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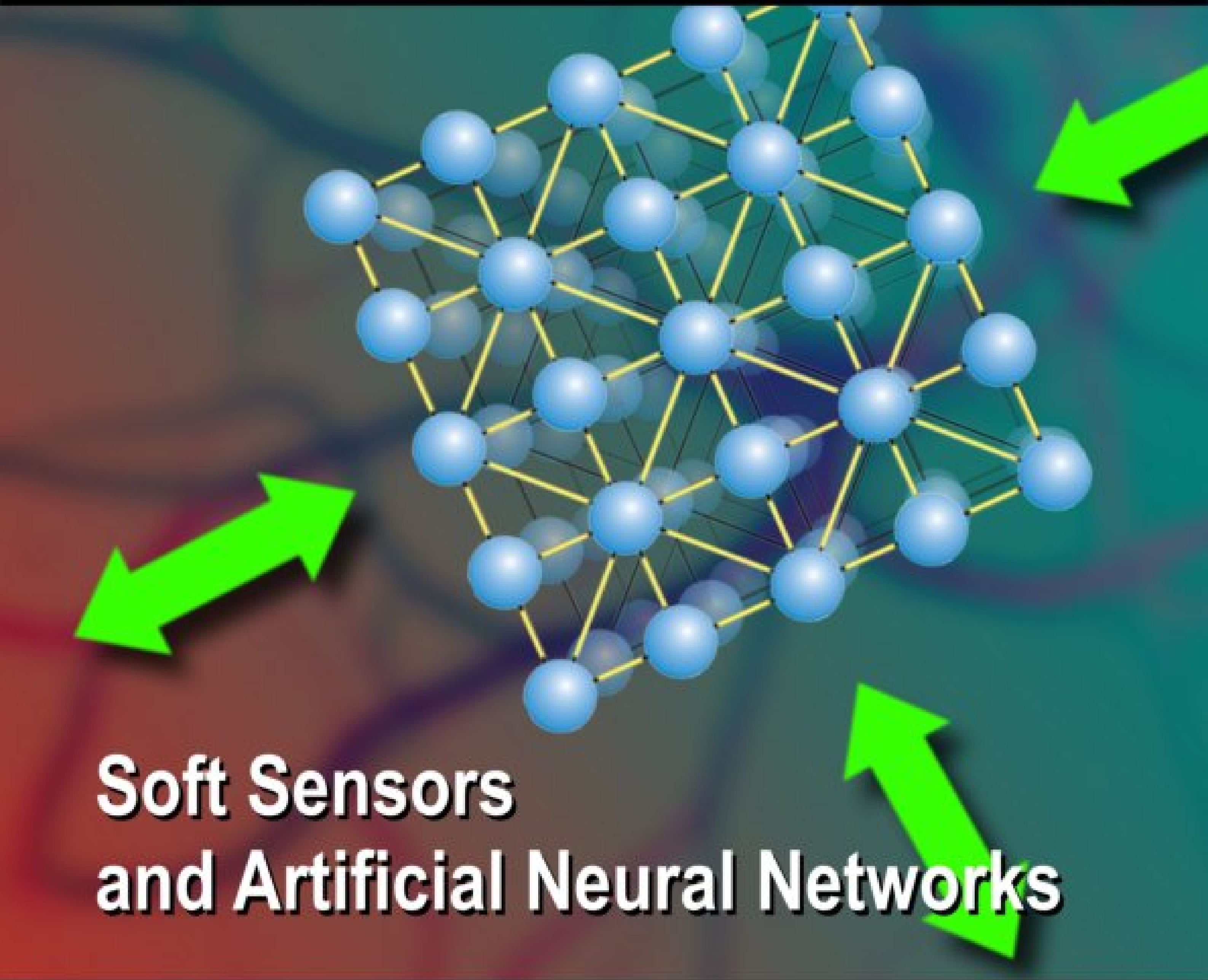

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A Calibration Method of Binocular Vision System for Large Forging Dimension Measurement

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Abstract: Binocular vision system has been employed to measure the large forging dimension, by virtue of the spectrum selective method proposed in our past work. However, under the complicated operation circumstance with high temperature, it is difficult to calibrate the cameras of the binocular vision system by the traditional calibration method. In this paper, a calibration method of binocular vision system is presented for measuring the dimensions of large forging. Moreover, according to the epipolar constraints, the distortion coefficient of two CCD cameras is considered and solved by LM algorithm, for improving the measurement precision of binocular vision system. Experiments on the field calibration in forging workshop are performed, and the results show the relative error of the dimension measurement is less than 0.338 %, which indicates that the proposed calibration method is efficient and effective for calibrating the binocular vision system for large forging dimension measurement in forging workshop. *Copyright © 2012 IFSA.*

Keywords: Large forging, High temperature, Calibration, Visual measurement.

