http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 11 (2): 276-282, 2012
ISSN 1812-5638 / DOI: 10.3923/itj.2012.276.282

An Approach for Camera Self-Calibration using Vanishing-Line

Y. Zhao and X.D. Lv
Institute of Mathematics and Statistics, Yunnan University, 2 Cuifu Northern Road,
650091, Kunming, Republic of China

Abstract: The vanishing line is a very important feature in the projective geometry. It has been used in the camera calibration for a long time. This paper introduced an approach how to compute the vanishing line using the circles and their respective center. Then the camera intrinsic parameters were computed by the theory of vanishing line and circular points. The template used in the paper was a planar template, which contained any three plane circles that were not mutually concentric circles. First, the camera was needed to take pictures of the template at three or more different orientations. Then the image coordinates of the circles and their respective center were extracted from the pictures. From the theory of projective geometry, the utilization of the relationship of the pole and the polar line, formed by the center of a circle and the vanishing, solved three simple linear equations so as to obtain the vanishing line. The center of a circle and the vanishing line was proved to be the relationship of the pole and the polar line, from which three simple linear equations were gotten. Then the vanishing line could be computed by the three equations. In the end, the camera intrinsic parameters were gotten by the properties of the circular points. The principle of the approach was simple and equipment on the requirement was low, so it was very suitable for the non-professionals.

Key words: Camera self-calibration, vanishing line, non-concentric circle, conic, circular points, polar line, pole

INTRODUCTION

3D reconstruction is a main part during the research of the computer vision, which includes feature extracting (Guo *et al*., 2011; Amirani *et al*., 2008) feature matching (Feng-Dong *et al*., 2009) and the camera calibration, etc. Camera calibration is a key step to get three-dimensional information from two-dimensional images of objects. Now there are many studies of calibration (Liao and Cho, 2008; Shang *et al*., 2012; Elatta *et al*., 2004). The camera calibration has been applied in many areas (Song *et al*., 2011; Arif *et al*., 2002; Babakhani *et al*., 2006). The camera calibration is to get its internal projection parameters, which is divided into intrinsic parameters and extrinsic parameters, from the information of the image. So far, there were a variety of methods for camera calibration already. These methods could be divided into three categories: the traditional calibration approach, the calibration approach based on active vision and the approach of self-calibration. For a high precision, the traditional calibration approach can be used in any camera model, such as the pinhole camera model and the central camera model, etc. But its process is quite complex. In a majority of practical situations, the calibration block can not be used. Calibration approach based on active vision can often be solved linearly with strong robustness but it can not be used in the condition when camera motion is unknown and out-of-control (Zhao *et al*., 2011). Self-calibration approach uses the corresponding points between images to get the intrinsic parameters without knowing the geometry information of object in the scene, so it is relatively easy to realize camera calibration (Arif *et al*., 2002). The vanishing line is a very significant feature which has been widely used in calibration already, such as literatures (Wang and Tsai, 1991; Beardsley *et al*., 1992; Lv *et al*., 2002; Meng and Hu, 2003). There are a large number of current literatures to figure out the vanishing line. The literatures (Schaffalitzky and Zisserman, 2000; Kang *et al*., 2001) got the vanishing line based on the definition of vanishing line, getting the image of the line at infinity, which can be computed through the intersection lines of a group of parallel planes on the image plane. The literatures (Minagawa *et al*., 2000; Meng and Hu, 2003) got the vanishing line from fitting the vanishing points which belong to the vanishing line. By making use of the conic to obtain the vanishing line, the result was much more stability than the way to use of the points and plane. Also, the conic could be much easier to use for the non-professionals because that the using the conic is very simple to solve the unit's matching or extracting problem (Meng and Hu, 2003). Base on this, this study proposes a new approach in an attempt to

Corresponding Author: Y. Zhao, Institute of Mathematics and Statistics, Yunnan University, 2 Cuifu Northern Road, 650091, Kunming, Republic of China

solve vanishing line by the relationship between the pole and polar line. This approach has no need to figure out a group of parallel planes and to solve the vanishing point, which can get the vanishing line just making use of fitting the images of three circles and their centers in the template and the knowledge of projective geometry. And then, the circular points can be gotten by the intersection of the vanishing line and one of the circles in the template and the intrinsic parameters can be solved. The principle is simple and the planar template is convenient in production, so it has a broader applicability. The results of simulation and real experiments show that the approach is feasible.

