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Camera Calibration in Binocular Stereo Vision of Moving Robot

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Abstract **–A method for camera calibration in robotic binocular stereo vision is introduced in this paper. Camera calibration is a necessary step in 3D computer vision in order to extract metric information from 2D images. Being different from with single camera calibration, binocular stereo vision system not only need to ascertain intrinsic parameters, but also the relative position relation of two cameras. We compute it in two steps: first, we compute the intrinsic and initial extrinsic parameters of camera by Zhang Plane-based Calibration Method; Second, we suppose the intrinsic parameter is invariable, camera's moving parameters can be computed by self-calibration method, through finding the stereo matching point and calculating the fundamental matrix and essential matrix.**

Index Terms – binocular stereo vision, camera calibration, Zhang Plane-based calibration, self-calibration.

I. Introduction

In recent years, there has been considerable interest in the research of intelligent humanoid robotic vehicles with the development of Distributed Artificial Intelligence. To realize a humanoid robot in real-world and unknown environment, the vision system is requested to get three-dimensional information of object, which is important for a robot that behaves in a real world. It is a seemingly effortless process that requires no conscious thought for the human beings, but a difficult computational problem for machines.

Binocular stereo vision is an important branch of computer vision. It means two or one camera in different places taking a photo of the same scene through translating or rotating. A basic problem in Binocular stereo vision is recovering 3D construction of a world scene or object from a pair of images. Camera calibration is a necessary process in this problem. It determines the internal camera geometric and optical characteristics (intrinsic parameters) and/or the 3D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters).

Much work has been done in camera calibration. We can classify those techniques roughly into two categories: Photogrammetric calibration [1,2] and Self-calibration [3,4]. Other techniques exist: vanishing points for orthogonal directions, and calibration from pure rotation[6].

Being different from with single camera calibration, binocular stereo vision system not only need to ascertain intrinsic parameters, but also the relative position relation of two cameras. Using traditional camera calibration technique to calibrate left and right camera and computer intrinsic or extrinsic parameters is a simple method, but it is only for static camera system. For the moving robots, the positional relation between cameras is volatile, on the other hand, vision system need to offer three-dimensional information about scene. So relative to world coordinate, its position should be fathomable.

In this paper, the camera calibration of moving robot is computed in two steps: first, we compute the intrinsic and initial extrinsic parameters of camera by Zhang Plane-based Calibration Method; Second, we suppose the intrinsic parameter is invariable, camera's moving parameters can be computed by self-calibration method, through finding the stereo matching point and calculating the fundamental matrix and essential matrix. A method for self-calibration of a camera, which is free to rotate and change its intrinsic parameters, can be finned in [5].

II. The Imaging Model Of Camera

Commonly we need define three main frames of coordinate before analyzing the image model:

1) In the world coordinate system, a 3D point is denoted as (X_w, Y_w, Z_w).

2) The coordinate system of camera: a 3D point is denoted as (X_c, Y_c, Z_c) in this coordinate system.

3) The coordinate system of image: the point of intersection between light axis and image plane is defined as its origin point, and supposed that its coordinate in *Ouv* coordinate system is (u_0, v_0) and the physic dimension of every pixel in x and y direction are dx and dy respectively, so the relation of every pixel between these two coordinate systems are as follows:

$$u = x/dx + u_0 \qquad v = y/dy + v_0$$

Denoting in homogenous equation as:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \frac{1}{dx} & 0 & u_0 \\ 0 & \frac{1}{dy} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{1}$$

The relation between camera coordinate system and world coordinate system can be described by rotation matrix R and translation matrix t. So, a random point M in space with different coordinate description (X_w, Y_w, Z_w) and (X_c, Y_c, Z_c), their homogenous coordinates can be written as:

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{2}$$

where R is 3×3 orthogonal identity matrix, t is three-dimensional translation vector.

III. FUNDAMENTAL MATRIX AND ESSENTIAL MATRIX

Fundamental matrix and essential matrix are two basic geometrical relations in nonstandard structural model. A simple presentation will be given in this section for the purpose of discussion in section 4.