1. Introduction

Binocular vision system has been employed for detecting the dimensions of large parts, due to its smart and easy operation. Moreover, the dimensions of large forging also can be measured by binocular vision method. However, under high temperature circumstance, due to the radiation and oxide coating of large forgings, the edges of forgings in shot image is very unclear, so that the profile of forgings cannot be detected easily in the process of image processing. Thus, in our past works, in order to solve this problem, the spectrum selective method has been proposed, and the clear images of large forging have been captured for further image processing [1]. Another problem, for acquiring the dimensions of large forging by binocular vision system, is to calibrate the CCD cameras, and the calibration results affect markedly the dimension measurement precision of large forging. Therefore, a field calibration method of CCD camera, which is practicable under the high temperature operation circumstance in forging workshop, is necessary for dimension measurement of large forging.

According to the traditional calibration methods of the stereo vision system, the camera is usually calibrated by the planar pattern board or 3D calibration block [2], with high calibration accuracy. Zhang et al [3] has established the calibration method using the planar pattern, which can be easily manufactured. However, it needs to capture several planar pattern images in different positions for the intrinsic parameters, which is hard to realize due to the complicated operation circumstance with high temperature. Another calibration method proposed by Sun et al [4], can operate under the circumstance of wide vision field by the baseline ruler. However, the baseline ruler has to be placed in different positions, which is also difficult to operate in forging workshop.

Self-calibration is usually performed by moving a camera around an unknown static scene, without any calibration object. By satisfying the epipolar constraints, the camera parameters can be calculated with the point or line correspondence. Sturm has improved the method and present the calibration method for variable focal system [5]. Triggs has presented the idea of self-calibration by using the absolute quadric [6]. Based on the absolute conic on the plane at infinity, Pollefeys et al presented a calibration method for active vision [7]. These approaches can be applied easily for most pre-existing images. However, a sufficient number of correspondences between images are necessary. Meanwhile, there are many parameters to estimate, we cannot always obtain reliable results.

In this paper, a calibration method of CCD camera based on the projected targets and the planar patterns is presented. The camera model with lens distortion is described in Section 2. The theory of calibration for CCD camera is introduced in Section 3, including the distortion factors computation. Thereafter, the projected pattern for the intrinsic parameters of CCD camera is elaborated in detail in Section 4, as well as the planar pattern for the extrinsic parameters of CCD camera. In Section 5, the experiments on field calibration of camera and dimension measurement are performed. Finally, the conclusion of this paper is given in Section 6.

2. Camera Model with Lens Distortion

As shown in Fig. 1, a 3D point in the world coordinate system $o_w x_w y_w z_w$ is denoted by (x_w, y_w, z_w). In the camera coordinate system $o_c x_c y_c z_c$, the optical center is defined by the center point o_c. In the computer image coordinate system $o_f uv$, with the scales in pixel, the origin o_f is at the top left corner of the CCD image plane, and the u and v axes are parallel with the x_c and y_c axes respectively. The ideal pixel image coordinates are defined by $(\hat{u}, \hat{v})$ in the $o_f uv$ system, with neglecting lens distortion. According to the linear pinhole model of camera, the perspective transformation of coordinate system from world to image system can be expressed as:

$$\begin{bmatrix} \hat{u} \\ \hat{v} \\ 1 \end{bmatrix} = \begin{bmatrix} f_u & 0 & u_0 & 0 \\ 0 & f_v & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix}, \tag{1}$$

where $f_u = f / d_x$, $f_v = f / d_y$; d_x and d_y indicate the physical dimensions of every pixel on X and Y direction, respectively; f is the focus of camera; (u_0, v_0) is the intersection point of optical axis and image coordinate system; f_u, f_v, u_0, v_0 are just the intrinsic parameters of camera to be calibrated; rotation matrix R=R3×3 and translation vector $T=[t_x\ t_y\ t_z]^T$ describe the position relationship between the camera coordinate system and world coordinate system, which are just the extrinsic parameters of camera to be calibrated.