NOTATION AND BASIC KNOWLEDGE

Camera model: The camera is a pinhole model (Ma and Zhang, 1998) in the study, which simplifies the process of optical imaging. In World Coordinate System (WCS) O_w-$x_w y_w z_w$, homogeneous coordinate of any point P in a space is $P_w(x_w y_w z_w\ 1)^T$, of which homogeneous coordinate in image coordinate system (u-v) is p(u v 1). From the imaging principle of the 3-dimensional space point on the image plane, we have:

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

where, λ is a non-zero scale factor:

$$K=\begin{bmatrix}f_u & s & u_0\\0 & f_v & v_0\\0 & 0 & 1\end{bmatrix}$$

is the camera intrinsic matrix, s is a parameter describing the skew of two images axes, f_u and f_v are the scale factors in image u and v axes, (u_0, v_0) is the principal point and [R, T] is called the extrinsic matrix, which shows the location of Camera Coordinate System (CCS) relative to WCS, where R is a 3×3 matrix, T is a translation vector.

Circular points: Let π is any plane in a space, of which equation is z = 0. The line at infinity in π is the intersection line between π and the vanishing plane, of which equation is as follows:

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

Suppose c is any circle in π, of which the center coordinate is $(x_0, y_0, 0, 1)^T$ and the radius is R. Then the equation of circle is:

$$\begin{Bmatrix}(x-x_0w)^2+(y-y_0w)^2=w^2R^2\\z=0\end{Bmatrix} \tag{3}$$

The intersection points between the line at infinity and the circle are circular points (Hartley and Zisserman, 2004). From Eq. 2 and 3, the coordinates of the circular points are $I = (1\ i\ 0\ 0)^T$, $J = (1\ {-i}\ 0\ 0)^T$.

It is easy to prove that the circular points are a pair of harmonic conjugate points in the absolute conic of plane at infinity.

Because the real projective transform can keep the property of elements (real and plural) unchanged, so the images of the circular points are a pair of conjugate imaginary points in the image of the absolute conic. Then suppose the coordinates are $m_i(x_r+x_i i,\ y_r+y_i i,\ 1)$ and $m_j(x_r-x_i i,\ y_r-y_i i,\ 1)$.

For the points in the absolute conic satisfy the equation as follows:

$$m^T K^{-T} K^{-1} m = 0 \tag{4}$$

where, $K^{-T}K^1$ is the matrix of the absolute conic's image.

So m_i, m_j can satisfy the Eq. 4, we have:

$$m_i^T K^{-T} K^1 m_i = 0,\ m_j^T K^{-T} K^1 m_j = 0 \tag{5}$$

Because of m_i, m_j are a pair of harmonic conjugate points, Eq. 5 can get two constraint equations as follows:

$$\begin{Bmatrix}Re\left(m_i^T K^{-T} K^{-1} m_i\right)=0\\Im\left(m_i^T K^{-T} K^{-1} m_i\right)=0\end{Bmatrix} \tag{6}$$

where, Re and Im are the real part and imaginary part.

Pole and polar line

Definition 1: If harmonic separating the two points of intersection of the line between the two distinct points and a conic Γ on a plane , then the two different points are called a pair of harmonically conjugate points about Γ, or conjugate points for short (Zhou, 2007).

Definition 2: Supposing P is a point in the plane, Γ is non-degeneracy conic, if P is not in the Γ, then the locus line p of the conjugate point P about Γ is the polar line of P about Γ, otherwise, the P is the pole of line p about Γ (Zhou, 2007).