A. Fundamental Matrix

The positional relation between the left and right camera can be described by a translation matrix t and a rotation matrix R . We define the origin of coordinate system in the center of left camera. On the assumption that left and right camera's calibration matrixes are K and K' , so to a arbitrary point M in the scene, its left projection u and right projection u' can be written as:

$$u = [K \mid 0] \begin{bmatrix} M \\ 1 \end{bmatrix} = KM \tag{3}$$

$$u' = [K'R \mid -K'Rt] \begin{bmatrix} M \\ 1 \end{bmatrix} = K'(RM - Rt) = K'M' \tag{4}$$

We can know, M , M' and t are coplanar. Using suffix L and R to distinguish the coordinates of two cameras, so M'_R instead of coordinate vector M' which is relative to right camera's coordinate system. Actually, it is a coordinate rotation, we can describe the free vector M'_R by left camera:

$$M'_R = RM'_L \text{ or } M'_L = R^{-1}M'_R \tag{5}$$

The equation representing the coplanar property can be written as:

$$M^T{}_L(t \times M'_L) = 0 \tag{6}$$

Instead of $M_L = K^{-1}u$ 、 $M'_R = (K')^{-1}u'$ and $M'_L = R^{-1}(K')^{-1}u'$, the equation can be rewritten as:

$$(K^{-1}u)^T(t \times R^{-1}(K')^{-1}u') = 0 \tag{7}$$

If translation vector $t = [t_x, t_y, t_z]^T$, $t \neq 0$, with it we can establish a antisymmetric matrix $S(t)$:

$$S(t) = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \tag{8}$$

We have known the rank of S is the number of liner independence rows in matrix S , so only if $t \neq 0$, the rank of S is 2. Using two matrixes replace two vectors in multiplication, for every regular matrix A , we can get:

$$t \times A = S(t)A$$

So, equation (7) can be rewritten as:

$$(K^{-1}u)^T(S(t)R^{-1}(K')^{-1}u') = 0 \tag{9}$$

or described as:

$$u^T(K^{-1})^T S(t)R^{-1}(K')^{-1}u' = 0 \tag{10}$$

Now, we can get a single matrix F which is fundamental matrix of two images:

$$F = (K^{-1})^T S(t)R^{-1}(K')^{-1} \tag{11}$$

Substitute F for (10), the relation of relative points in two images is given as:

$$u^T F u' = 0$$

It is obvious that if the problem of fundamental matrix has been solved, the fundamental matrix includes all the information of a pair of images, which can be recovered. We will discuss it detailedly in section 4.

B. Essential Matrix

To computer a camera's moving parameters in space or relative positional parameters of two cameras is a valuable work for robot vision. Luckily, we can get all of these through essential matrix.

If we have known cameras' calibration matrixes are K and K' , we can standardize the measure in left and right images. The calibration matrix give a relation as:

$$\breve{u} = K^{-1}u \, , \quad \breve{u}' = (K')^{-1}u' \tag{12}$$

where $\breve{u}$ is standard left projection, $\breve{u}'$ is standard right projection.

Through (10)(12), we can get:

$$\breve{u}^T S(t)R^{-1}\breve{u}' = 0 \tag{13}$$

Also, it is rewritten as:

$$\breve{u}^T E \breve{u}' = 0$$

where $E = S(t)R^{-1}$ is essential matrix.

It is another bilinear relation between two images. The essential matrix E include all the information of camera's moving from one position to another. The rotation matrix and translation matrix can be computed if E has been calculated.

To a moving robot, its vision system need to offer three-dimensional information about the scene, but the robot's position relative to world coordinate changes at all time. In this paper, we will use self-calibration method to calculate the camera's moving parameters based on fundamental matrix and essential matrix.

IV. ZHANG PLANE-BASED CALIBRATION METHOD

Zhang recently proposed a flexible camera calibration technique by replacing an expensive classical calibration grid with a planar pattern [6]. Zhang's technique needs to print a dotted sheet (see Fig. 1) as the model plane, and the Euclidean coordinates of every dot on the model plane should be measured accurately. After taking a few images of the model plane at different orientations by moving either the model plane or the camera, the homographies between the model plane and its projections can be determined, and then camera's intrinsic parameters can be derived linearly from these homographies. Zhang's technique is flexible and cheap, its accuracy is generally higher than self-calibration.

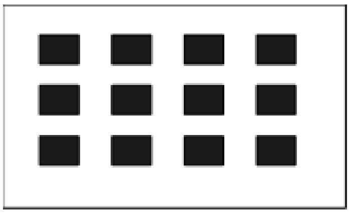


Fig. 1 Zhang's planar pattern

The basic steps of this method are as follows: print a chessboard pane picture and paste it on a plane, shoot more than 3 model images from different angels, detect the feature points from every image, calculate the plane projection matrix H for every image through the detected points, at last determine the parameters of camera.