In order to achieve high precision of measuring the dimensions of large forging, we will consider lens distortion of CCD camera. Thus, the linear projective relation between space coordinates and image coordinates in Equation (1) is changed to a nonlinear model. Then, for easily calculating and solving the projective model, camera distortion is considered as an integral of a camera. Therefore, the distorted pixel image coordinates are expressed as (u, v), and the ideal pixel image coordinates $(\hat{u}, \hat{v})$ can be obtained from the distorted pixel image coordinates (u, v) as follows:

$$\begin{aligned}\hat{u}&=(u-u_0)[1+(u-u_0)^2 kd_x^2+(v-v_0)^2 kd_y^2]\\ \hat{v}&=(v-u_0)[1+(u-u_0)^2 kd_x^2+(v-v_0)^2 kd_y^2]\end{aligned}, \tag{2}$$

where k is the first order coefficient of radial distortion of CCD camera.

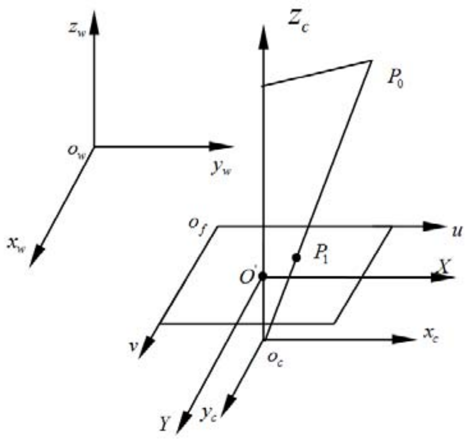

Fig. 1. Schematic of the linear camera model.

3. Theory of Calibration

In this section, based on the projected targets and the planar patterns, a calibration method of CCD camera with considering lens distortion is presented. Firstly, according to the linear projective relation between the space coordinates and the image coordinates, the intrinsic and extrinsic parameters of CCD camera are initially estimated by using the projected targets and the planar patterns, respectively. Then, based on these estimated values and the epipolar constraint, with taking into account the camera distortion, the coefficients of the radial distortion are solved, and the estimated values of intrinsic and extrinsic parameters of CCD camera can be refined finally.

3.1. Intrinsic Parameters Calibration

The intrinsic parameters of CCD camera are calibrated by capturing the projected pattern through four group of orthogonal motion of camera, with simultaneously changing the poses of camera, driven by the electrically-controlled platform. According to active vision theory [8], when camera conducts a group of orthogonal motion, two epipoles can be got as shown in Fig. 2. I_1 and I_2 are the image before motion and the image after motion, respectively. The points P_1 and P_2 are the projections of the same space point P in the images I_1 and I_2 . Line $\overline{P_1P_2'}$ is defined by the corresponding point line, where P_2' is the corresponding point of P_2 in the image I_1 , with the same coordinate as that in the image I_2 . The corresponding point lines of the image before motion and the one after motion cross each other at the epipole, and the vector O_1e_1 from the optical center to the epipole e_1 is parallel with the motion vector. When four group of orthogonal motions in one plane are conducted, O_1e_1 and O_1e_2 represent two orthogonal vectors, with the relation of $O_1e_1 \cdot O_1e_2 = 0$ [8]. Thus, one can be obtained as follows:

$$Ax=b\,, \tag{3}$$

where $A=\begin{bmatrix} u_{11}+u_{12}-u_{21}-u_{22} & v_{11}+v_{12}-v_{21}-v_{22} & v_{21}v_{22}-v_{11}v_{12} \\ u_{21}+u_{22}-u_{31}-u_{32} & v_{21}+v_{22}-v_{31}-v_{32} & v_{31}v_{32}-v_{21}v_{22} \\ u_{31}+u_{32}-u_{41}-u_{42} & v_{31}+v_{32}-v_{41}-v_{42} & v_{41}v_{42}-v_{31}v_{32} \end{bmatrix}$, $x=\begin{bmatrix} u_0 \\ \frac{v_0 fx^2}{fy^2} \\ \frac{fx^2}{fy^2} \end{bmatrix}$, $b=\begin{bmatrix} u_{11}u_{12}-u_{21}u_{22} \\ u_{21}u_{22}-u_{31}u_{32} \\ u_{31}u_{32}-u_{41}u_{42} \end{bmatrix}$,

where (u_{ij}, v_{ij}) ($i=1,2,3,4;\ j=1,2$) are the image coordinates of each group in left image coordinate system, (u_{i2}, v_{i2}) ($i=1,2,3,4$) are the image coordinates of each group in right image coordinate system. Moreover, the orthogonal motion mode of one panning and two tilting is selected in the four groups of orthogonal motions [9], to calibrate the intrinsic parameters of camera.