Theorem: The locus of conjugate points $P(p_i)$ is a line about a conic Γ and the equation is $S_p = 0$, where S = 0 is the equation of Γ (Zhou, 2007).

Corollary: The polar line of any point P on plane about conic Γ is unique existent. And the equation of polar line is $S_p = 0$, otherwise, the pole of any line p on plane about Γ is unique existent (Zhou, 2007).

FITTING THE IMAGE OF CONIC

Suppose a circle C, of which image on the image plane is Q, usually the Q is an ellipse.

There are many methods to extract the ellipse. The least square method based on algebraic distance is used in this paper to fit a conic. Let the general equation of ellipse is as follows:

$$Q(x,y) = Ax^2 + 2Bxy + Cy^2 + 2Dx + 2Ey + F = 0$$

Chose the target function as follows:

$$I(A,B,C,D,E,F) = \sum_{i=1}^{n}\left(Ax_i^2 + 2Bx_iy_i + Cy_i^2 + 2Dx_i + 2Ey_i + F\right)^2 \quad (7)$$

where, $(x_i\ y_i)^T$ are the data points of a curve Q. A, B, C, D, E, F can still satisfy Q up to a scale, so some constraint conditions can be added, such as $A^2+B^2+C^2+D^2+E^2+F^2 = 1$, to make I minimize. A matrix, as follows, can be structured using the least-square method in order to solve the coefficients:

$$W = \begin{bmatrix} x_1^2 & 2x_1y_1 & y_1^2 & 2x_1 & 2y_1 & 1 \\ x_2^2 & 2x_2y_2 & y_1^2 & 2x_2 & 2y_2 & 1 \\ & & \cdots & & & \\ x_n^2 & 2x\,y_n & y_n^2 & 2x_n & 2y_n & 1 \end{bmatrix} \quad (8)$$

Let A, B, C, D, E, F be the eigenvectors corresponding to the smallest eigenvalue of $W^T W$. Then, the matrix of the ellipse can be expressed as follows:

$$Q = \begin{bmatrix} A & B & D \\ B & C & E \\ D & E & F \end{bmatrix} \quad (9)$$

SOLVING THE COORDINATES OF VANISHING LINE

Figure 1 is the template plane. In the template, A_1B_1, C_1D_1`, $A_2B_2$, $C_2D_2$`, A_3B_3, C_3D_3 are three groups of orthogonal diameters, which belong to three plane circles O_1` $O_2$` O_3.

Let the infinite points of A_1B_1, C_1D_1, A_2B_2, C_2D_2, A_3B_3, C_3D_3 be $P_{11\infty}$, $P_{12\infty}$, $P_{21\infty}P_{22\infty}$, $P_{31\infty}$, $P_{32\infty}$, respectively.

Figure 2 is the image of template. Let the corresponding points, the vanishing points $P_{11\infty}$, $P_{12\infty}$,

