A Novel Global Calibration Method for Multi-vision Sensors

Xinghua Li, Jingmei Zhang, and Peifen Chen

Abstract A novel high-precision global calibration method based on structured light and 2D target is proposed for the multiple vision sensors (MVS) measuring system. By capturing a series of feature points on the light plane at the same time, the relative position of local coordinate system and global coordinate system (GCS) can be acquired in the constraint condition of the uniqueness of a world point. The method is simple and low-cost, which is feasible for on-line measurement. The experiment is designed to illustrate the high-precision of the proposed method. The result shows that the average projection error is less than 0.5 pixel, which can meet the accuracy requirement of multiple camera.

Keywords Multi-sensor • Global calibration • Structure light • Local calibration

1 Introduction

Because of its high accuracy, timeliness, and other advantages, vision sensors measurement is widely used in industrial measurement in recent years [1, 2]. MVS measurement technology has obvious advantages in the industrial measurement. In MVS system, each sensor has independent coordinates, which make it impossible for different sensors to describe the scene in consistency, unless a global calibration is achieved.

Researches on the global calibration method of MVS have been done by lots of scholars and various solutions have been proposed. Kumar etc used plane mirror to achieve the global calibration [3]. This method requires a strict restriction for the location of the mirrors and the precision of calibration is not stable. Zhang Guang-jun etc suggested the global calibration based on 1D target [4]. It is simple, but only

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B. Zhang et al. (eds.), *The Proceedings of the Second International Conference on Communications, Signal Processing, and Systems*, Lecture Notes in Electrical Engineering 246, DOI 10.1007/978-3-319-00536-2_11,

one feature point can be obtained in each moving of the target and the extracting accuracy of feature point on target cannot be guaranteed. Hu Hao proposed a precise camera calibration method which based on close-range photogrammetry technology [5]. But this technique needs a large target and not portable, so it is inconvenient to use.

This paper proposed a simple and practical method of MVS's global calibration. The system just need a checkerboard which can be printed in lab and a structured light, What's more, this system has a lot of advantages. For example, it can calibrate the relationship of the position of all sensors quickly, the times of coordinate transformation in the proposed method are few. It has a high precision which has been confirmed by experiments.

2 Mathematical Model of Structured Light Vision Sensor

Figure 1 shows the geometrical model [6] of a structured light. The world coordinate frame and the camera coordinate frame $o_c\_x_c y_c z_c$ are the same, and the image plane coordinate are defined as $O\text{-}XY$. The relation between the world coordinates and the image coordinates can be illustrated by (1).

$$\begin{cases} \rho \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = A \begin{bmatrix} x \\ y \\ z \end{bmatrix} \\ ax + by + cz + d = 0 \end{cases} \tag{1}$$

$A = \begin{bmatrix} \alpha_x & 0 & \mu_0 \\ 0 & \alpha_y & \nu_0 \\ 0 & 0 & 1 \end{bmatrix}$ is the known intrinsic matrix of the camer.ρis a unknown scale. $ax + by + cz + d = 0$ is the function of the light plane in the world coordinate.

3 Global Calibration for Multi-vision Sensors

3.1 Calibration of Single Structured Light Vision Sensor

The process to calibrate a structured light vision sensor includes two parts: camera calibration and projector calibration.

As the camera calibration, we use Zhang's method [7] to get camera intrinsic parameters and distortion factors [8]. In the experiment, we will correct image distortion before processing image.

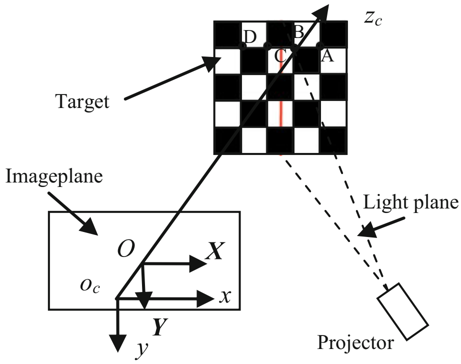

Fig. 1 Geometrical model of a structured light

As the projector calibration method, we use the method in the literature [6] and the method introduction is as follows.

