Optik 123 (2012) 731–734

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Stereo vision sensor calibration based on random spatial points given by CMM

Gang Chen [a,*], Yubo Guo [a], Hanping Wang [b], Dong Ye [a], Yanfeng Gu [c]

[a] Department of Automatic Measurement and Control, Harbin Institute of Technology, Harbin 150001, China
[b] College of Automatic Engineering, Qingdao University, Qingdao 266071, China
[c] School of Electronics information Engineering, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 31 December 2010
Accepted 29 May 2011

Keywords:
Stereo vision
Calibration
Spatial point
Coordinates measuring machine

ABSTRACT

This paper presents a new, high-precision calibration method for stereo vision sensor based on virtual template. Given 3D spatial points coordinates by coordinates measurement machine (CMM) and corresponding image points coordinates, the technique is realized by taking the projection matrix elements as unknown and using singular value decomposition to solve the least-squares solutions. The method avoids solving intrinsic and extrinsic parameters of each camera and introducing the calibration error which caused by template machining and measurement error. We measure the 3D coordinates of a group of random spatial points by the calibrated stereo vision sensor then compare the results with CMM measurement values, the errors are less than 0.05 mm in the Z axis direction, and less than 0.01 mm in the X and Y axis direction, the experiment results show that the technique is feasible and effective.

1. Introduction

As an essential topic in the computer vision field, Stereo vision aims to reconstruct the three-dimensional geometric information of a scene [1]. Stereo vision sensor consists of two indicators of the same camera and features by simple structure, easy to move, quick and easy data acquisition, a non-contact measurement, etc. So, it finds widely applied in online inspection of automobile manufacturing, autonomous navigation for mobile robot, remote sensing measurement, object coordinate measurement, industrial automation systems and so forth [2,3].

The realization of computer vision system relies on stereo vision sensor calibration as the premise and foundation. And through the establishment of a relational model between a known object and its corresponding image points, the exact model parameters can be obtained to determine the relationship between the three-dimensional coordinate of a point and its projective image coordinate in the camera plane. However, in the traditional stereo vision system calibration process, not only the parameters of the two cameras should be determined, but also the relative position and orientation of them. Through the information obtained by its 2D image, the 3D information about the measured target is found [4].

Presently, the most common calibration method is to place the calibration template of checkered or 3D pattern in the camera field of view, and the template can provide accurate coordinates of calibration points during this calibration process [5]. However, due to the limitation of manufacturing and measurement accuracy, it is difficult to improve the templates accuracy, and the errors of relative position of each point will bring calibration errors as well [6]. So, how to get accurate coordinates of calibration points is a significant task.

2. Stereo vision sensor imaging equation

The same spatial point form images respectively in the Left and right camera of a stereo vision sensor, and the relationship between its three-dimensional position and its corresponding location on the image is shown in Fig. 1.

Supposing in space, a point $P(X_w,Y_w,Z_w)$ formed the corresponding points p_1, p_2 in the two cameras respectively. And if the centers $O_{1,}$ O_2 of the two camera lens are as follows, then the equation of line $O_1\,p_1$ is shown below:

$$Z_{c1}\begin{bmatrix} X_{f1} \\ Y_{f1} \\ 1 \end{bmatrix} = \begin{bmatrix} m_{x1}^1 & m_{y1}^1 & m_{z1}^1 & m_1^1 \\ m_{x2}^1 & m_{y2}^1 & m_{z2}^1 & m_2^1 \\ m_{x3}^1 & m_{y3}^1 & m_{z3}^1 & m_3^1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \tag{1}$$

The establishment of this equation has been discussed in detail, so no introduction here [7]. The first equation is a 3×4 matrix, contains the intrinsic and extrinsic parameters of each camera, and called matrix m. After expanding the first equation:

$$\{ \tag{2}$$

* Corresponding author. Tel.: +86 13945067581.
E-mail address: chenganghit@hit.edu.cn (G. Chen).

0030-4026/$ – see front matter © 2011 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2011.05.030

Table 1
Inputted spatial points' coordinates (10 points).

ID	World coordinate system (mm)			Spatial point coordinate (pixel)			
				Left eye		Right eye	
	X_w	Y_w	Z_w	X_f	Y_f	X_f	Y_f
1	0	0	0	442.93	381.44	174.13	347.81
2	−8.1480	−11.4210	2.9710	422.83	377.78	161.10	343.57
3	−22.1650	11.8795	−7.8090	454.78	394.34	201.00	361.47
4	18.0490	38.5500	26.5725	507.16	335.92	226.11	304.67
5	−3.7330	91.2355	53.9115	576.47	294.19	316.76	264.39
6	−59.8490	132.5280	83.3125	609.24	258.44	394.96	228.51
7	−117.2000	62.8935	120.7160	490.53	218.21	310.69	186.56
8	−292.6290	124.7630	144.6385	514.70	219.24	428.17	188.46
9	−381.2740	17.8320	177.7030	372.48	198.74	321.82	167.25
10	−313.3690	−50.8145	94.45650	306.57	285.38	225.51	252.34