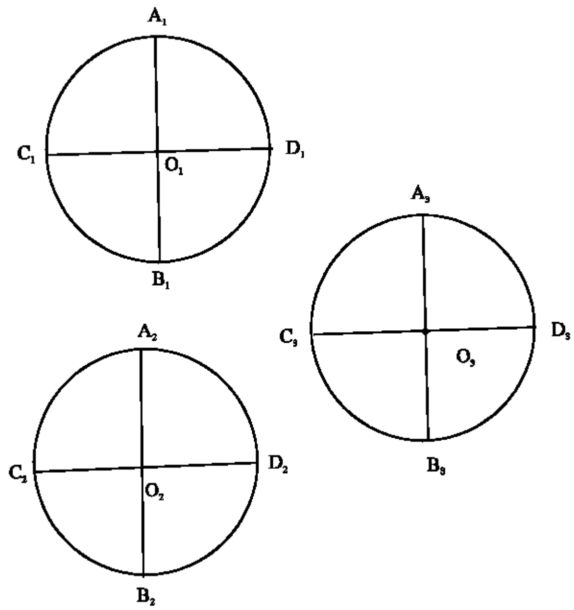

Fig. 1: The template plane

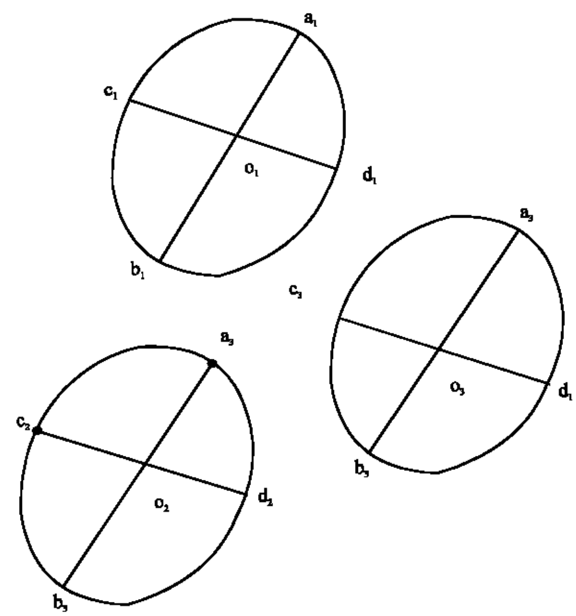

Fig. 2: The image of template

$P_{21\infty}P_{22\infty}$, $P_{31\infty}$, $P_{32\infty}$ be P_{11}, P_{12}, P_{21}, P_{22}, P_{31}, P_{32} on the image plane and the corresponding points A_1, B_1, C_1, D_1, O_1, A_2, B_2, C_2, D_2, O_2, A_3, B_3, C_3, D_3, O_3 be a_1, b_1, c_1, d_1, o_1, a_2, b_2, c_2, d_2, o_2, a_3, b_3, d_3, o_3 on the image plane, of which coordinates are $(u_{a1}, v_{a1})^T$, $(u_{b1}, v_{b1})^T$, $(u_{c1}, v_{c1})^T$, $(u_{d1}, v_{d1})^T$, $(u_{o1}, v_{o1})^T$, $(u_{a2}, v_{a2})^T$, $(u_{b2}, v_{b2})^T$, $(u_{c2}, v_{c2})^T$, $(u_{d2}, v_{d2})^T$, $(u_{o2}, v_{o2})^T$, $(u_{a3}, v_{a3})^T$, $(u_{b3}, v_{b3})^T$, $(u_{c3}, v_{c3})^T$, $(u_{d3}, v_{d3})^T$, $(u_{a3}, v_{o3})^T$.

Proposition: If there exist any three circles which are mutually eccentric circles in a plane, the line at infinity in the plane can be solved from their three centers of circles.

Prove: Let the three circles be C_1` C_2 and C_3. Because O_1 is the midpoint of A_1B_1, according to the conjugate relations of the four collinear points and the invariance of cross ratio in the projective geometry, the equation can be written as $(A_1B_1,\ O_1P_{11\infty}) = (a_1b_1,\ o_1p_{11}) = -1$. Then, according to Definition 1, point p_{11} and point o_1 is a pair of conjugate points about the image of circle C_1.

Similarly, from the diameter C_1D_1, we obtain $(C_1D_1,\ O_1P_{12\infty}) = (c_1d_1,\ o_1p_{12}) = -1$. Then point p_{12} and point o_1 is a pair of conjugate points about the image circle C_1. Because p_{11} and p_{12} are two vanishing points on the vanishing line, so according to Definition 2, the vanishing line is the polar line of point o_1 about the image of circle C_1.

Similarly, in a plane, the vanishing line is the polar line of points o_2 and o_3 about the images of circles C_2 and C_3, respectively.