Supposed that the model plane coincides with the plane in the world coordinate system where $Z=0$. K indicates the internal parameter matrix of the camera, r_i is the i^{th} vector of R, for every point in the model plane we have

$$s\begin{bmatrix}u\\v\\1\end{bmatrix}=K\begin{bmatrix}r_1 & r_2 & r_3 & t\end{bmatrix}\begin{bmatrix}X\\Y\\0\\1\end{bmatrix}=K\begin{bmatrix}r_1 & r_2 & t\end{bmatrix}\begin{bmatrix}X\\Y\\1\end{bmatrix} \tag{14}$$

Let $H=K\begin{bmatrix}r_1 & r_2 & t\end{bmatrix}$, so we get a homography H between the point in model plane and its corresponding image point, if known the coordinate of the point in model plane, we can compute the homography H.

For $s\begin{bmatrix}u\\v\\1\end{bmatrix}=H\begin{bmatrix}X\\Y\\1\end{bmatrix}$, Let $H=\begin{bmatrix}h_{11} & h_{12} & h_{13}\\ h_{21} & h_{22} & h_{23}\\ h_{31} & h_{32} & 1\end{bmatrix}$

We have

$$\begin{cases}uXh_{31}+uYh_{32}+u=h_{11}X+h_{12}Y+h_{13}\\ v_{31}Xh+vYh_{32}+v=h_{21}X+h_{22}Y+h_{23}\end{cases} \tag{15}$$

Let

$$h'=\begin{bmatrix}h_{11} & h_{12} & h_{13} & h_{21} & h_{22} & h_{23} & h_{31} & h_{32} & 1\end{bmatrix}^T$$

We have

$$\begin{bmatrix}X & Y & 1 & 0 & 0 & 0 & -uX & -uY & -u\\ 0 & 0 & 0 & X & Y & 1 & -vX & -vY & -v\end{bmatrix}h'=0 \tag{16}$$

We can detect some feature points in one image, then we have $Sh'=0$, through computing these equations by using least square method, we can get h' and H.

After we get the homography matrix, the next is to compute the internal parameter.

Let's define every row of H as h_i, then we have

$$\begin{bmatrix}h_1 & h_2 & h_3\end{bmatrix}=\lambda K\begin{bmatrix}r_1 & r_2 & t\end{bmatrix} \tag{17}$$

Because r_1 and r_2 are orthonormal, we have

$$h_1^T K^{-T}K^{-1}h_2=0$$
$$h_1^T K^{-T}K^{-1}h_1=h_2^T K^{-T}K^{-1}h_2$$

Let $B=K^{-T}K^{-1}=\begin{bmatrix}B_{11} & B_{12} & B_{13}\\ B_{21} & B_{22} & B_{23}\\ B_{31} & B_{32} & B_{33}\end{bmatrix}$

$$=\begin{bmatrix}\frac{1}{\alpha^2} & -\frac{\gamma}{\alpha^2\beta} & \frac{v_0\gamma-u_0\beta}{\alpha^2\beta}\\ -\frac{\gamma}{\alpha^{2\beta}} & \frac{\gamma^2}{\alpha^2\beta^2}+\frac{1}{\beta^2} & -\frac{\gamma(v_0\gamma-u_0\beta)}{\alpha^2\beta^2}-\frac{v_0}{\beta^2}\\ \frac{v_0\gamma-u_0\beta}{\alpha^2\beta} & -\frac{\gamma(v_0\gamma-u_0\beta)}{\alpha^2\beta^2}-\frac{v_0}{\beta^2} & \frac{(v_0\gamma-u_0\beta)^2}{\alpha^2\beta^2}+\frac{v_0^2}{\beta^2}+1\end{bmatrix} \tag{18}$$

Note that B is symmetric, which is defined by a 6D vector

$$b=\begin{bmatrix}B_{11} & B_{12} & B_{22} & B_{13} & B_{23} & B_{33}\end{bmatrix}^T$$

Let the ith column vector of H be

$$h_i=\begin{bmatrix}h_{i1} & h_{i2} & h_{i3}\end{bmatrix}^T,$$

then we have

$$h_i^T Bh_j=V_{ij}^T b \quad \text{with}$$

$$V_{ij}=\begin{bmatrix}h_{i1}h_{j1} & h_{i1}h_{j2}+h_{i2}h_{j1} & h_{i2}h_{j2} & h_{i3}h_{j1}+h_{i1}h_{j3} & h_{i3}h_{j2}+h_{i2}h_{j3} & h_{i3}h_{j3}\end{bmatrix}^T$$

then we write an equation about B:

$$\begin{bmatrix}V_{12}^T\\ V_{11}^T-V_{22}^T\end{bmatrix}b=0 \tag{19}$$

If there are n images, we have such equations through (19):

$$Vb=0 \tag{20}$$

where V is a $2n\times 6$ matrix.