In the same way, the equation of line $O_2\,p_2$ is as follows:

$$Z_{c2}\begin{bmatrix} X_{f2} \\ Y_{f2} \\ 1 \end{bmatrix} = \begin{bmatrix} m_{x1}^2 & m_{y1}^2 & m_{z1}^2 & m_1^2 \\ m_{x2}^2 & m_{y2}^2 & m_{z2}^2 & m_2^2 \\ m_{x3}^2 & m_{y3}^2 & m_{z3}^2 & m_3^2 \end{bmatrix}\begin{bmatrix} X_W \\ Y_W \\ Z_W \\ 1 \end{bmatrix} \tag{3}$$

Expanding the third equation, the fourth set is got:

$$\{ \tag{4}$$

As a consequence, the equation group of the two lines is formed, and their intersecting point just is the point P. Given the values of this projection matrix elements and corresponding image point coordinates presented by the left and right camera in stereo vision sensor, its only coordinate $P(X_W, Y_W, Z_W)$ can be determined in the world coordinate system (O_W,X_W,Y_W,Z_W). But as an overdetermined set, a unique solution does not exist. In this case, singular value decomposition can be used to solve the least-squares solutions.

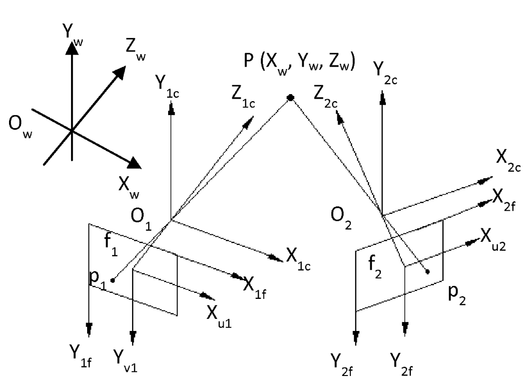

Fig. 1. Spatial points imaging model in the stereo vision.

3. Solution for projection matrix

During the calibration procedure, choosing six known points in the world coordinate system (O_W,X_W,Y_W,Z_W), after image processing, their corresponding image point coordinate (X_f, Y_f) is got, namely twelve equations which are more than the number of unknown parameters so that their solutions can be found. Supposing n spatial points ($n \geq 6$), we get $2n$ linear equations about matrix elements and the formation is shown below:

$$\begin{bmatrix} X_{w1} & Y_{w1} & Z_{w1} & 1 & 0 & 0 & 0 & 0 & -X_{w1}X_{f1} & -Y_{w1}X_{f1} & -Z_{w1}X_{f1} \\ 0 & 0 & 0 & 0 & X_{w1} & Y_{w1} & Z_{w1} & 1 & -X_{w1}Y_{f1} & -Y_{w1}Y_{f1} & -Z_{w1}Y_{f1} \\ & & & & \cdots & \cdots & \cdots & \cdots & & & \\ & & & & \cdots & \cdots & \cdots & \cdots & & & \\ X_{wn} & Y_{wn} & Z_{wn} & 1 & 0 & 0 & 0 & 0 & -X_{wn}X_{fn} & -Y_{wn}X_{fn} & -Z_{wn}X_{fn} \\ 0 & 0 & 0 & 0 & X_{wn} & Y_{wn} & Z_{wn} & 1 & -X_{wn}Y_{fn} & -Y_{wn}Y_{fn} & -Z_{wn}Y_{fn} \end{bmatrix} \times \begin{bmatrix} m_{x1} \\ m_{y1} \\ m_{z1} \\ m_1 \\ m_{x2} \\ m_{y2} \\ m_{z2} \\ m_2 \\ m_{x3} \\ m_{y3} \\ m_{z3} \end{bmatrix} = \begin{bmatrix} X_{f1} \\ Y_{f1} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ X_{fn} \\ Y_{fn} \end{bmatrix} \tag{5}$$

The abbreviated formula of Eq. (5) is shown as:

$$Wm = F \tag{6}$$

To reduce errors, in actual solving process, we should select more than 6 spatial points. When $2n > 11$, the least square method can be used to solve the over determined set.

Let $r = F - Wm$, under normal circumstances, over determined equations don't have ordinary meaning solution that is there is no existence of matrix m to make $r = 0$. To calculate this kind of equation, the m should be found firstly, and meet the condition:

$$||r||^2 = ||F - Wm||^2 = \min \tag{7}$$

Define m as the least squares solution for the equation $Wm = F$.

When solving the least squares solution, the generalized inverse matrix W^+ should be first got from its coefficient matrix W. Therefore, the solution for $Wm = F$ is $m = W^+F$.

Solving W^+ matrix is just to apply singular value decomposition method for W matrix and get two orthogonal matrices, as U and V matrix, which meet the condition $W = UAV^T$, where A is a n-order diagonal matrix and its diagonal elements are non-negative square roots of W^TW matrix eigenvalues.

$$A^+ = \mathrm{diag}(a_1^*, a_2^*, \cdots, a_n^*)$$

Therefore $W^+ = UA^+V^T$, among which,

$$a_i^* = \begin{cases} 0, a_i = 0 \\ 1/a_i, a_i \neq 0 \end{cases} \quad i = 1, 2, \ldots, n$$