Let the matrix of image of circle C_i (i = 1, 2, 3) be c_i (i = 1, 2, 3). Let the coordinate of vanishing line be p[x, y, z]. Then according to Corollary 1 satisfy:

$$\begin{cases} (u_{o1}, v_{o1}, 1)c_1(x,y,z)^T = 0 \\ (u_{o2}, v_{o2}, 1)c_2(x,y,z)^T = 0 \\ (u_{o3}, v_{o3}, 1)c_3(x,y,z)^T = 0 \end{cases} \tag{10}$$

Expanding the formula (10), three equations about x, y, z can be written:

$$\begin{cases} (u_{o1}c_1(1,1) + v_{o1}c_1(2,1) + c_1(3,1))x + (u_{o1}c_1(1,2) + v_{o1}c_1(2,2) + c_1(3,2))y + \\ (u_{o1}c_1(1,3) + v_{o1}c_1(2,3) + c_1(3,3))z = 0 \\ (u_{o2}c_2(1,1) + v_{o2}c_2(2,1) + c_2(3,1))x + (u_{o2}c_2(1,2) + v_{o2}c_2(2,2) + c_2(3,2))y + \\ (u_{o2}c_2(1,3) + v_{o2}c_2(2,3) + c_2(3,3))z = 0 \\ (u_{o3}c_3(1,1) + v_{o3}c_3(2,1) + c_3(3,1))x + (u_{o3}c_3(1,2) + v_{o3}c_3(2,2) + c_3(3,2))y + \\ (u_{o3}c_3(1,3) + v_{o3}c_3(2,3) + c_3(3,3))z = 0 \end{cases} \tag{11}$$

There are three unknown numbers and three equations, then, we can figure out the unique vanishing line p[x, y, z], Proof is completed.

SOLVING OF THE CAMERA INTRINSIC PARAMETERS

Because any circle in a plane and the line at infinity must intersect at the two circular points, accordingly according to the nature of perspective transformation, the points of intersection between the image of circle and the image of line at infinity are the image of circular points on the image plane (Meng and Hu, 2003). In the template, if the vanishing line is known, the circular points can be figured out using the intersection between the vanishing line and any circle. From Eq. 6, each pair of circular points can get two constraint equations about camera intrinsic parameters, so $K^{-T}K^{1}$ can be solved using three or more pictures. K^{-1} can be gotten by the Cholesky decomposition of $K^{-T}K^{1}$, where the K can be solved by the matrix inversion K^{-1}. Then normalizing the last element of K, the matrix of the intrinsic parameters can be figured out and then the calibration is completed.

Summing up the above discussions, the calibration process can be summarized as follows:

Step 1: Print a plane template which contains any three plane circles that are mutually eccentric circles and paste it on a hard surface.
Step 2: Change the relative position between the camera and the template and take 3 or more different pictures.
Step 3: Input these pictures and extract their points and centers of the ellipses (Zhao *et al*., 2011).
Step 4: Figure out the matrix of ellipse according to Eq. 7 and 9 and get the equation of the ellipse.
Step 5: Get the vanishing line from Eq. 10, solve the image of the circular points according to the equations of ellipses and vanishing line.
Step 6: According to (6), make out the intrinsic parameters and complete the calibration.

EXPERIMENTS RESULTS

Simulation experiments result: In all the subsequent computer simulations, the template was as shown in Fig. 3. Let the radiuses of all circle be 10, whose centers were (0, 0), (20, 0) and (-20, 0), respectively. The camera

