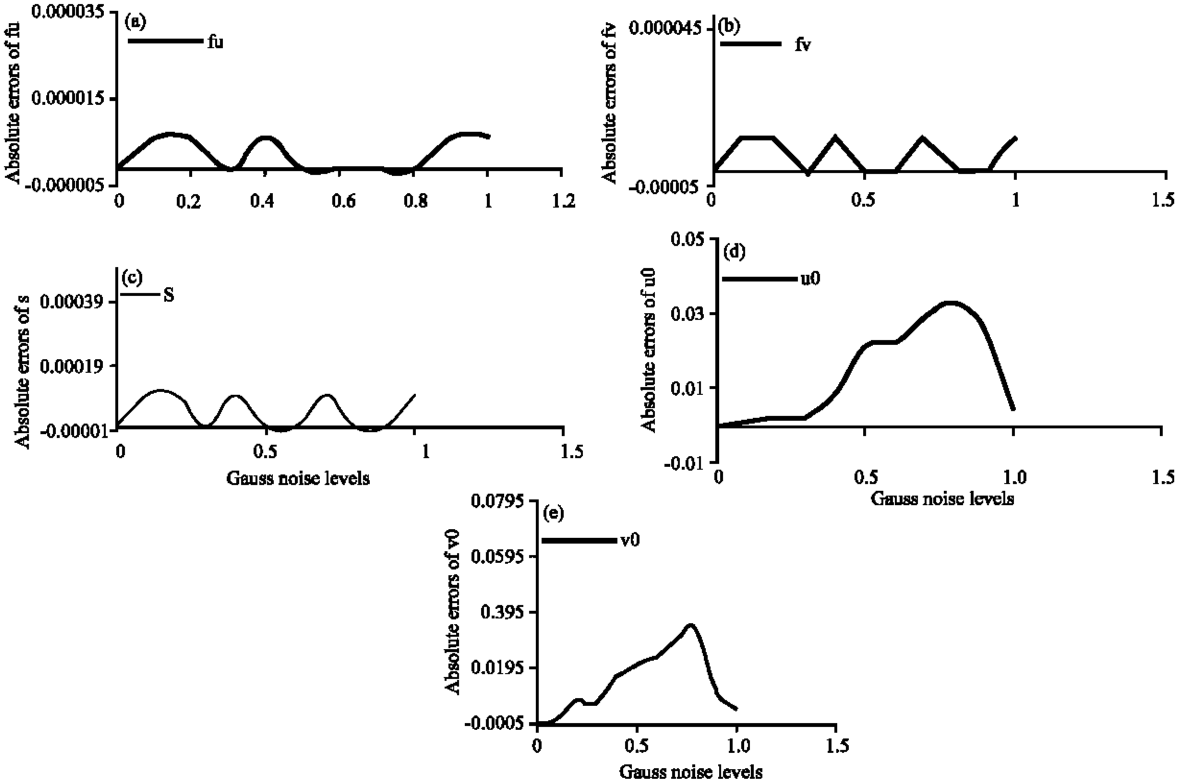

Fig. 3(a-e): Absolute errors of intrinsic parameters under different noise level

Fig. 4: The real image of calibration object

intrinsic parameters at each different noise level were computed, which were shown in Fig. 3.

Real data: The edge length of the calibration object was 7 cm, which were shown in Fig. 4 and the image size was 640×480. In order to compare the results, the DLT algorithm has been done (Hartley and Zisserman, 2004), too. The results were shown in Table 2.

Table 2: The comparison of the results of the two approaches

Calibration method	f_u	f_v	u_0	v_0	s
The algorithm of this study	683.31	749.38	235.62	310.99	-10.46
DLT algorithm	724.87	722.09	235.37	308.59	-8.46

CONCLUSIONS

In this study, we proposed a method of camera calibration using the special relationships between the edges of the positive tri-prism. According to photography geometry, the image coordinates of circular points were solved. Computer simulation and real data proved the accuracy and robustness of this method. And the proposed algorithm had a considerable flexibility compared with classical algorithm.

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