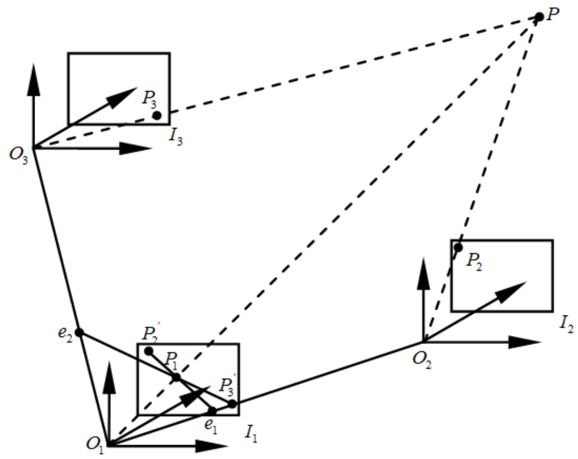

Fig. 2. Calibration principle of camera intrinsic parameters.

3.2. Extrinsic Parameters Calibration

The extrinsic parameters of CCD camera can be acquired by the position relationship between the left and right cameras. Coinciding with the world coordinate system, the extrinsic parameters of the left camera can be described by $R=diag(1,1,1)$, $T=[0\ \ 0\ \ 0]$. Then, the extrinsic parameters of the right camera can be estimated by eigenvalue decomposition of the essence matrix E . The estimated values of extrinsic parameters are not the actual ones, but the ones with a proportional factor. Therefore, a pairs of planar patterns are employed to determine the proportional factor, for acquiring the extrinsic parameters of CCD camera.

Eight corresponding feature points in the left and right images are extracted and matched by the SIFT algorithm [10]. The fundamental matrix F can be calculated, which reflects the interrelationship of these corresponding feature points in the left and right images. Suppose that x_l and x_r represent the corresponding feature point of left and right images respectively, then, $x_l^T F x_r = 0$.

The essential matrix E, which is equal to the product of the intrinsic parameters K_l (left camera), K_r (right camera) and the fundamental matrix F, is the special form of the fundamental matrix F in the normalization image coordinate, and the relationship can be given by:

$$E = K_r^T (K_r^T [T]_\times R K_l^{-1}) K_l = K_r^T F K_l , \tag{4}$$

where $[T]_\times$ is the anti-symmetrical matrix of T.

The matrixes R and T can be solved by the eigenvalue decomposition of E [9], $E = USV^T$, where $S = diag(g, g, 0)$. Then the matrix R and T can be expressed as:

$$R \approx UQV^T, \ [T]_\times = VZV^T , \tag{5}$$

where $Q = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, Z = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$.

According to Equation (5) and $[T]_\times T = 0$, the translation vector between two cameras can be described by $T = U(0,0,1)^T$. The solution of Equation (5) is obtained by the assumption of $\|T\| = 1$. Since the epipolar line constraint cannot define the proportional factor of 3D information, the actual translation vector T' can be given by $T' = sT$, while the actual rotation matrix is just the matrix R. Through the reconstruction of two known edge, the scale factor s can be obtained as follows:

$$s = \frac{L}{L'} , \tag{6}$$

where L is the real length of the edge and L' is the reconstruction length of the edge without the scale factor.

3.3. Calibration Parameters Optimization

After acquiring the estimated initial values of intrinsic and extrinsic parameters of CCD camera, we will compute the radial distortion coefficient, and refine and optimize the camera parameters.