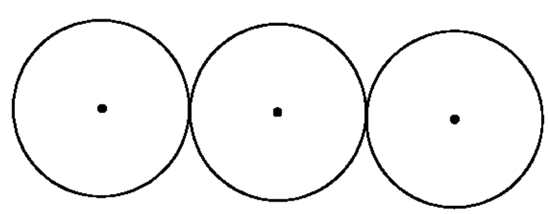

Fig. 3: Simulation picture

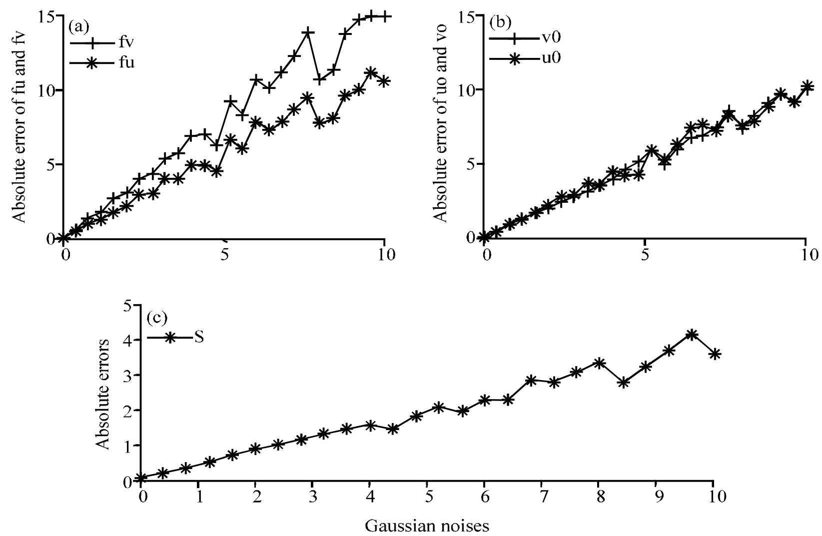

Fig. 4(a-c): The curve of the absolute error of the five camera intrinsic parameters under different noises levels

Table 1: The comparison of the results of the two approaches

Calibration method	5 intrinsic parameters
The approach in this paper	$\begin{bmatrix} f_u = 519.4791, f_v = 522.0506 \\ s = 3.2001, u_0 = 326.8834, v_0 = 221.4430 \end{bmatrix}$
The approach in the literature (Zhang, 2000)	$\begin{bmatrix} f_u = 527.493, f_v = 529.325 \\ s = 0, u_0 = 312.857, v_0 = 225.328 \end{bmatrix}$

intrinsic parameters were set to $f_u = 2000$, $f_v = 2000$, $s = 0.2$, $u_0 = 800$, $v_0 = 650$. Three pictures were used in the experiment and the rotation matrixes of the camera were as follows:

$$R1 = \begin{bmatrix} 0.0080953 & 0.96861 & -0.24845 \\ 0.97668 & -0.060969 & -0.20587 \\ -0.21455 & -0.24099 & -0.94651 \end{bmatrix},$$

$$R2 = \begin{bmatrix} -0.030761 & 0.99932 & -0.02043 \\ 0.98461 & 0.026778 & -0.17269 \\ -0.17202 & -0.025428 & -0.98476 \end{bmatrix}$$

$$R3 = \begin{bmatrix} -0.42245656512663 & -0.28102183151253 & -0.86171757600432 \\ -0.62381212869549 & -0.59958188366975 & 0.50135814830063 \\ -0.65756283249117 & 0.74935191665090 & 0.07799247616154 \end{bmatrix}$$

The Translation vectors of the camera were as follows:

$$T_1 = [-115.05; -65.925; 431.2], T_2 = [-101; -77.591; 381.17], \\ T_3 = [-142.56; -34.891; 521.456]$$

To verify the robustness of the approach in the paper, a Gaussian noise with 0 mean and σ standard deviation was added to each image point. The noise varied from 0 to 10 pixels. All the results in the experiments were the average value of 100 independent trials. The standard deviations of the five intrinsic parameters at each different noise level were computed, which were shown in Fig. 4a-c.

We compared with the approach in the paper and the literature (Meng and Hu, 2003). All the parameters were set to the same in the process of calibration of the two approaches, such as the intrinsic and extrinsic parameters, the numbers of pictures and the feature points and so on, so as to ensure the comparability of the experiment results. The absolute errors of the five intrinsic parameters gained by the two approaches were list in Fig. 5a-e, where the solid line represented the results of the approach in this paper and the dashed line represented the results of the approach in the literature (Meng and Hu, 2003), respectively. What we can know from the changing curve was that the two calibration results were similar increasing linearly with the increasing of the noises and the curves of the two results were basically coincided, which was said that the results accuracy of this paper and the literature (Meng and Hu, 2003) were consistent.