We can calculate b and B from (18). The internal parameters can be obtained by using Choleski decomposition.

$$\begin{cases}v_0=(B_{12}B_{13}-B_{11}B_{23})/(B_{11}B_{22}-B_{12}^2)\\ \lambda=B_{33}-[B_{13}^2+v_0(B_{12}B_{13}-B_{11}B_{23})]/B_{11}\\ \alpha=\sqrt{\lambda/B_{11}}\\ \beta=\sqrt{\lambda B_{11}/(B_{11}B_{22}-B_{12}^2)}\\ \gamma=-B_{12}\alpha^2\beta/\lambda\\ u_0=\gamma v_0/\alpha-B_{13}\alpha^2/\lambda\end{cases} \tag{21}$$

where λ is an arbitrary proportional factor of $B=\lambda K^{-T}K$.

According to the following formulae, the external parameters from different angles of view can be computed by using the internal parameter K and plane projection matrix H,

$$\begin{cases}r_1=\lambda A^{-1}h_1\\ r_2=\lambda A^{-1}h_2\\ r_3=r_1\times r_2\\ t=\lambda A^{-1}h_3\\ \lambda=1/\left\|A^{-1}h_1\right\|=1/\left\|A^{-1}h_2\right\|\end{cases} \tag{22}$$

V. Estimation Of The External Parameters

In section 1,we have known the relation can be described by a rotation matrix and a translation matrix. These matrixes also can be computed after the estimation of the fundamental matrix and essential matrix. Unlike general motion, stereo vision assumes that there are only two shots of the scene. In principle, then, one could apply stereo vision algorithms to a structure from motion task. The epipolar geometry describes two-view projective geometry and can be expressed in terms of the fundamental matrix. In other words, the fundamental matrix contains all geometric information necessary for establishing point correspondences between two images, from which projective reconstruction of the scene or object can be inferred. Therefore, projective reconstruction for two views becomes a problem of estimating the fundamental matrix.

The essential matrix is independent of camera's intrinsic parameters, but has a relation with camera's rotation matrix and translation matrix. We can obtain the essential matrix E through the fundamental matrix F and the calibration matrix K . Their relation is shown as follows:

$$E = K^T F K \tag{23}$$

We have already known that $E = RS(t)$, where $S(t)$ is a dissymmetry matrix which is determined only by vector t . It shows that the essential matrix is the product of an orthogonal matrix and a dissymmetry matrix, according to some related literatures, this kind of matrix can get a D matrix which certainly satisfies that it have two positive values and a zero after SVD decomposition. But this is true only under the ideal state. Actually matrix E cannot satisfy this condition due to the noise and some other disturbances while calculating. So we should modify it at first, Refer to method of Hartley, supposed that we have $E = UDV^T$ after SVD, where $D = diag(r,s,t)$ with $r \ge s \ge t$, let $k = (\mathrm{r}+\mathrm{s})/2$, we have a new diagonal matrix $D' = diag(k,k,0)$, replace D by D' , then we have $E' = UD'V^T$. Then we get two unitary matrix U and V by using SVD to this new essential matrix.

Let $$G = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

So the rotation matrix can be computed: $R = UGV^T$ or $R = UG^T V^T$.

Without regard to scale, the vector t is definite. If we limit $\|t\| = 1$, we can obtain t :

$$t = U\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \text{ or } t = U\begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \tag{24}$$

The scene shot by the camera is always in front of the camera, in other words, the calculated Z coordinate of the space point in coordinate system of camera should be positive, we can obtain R and t exclusively.