When two points (u_l, v_l) of the left image and (u_r, v_r) of the right image in correspondence are given, there is a constraint between the two points, even though the two images exist lens distortion. Then, the ideal coordination of them $(\hat{u}_l, \hat{v}_l)$ and $(\hat{u}_r, \hat{v}_r)$ can be obtained by Equation (2), and the epipolar constraint between them can be expressed as:

$$t(u_l, v_l; u_r, v_r) \equiv [\hat{u}_l, \hat{v}_l, 1] F [\hat{u}_r, \hat{v}_r, 1]^T = 0 , \tag{7}$$

Let f be the vector containing the parameters of the fundamental matrix F. Only considering the radial distortion, we can estimate the distortion coefficients by solving a minimization problem:

$$\min_{k_l, k_r, f}\left[\frac{1}{n}\sum_{i=1}^{n} t(u_l, v_l; u_r, v_r)\right], \tag{8}$$

where k_l, k_r are the distortion coefficients of the left and right camera, and n represent the number of the points in correspondence, which may be extracted enough. The estimation of (k_l, k_r) and f are separated to conduct using Levenberg-Marquardt algorithm [11]. The estimation of f is performed in each optimization step for (k_l, k_r). After the distortion coefficients are estimated, the fundamental matrix F can be recalculated, and the intrinsic and extrinsic parameters of CCD camera also can be refined.

4. Pattern Design

Under the complicated operation circumstance with high temperature, to realize the calibration method mentioned above in large forging workshop, it is critical to design a set of practical projected pattern and planar patterns in this section.

4.1. Pattern Design for the Intrinsic Parameters Calibration

The projected pattern for calibrating the intrinsic parameters of camera is composed of circular control point, as shown in Fig. 3, where three larger-size circularities for locating the target are placed in the corner of the array, which is the location datum mark for the other circularities. The locating process of the circularity array consists of the pretreatment, automatic threshold segmentation, noise reduction, image filtering, circularity identification, elliptic center extraction, and topological locating.

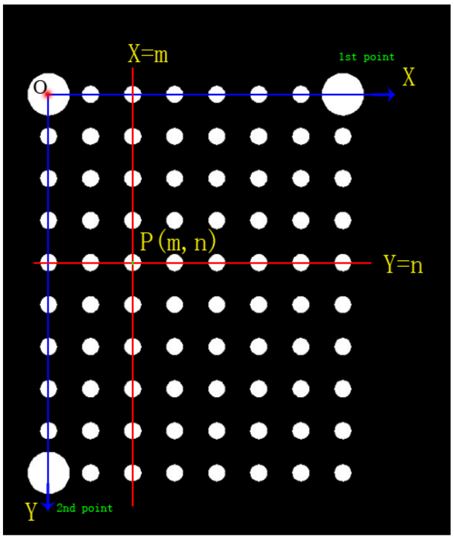

Fig. 3. Coordinates identification of the target for calibrating intrinsic parameters.

After the identification of all the circular control points, the centers of three larger-size circular control points are recognized and located by the circular area. For each center, the summation of the distance to the other centers is calculated, and the minimum one is defined by the origin O. The nearer center point to origin is defined as 1st point, and the other as the 2nd point. Consequently, the OXY axes are determined, as shown in Fig. 3, the X axis is the line from origin to 1st point, and the Y axis is the line from origin to 2nd point. The circle centers of pattern are lined to fabricate the line Y=1, 2, … , n, as well as the line X=1, 2, … , m. If a point P is both on the X=m line and on Y=n line simultaneously, its coordinate is defined by (m, n), which finishes the locating of all the points on the pattern.

During the motion of the camera, different images of the pattern projected onto the wall of workshop are captured. It is noticeable that the pattern would fully fill the screen to reduce the distortion error.

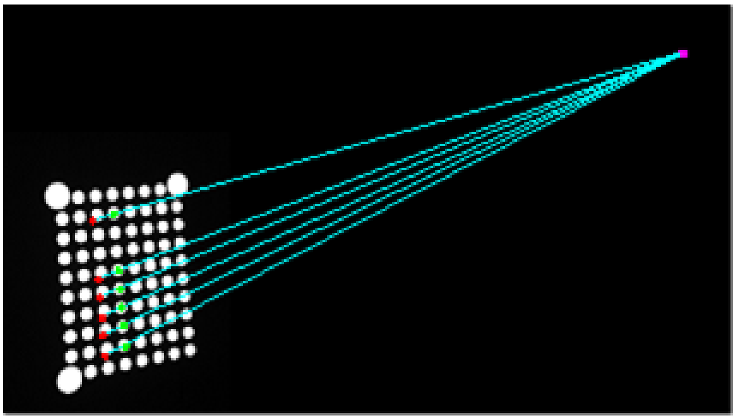

Fig. 4. Epipole estimation (the green points are the circle centers in origin image. The red points are the circle centers in image after motion. The magenta points are the epipole estimated).