Real experiments result: In real experiments, the template was contained a three CDS with given centers. Pasted three CDS on the wall and took many pictures from different orientations, three of which were shown in Fig. 6. The image resolution was 640×480. Using three pictures to calibrate camera, the method in this study was compared with the method in the literature (Zhang, 2000). The results of the two approaches were shown in Table 1.

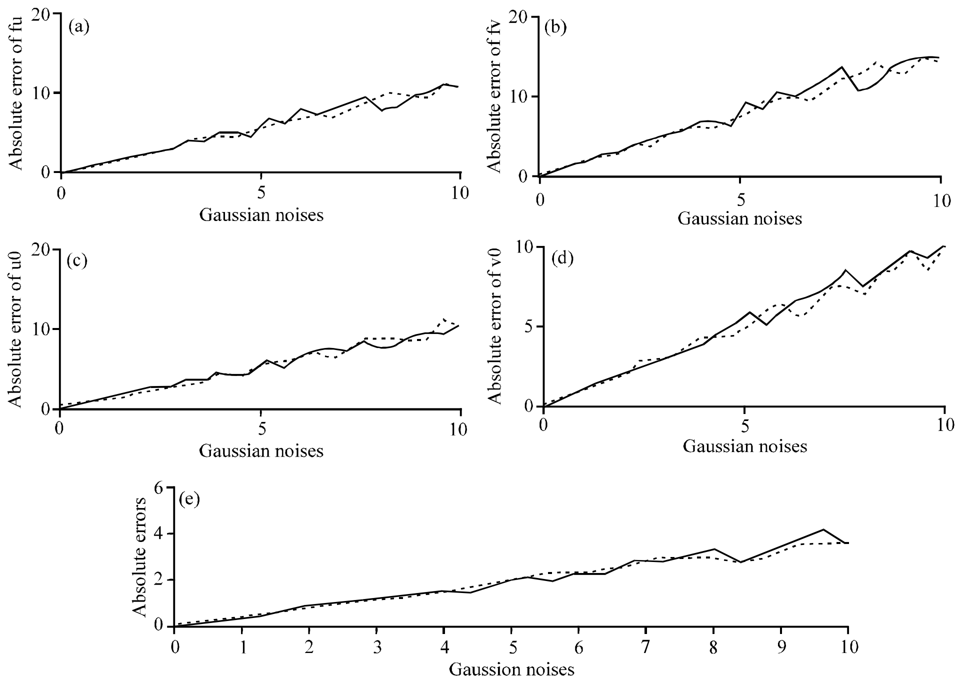

Fig. 5(a-e): The comparison of the calibration results between the methods in this paper and the literature (Meng and Hu, 2003)in the simulation experiments

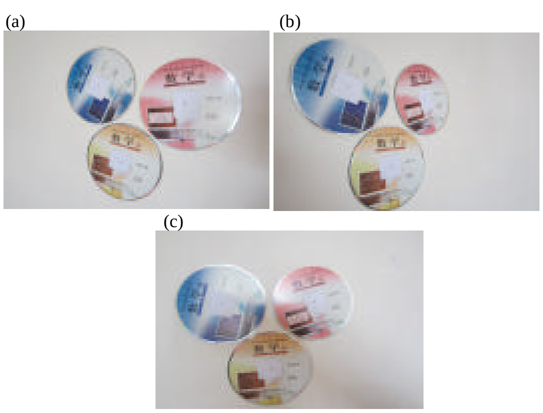

Fig. 6(a-c): Pictures in the real experiments

CONCLUSIONS

A self-calibration approach based on computing the vanishing line is proposed in the study. This method has no need to know either the matching relation between the template and image points, or camera movement or template movement, so the whole calibration process is very simple. The simulation and the real experiment show the approach proposed in this paper has high accuracy and robustness. But the shortcoming is we have to know the circle center of the three circles before the calibration, which is the limitation to promote this method. So how to get the high precision circle center automatically is our further study.