Concrete method for computing the Z coordinate is introduced in [9]. P is a point in the scene, its coordinates in two camera's coordinate systems are (X_1, X_2, X_3) and (X_1', X_2', X_3') . After projection, its coordinates in each image plane are:

$$\begin{aligned} (x_1, x_2, 1) &= (X_1/X_3, X_2/X_3, 1) \\ (x_1', x_2', 1) &= (X_1'/X_3', X_2'/X_3', 1) \end{aligned} \tag{25}$$

Suppose that the relation between two view points is defined by rotation matrix R and translation matrix t , we define two coordinates (X_1, X_2, X_3) and (X_1', X_2', X_3') as vector X and X' ,the relation should be written as:

$$X' = R(X - t) \tag{26}$$

From (25) and (26) we can know:

$$x_1' = \frac{R_1 \cdot (X-t)}{R_3 \cdot (X-t)} = \frac{R_1 \cdot (x - t/X_3)}{R_3 \cdot (x - t/X_3)} \tag{27}$$

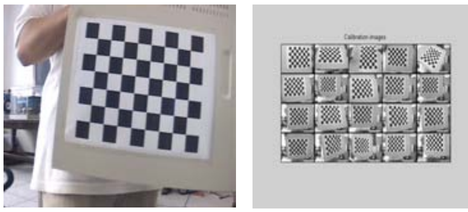
where R_i is the *ith* row vector of R , $x = (x_1, x_2, 1)^T$. It can be rewritten as: $X_3 = \dfrac{(R_1 - x_1' R_3) \cdot t}{(R_1 - x_1' R_3) \cdot x}$ (28)

VI. Experimental Results

Based on the Zhang Plane-based Calibration Method, we calibrate the camera used in our experiment. All the calibration functions are Matlab functions from Internet offered by doctor Jean-Yves Bouguet in Caltech University, America[10]. We use a 19×7 black-and-white graph template and the physical dimension of every little pane is 3cm×3cm. The main steps are as follows:

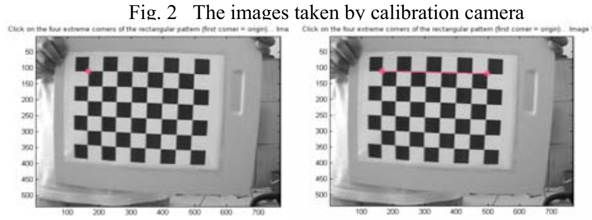
First, we get the images of template in different positions. In our experiment, we use 20 images. You can see one of them in Fig. 2.

Second, we need to ascertain valid areas of the image in some key points, than detect the intersection points of each square in valid area. You can see in Fig. 3 and Fig.4.

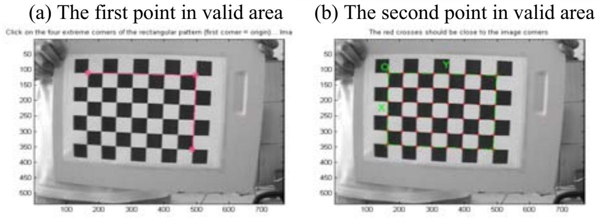


(a) one image taken by calibration camera (b) 20 images loaded by calibration program

Fig. 2 The images taken by calibration camera



(a) The first point in valid area (b) The second point in valid area



(c) The third point in valid area (d) The forth point in valid area

Fig.3 The process of ascertain valid areas

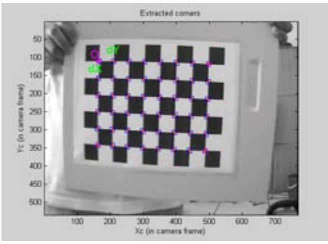


Fig.4 The calibration program get the boundary points through image processing technique

The third, calculate the camera's essential parameters through the laws of perspective transpositional matrix:

Calibration parameters after initialization:

Focal Length:

$$fc = [816.97974 \quad 814.86529] \pm [5.44167 \quad 5.47724]$$

Principal point:

$$cc = [384.09035 \quad 234.27492] \pm [7.44820 \quad 6.87201]$$

Skew:

$$alpha\_c = [0.00000] \pm [0.00000]$$

So,

$$angle \quad of \quad pixel \quad axes = 90.00000 \pm 0.00000 \deg rees$$

Distortion:

$$kc = [-0.43205 \quad 0.62119 \quad -0.00039 \quad 0.00033 \quad 0.00000]$$
$$\pm [0.02213 \quad 0.11315 \quad 0.00162 \quad 0.00115 \quad 0.00000]$$

Pixel error:

$$err = [0.47812 \quad 0.39914]$$

where fc is focal length with the units of pixel; Here, the focal length is 816.97974 which is calculated by horizontal data of image while 814.86529 by vertical data. The errors are 5.44167 and 5.47724 respectively. Obviously, two focal lengths are almost equal and the pixel of image plane is square. For the nominal value is 8cm, the proportional factors in horizontal and vertical are about 0.01cm/pixel. cc is primary point or the centre of image. The centre of image is $(384.09035, \quad 234.27492)$ and the maximal error is $(7.44820, \quad 6.87201)$. $alpha\_c$ is aberrant angle between x-axis and y-axis in pixel coordinate system. Here, the measured value is 0 degree, so the angle of x-axis and y-axis in relevant pixel coordinate system is 90 degrees. kc is radial and normal coefficients of skew in horizontal and vertical directions. The unit of it is pixel.