In order to reduce the error of epipole estimation, more than one pair of the feature points are required. Since the lines fabricated by two nearby points have the similar slopes, the epipoles estimated by them are vulnerable to the noise. Thus, instead of using all the combination of the points, the two points of $P_1(x_1, y_1)$ and $P_2(x_2, y_2)$ for the epipole estimation, should not be too near from each other, and their Y coordinates need meet the equation: $y_2 - y_1 \geq 3$. For example, the Y coordinate of the first point $P_1(x_1, y_1)$ is $y_1 = 2$, and that of the second point $P_2(x_2, y_2)$ is selected by $y_2 \geq 5$, as shown in Fig. 4.

4.2. Planar Pattern Design for the Extrinsic Parameters Calibration

In order to refine the fundamental matrix F and estimate the distortion factor k_l, k_r an abundance of points in correspondence are required. Two planar pattern boards are placed in the vision field as shown in Fig. 5. The corner points of the chess board in correspondence are extracted as the point matches. Moreover, according to Equation (6), through the reconstruction of the known edge of the planar pattern board, the scale factor s can be obtained.

5. Experiments and Analysis

In order to verify the calibration method proposed, experiments on field calibration of CCD camera are conducted in forging workshop. The dimension measurement and camera calibration system for large forging, as shown in Fig. 6, consists of two digital CCD cameras (REDLAKE, ES4020) with the image resolution of 2048×2048 pixels, a low-pass filter (BD, 450SP) in front of each camera, a DLP projector (3M, PD80X), a computer and two electrically-controlled platforms. The DLP projector is arranged between the two cameras to project the patterns for calibrating the intrinsic parameters of CCD cameras. The cameras and projector are both connected to a computer with control wires. In addition, two CCD cameras are fixed onto the electrically-controlled platforms, as shown in Fig. 6, and their positions and angles are changed for calibrating the intrinsic parameters of camera, which has been introduced in detailed in Section 4.1 and 5.1.

(a) (b)

Fig. 5. Planar pattern boards for acquiring the point matches (a) left image (b) right image.

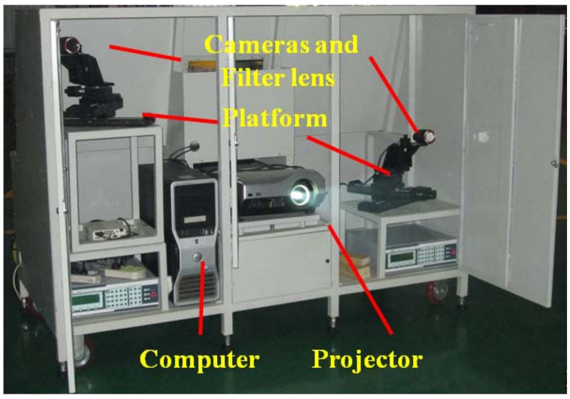

Fig. 6. The dimension measurement system for large forging based on binocular vision.

5.1. Experiments on Camera Calibration and Dimension Measurement

In the process of the calibration of the intrinsic parameters, the motion parameters of CCD cameras driven by the electrically-controlled platforms are shown in Table 1. The projected patterns onto a board are captured by two CCD cameras. After the radial distortion coefficient value estimated and the fundamental matrix F are recalculated through 120 known points, R and T of the cameras can be obtained. According to Equation (8), the intrinsic and extrinsic parameters refined of two CCD cameras are shown in Table 2, where the radial distortion coefficients of the left and right CCD camera are -9.0212e-10, -7.4429e-10, respectively(the minus represents the pincushion distortion).

The dimensions of large forging are measured based on the intrinsic and extrinsic parameters of two CCD cameras achieved above, as shown in Fig. 7, with employing light stripes [12]. Fig. 8 shows the forging images captured by two CCD cameras. Since the measured hot forging is cylinder, and the light stripes are not perpendicular to the axis of forging, the reconstruction model meant to be elliptical. The 8 light stripes are reconstructed and fitted by the ellipse model. The local diameter of the forging is defined by the shorter axis of the ellipse, and the measurement result is shown in Table 3.

Table 1. Motion parameters for the four groups of orthogonal motions.