ACKNOWLEDGMENT

This study is supported by the Scientific Research Foundation of Yunnan Education Department of China (2010Y245) and the Scientific Research Foundation of Yunnan University (2010YB021).

REFERENCES

Amirani, M.C., Z.S. Gol and A.A.B. Shirazi, 2008. Efficient feature extraction for shape-based image retrieval. J. Applied Sci., 8: 2378-2386.

Arif, M., H. Xinhan and W. Min, 2002. Stratified approach to 3D reconstruction. Inform. Technol. J., 1: 75-79.

Babakhani, A., Z. Du, L. Sun, M.A. Fereidoon and K.M. Reza, 2006. 3D reconstruction of ultrasonic images based on matlab/simulink. Pak. J. Biol. Sci., 9: 2818-2822.

Beardsley, P., D. Murray and A. Zisserman 1992. Camera calibration using multiple images. Proceedings of the 2nd European Conference On Computer Vision, May 19-22, 1992, Santa Margherita Ligure, Italy, pp: 312-320.

Elatta, A.Y., L.P. Gen, F.L. Zhi, Y. Daoyuan and L. Fei, 2004. An overview of robot calibration. Inform. Technol. J., 3: 74-78.

Feng-Dong, C., B.R. Hong and G.D. Liu, 2009. Planar displacement detection with point feature matching. Inform. Technol. J., 8: 383-387.

Guo, Y., Y. Gu and Y. Zhang, 2011. Invariant feature point based ICP with the RANSAC for 3D registration. Inform. Technol. J., 10: 276-284.

Hartley, R. and A. Zisserman, 2004. Multiple View Geometry in Computer Vision. 2nd Edn., Cambridge University Press, Cambridge, UK., Pages: 655.

Kang, H., S. Pyo, K. Anjyo and S. Shin, 2001. Tour into the picture using a vanishing line and its extension to panoramic images. Comput. Graphics Forum., 20: 132-141.

Liao, H.C. and Y.C. Cho, 2008. A new calibration method and its application for the cooperation of wide-angle and pan-tilt-zoom cameras. Inform. Technol. J., 7: 1096-1105.

Lv, F., T. Zhao and R. Nevatia, 2002. Self-calibration of a camera from video of a walking human. Proceedings of the International Conference on Pattern Recognition, August 11-15, 2002, Quebec City, Canada.

Ma, S. and Z. Zhang, 1998. Computer Vision-Theory and Algorithm Base. Beijing Science Press, Beijing.

Meng, X.Q. and Z.Y. Hu, 2003. A new easy camera calibration technique based on circular points. Pattern Recogn., 36: 1155-1164.

Minagawa, N. Tagawa, T. Moriya and T. Gotoh, 2000. Vanishinig point and vanishing line estimation with line clustering. IEICE Trans. Inf. Syst., 83: 1574-1582.

Schaffalitzky, F. and A. Zisserman, 2000. Planar grouping for automatic detection of vanishing lines and points. Image Vision Comput., 9: 647-658.

Shang, Y., Z. Yue, M. Chen and Q. Song, 2012. A new method of camera self-calibration based on relative lengths. Inform. Technol. J., (In Press)

Song, B., Y. Fu and J. Wang, 2011. Automatic panorama creation using multi-row images. Info. Technol. J., 10: 1977-1982.

Wang, L.L. and W.H. Tsai, 1991.. Camera calibration by vanishing lines for 3-d computer vision.. IEEE Trans. Pattern Anal. Mach. Intell., 13: 370-376.

Zhang, Z., 2000. A flexible new technique for camera calibration. IEEE Trans. Pattern Anal. Mach. Intell., 22: 1330-1334.

Zhao, Y., X.D. Lv and A.J. Wang, 2011. A nonlinear camera self-calibration approach based on active vision. JDCTA, 5: 34-42.

Zhou, X., 2007. Higher Geometry. Science Press, Beijing, China.