The last step is optimizing the camera parameters based on the initializing value above.

Calibration results after optimization (with uncertainties):

Focal Length:

$$fc = [807.82866 \quad 806.10299] \pm [3.33520 \quad 3.33104]$$

Principal point:

$$cc = [382.32256 \quad 233.49004] \pm [5.01932 \quad 4.43048]$$

Skew:

$$alpha\_c = [0.00000] \pm [0.00000]$$

$$angle \quad of \quad pixel \quad axes = 90.00000 \pm 0.00000 \deg rees$$

Distortion:

$$kc = [-0.36978 \quad 0.20033 \quad -0.00004 \quad 0.00006 \quad 0.00000]$$
$$\pm [0.01224 \quad 0.05682 \quad 0.00103 \quad 0.00070 \quad 0.30006]$$

Pixel error:

$$err = [0.22837 \quad 0.30006]$$

By optimizing process, all the errors decrease. Fig. 5 is error-distributing diagram on image coordinate gotten by projection of camera parameters.

ACKNOWLEDGMENT

In this paper the Binocular Stereo Camera Calibration is based on the combination of Zhang plane-based calibration method and self-calibration method based on the fundamental matrix, we obtain the initial values of internal and external parameters by Zhang plane-based calibration method, in the moving process of the robot, and determine the external parameters by self-calibration method.

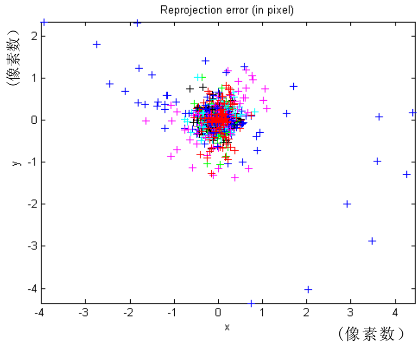


Fig. 5 error distributing diagram on image coordinate gotten by projection of camera parameters

REFERENCES

[1] O. Faugeras. Three-Dimensional Computer Vision: a Geometric Viewpoint. MIT Press, 1993.

[2] R. Y. Tsai. A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off-the-shelf tv cameras and lenses. IEEE Journal of Robotics and Automation, 3(4):323–344, Aug. 1987.

[3] S. J. Maybank and O. D. Faugeras. A theory of self-calibration of a moving camera. The International Journal of Computer Vision , 8(2):123–152, Aug. 1992.

[4] Q.-T. Luong and O. Faugeras. Self-calibration of a moving camera from point correspondences and fundamental matrices . The International Journal of Computer Vision, 22(3):261–289, 1997.

[5] L. de Agapito, E. Hayman and I. Reid. Self-Calibration of a Rotating Camera with Varying Intrinsic Parameters.

[6] Z.Y.Zhang. Flexible Camera Calibration by Viewing a Plane from Unknown Orientations. In: IEEE kim.L.Boyer,Sudeep.Sarkar, eds.IEEE International Conference on Computer Vision, Greece. Washington: IEEE Computer Society, 1999：666-673P.

[7] X. Armangue and J. Salvi. Overall view regarding fundamental matrix estimation. Image and Vision Computing 21 (2003), pp.205–220.

[8] T. S. Huang and O. Faugeras. Some properties of the E matrix in two-view motion estimation. IEEE Trans. Pattern Analysis and Machine Intell., 11(12):215–244, 1989.

[9] S. Maybank and O. Faugeras. A theory of self-calibration of a moving camera. Int. Journal of Computer Vision, 8(2):123–151, 1992.

[10]Janne Heikkila, Olli Silven. A four step camera calibration procedure with implicit image correction. Proc IEEE Comput. Soc. Conf. Comput. Vision and Pattern Recogn. 1997:1106-1112P.

[11]R. Hartley. Self-calibration from multiple views with a rotating camera. In Proc. 3rd European Conference on Computer Vision, pages 471–478, Stockholm, Sweden, May 1994.