Groups	Camera pose	Location parameter (x, y)/mm		
First group	Tilting angle 15°/Panning angle 40°	0, 100	0, 0	100, 0
Second group	Tilting angle 0°/ Panning angle 40°	100, 0	0, 0	0, 100
Third group	Tilting angle 0°/ Panning angle 50°	0, 100	0, 0	100, 0
Fourth group	Tilting angle -15°/ Panning angle 50°	100, 0	0, 0	0, 100

Table 2. The calibration results of the CCD camera.

Parameters	Left camera	Right camera
K	$\begin{bmatrix} 5121 & 0 & 1268.9 \\ 0 & 5260.2 & 920.6 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 4848.2 & 0 & 962.34 \\ 0 & 4874.7 & 1260.1 \\ 0 & 0 & 1 \end{bmatrix}$
R	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0.96623964 & 0.02452922 & 0.25647471 \\ 0.00276983 & 0.99441116 & -0.10554041 \\ -0.25763013 & 0.10268772 & 0.96077154 \end{bmatrix}$
T	$[0 \quad 0 \quad 0]$	$\begin{bmatrix} 1245.38762536 & -352.89737711 & -284.52172281 \end{bmatrix}$
k	$-9.0212e^{-10}$	$-7.4429e^{-10}$
F	$\begin{bmatrix} 3.2499e^{-8} & 8.6695e^{-8} & -0.00075860 \\ 1.7015e^{-8} & -3.6120e^{-8} & -0.0021202 \\ 0.00053407 & 0.0020203 & 0.17786 \end{bmatrix}$	

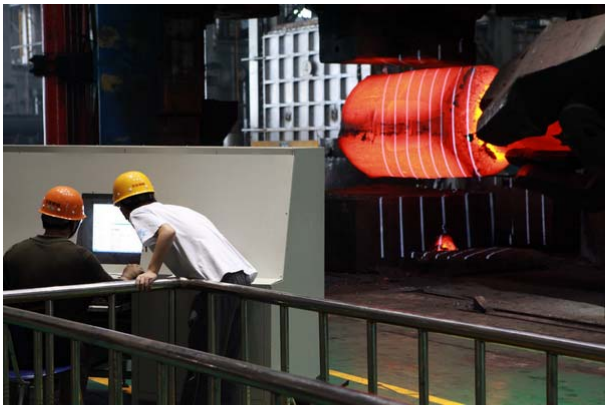

Fig. 7. The image of dimension measurement for large forging.

Table 3. Diameter measurement results of the light stripes.

No.	1	2	3	4	5	6	7	8
Diameter (mm)	594.84	957.88	1113.95	962.29	977.04	932.97	994.95	1001.33

(a) (b)

Fig. 8. Images captured for forging measurement (a) left image (b) right image.

5.2. Estimation of Calibration Precision

In order to testify the calibration precision of CCD cameras of the proposed method in this paper, a calibration experiment with the planar pattern is performed in the forging workshop. Fig. 9 shows the six lines connected by the corner points of the chess, and the actual length value of each line is 765mm in planar pattern. The lengths of the six lines are measured by using the CCD cameras parameters listed in Table 4. The reconstruction results are shown in Table 3, where the RMS is 1.539 mm, and the relative error of dimension measurement is less than 0.338%, which is allowable in the workshop.

(a) (b)

Fig. 9. Reconstruction of the known edges in the left image (a) and in the right image (b).

Table 4. Diameter measurement results of the light stripes.

No.	1	2	3	4	5	6
Measurement value (mm)	765.6396	765.1543	764.1616	763.3969	763.0474	762.4139
Relative error (%)	0.083	0.020	0.110	0.210	0.255	0.338

6. Conclusions

In this paper, a calibration method of binocular vision system is presented, for large forging dimension measurement. The intrinsic parameters of CCD camera are initially estimated by using the projected patterns and cameras orthogonal motions. The extrinsic parameters of CCD camera are initially calculated by eigenvalue decomposition of essential matrix, and the planar pattern. Moreover, the radial distortion coefficient of camera lens is considered and estimated by virtue of the epipolar constraint, and the refined values of intrinsic and extrinsic parameters of CCD camera are obtained. The experiment results in forging workshop indicate that the proposed method is practicable and suitable for calibrating the CCD camera of dimension measurement system of large forging. Further study is suggested focusing on improving further the calibration precision by other nonlinear optimizations of camera parameters.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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