Firstly we will determine the world coordinates of the target feature points. A plane chessboard is selected as the target. Corner points in each line of the chessboard can be seen as a 1D target, such as A B C D shown in Fig. 1. The laser should intersect with the target. The world coordinates of A C D are denoted by (x_A, y_A, z_A), (x_C, y_C, z_C) and (x_D, y_D, z_D). According to the relative positional relationship between the three points, we obtain the following equation:

$$(x_C, y_C, z_C)^T = (x_A, y_A, z_A)^T + h((x_D, y_D, z_D) - (x_A, y_A, z_A))^T \tag{2}$$

Where h is a known parameter. The image coordinates of A, C and D are denoted by (X_A, Y_A), (X_C, Y_C) and (X_D, Y_D), and they can be got from the Chessboard target. Depending on the camera imaging model and (2), we can get (3):

$$\begin{aligned}
&\alpha_x x_A - (X_A - \mu_0) z_A = 0 \\
&\alpha_y y_A - (Y_A - \nu_0) z_A = 0 \\
&\alpha_x x_D - (X_D - \mu_0) z_D = 0 \\
&\alpha_y y_D - (Y_D - \nu_0) z_D = 0 \\
&\alpha_x (1-h) x_A - \big(1-h\big)\big(X_C - \mu_0\big) z_A + \alpha_x h x_D - h\big(X_C - \mu_0\big) z_D = 0 \\
&\alpha_y (1-h) y_A - \big(1-h\big)\big(Y_C - \nu_0\big) z_A + \alpha_y h y_D - h\big(Y_C - \nu_0\big) z_D = 0
\end{aligned} \tag{3}$$

Because the distance L between A and D is known, we can get (4)

$$\|(x_D, y_D, z_D) - (x_A, y_A, z_A)\| = L \tag{4}$$

According to (3) and (4), we can get the world coordinates of the target feature points A and D. Then the world coordinates of point C can be determined by (2).

Secondly we will calculate the world coordinates of light plane feature point. The advantages of using corner points in each line of the chessboard as a 1D target are listed as follows. Firstly, at each position, more than one light plane feature points can be got. Secondly, the image coordinates of feature points in light plane can be determined by two intersecting lines: one line is fit by the structured light and the other is matched through each row corner points in chessboard, such as corner points A C D shown in Fig. 1. This can improve the accuracy of the image coordinates of light plane feature point. The image coordinates of B is denoted by (X_B, Y_B). According to the camera imaging model, we can get (5).

$$\rho(X_B, Y_B, 1)^T = A(x_B, y_B, z_B)^T \tag{5}$$

The relative positional relationship of A, B and D is described in (6)

$$(x_B, y_B, z_B)^T = (x_A, y_A, z_A)^T + h_x((x_D, y_D, z_D) - (x_A, y_A, z_A))^T \tag{6}$$

Where h_x is unknown. According to (5) and (6), we can get h_x and obtain the world coordinates of point B by (6).

Thirdly we will get light plane coefficients assuming. we freely place the target at n positions within the FOV, light plane feature points denoted as (x_{Bi}, y_{Bi}, z_{Bi}) (i = 1,2,3... kn) can be obtained and k can be determined by the size of the chessboard. According to (1), the following objective function are created:

$$e(t) = \sum_{i=1}^{kn} F(x_{Bi}, y_{Bi}, z_{Bi}) \tag{7}$$

Where F(x_{Bi}, y_{Bi}, z_{Bi}) = $(ax_{Bi} + by_{Bi} + cz_{Bi} + d)^2$. Using the least squares method, light plane coefficients a, b, c and d can be got. Calibration of single structured light vision sensor is finished.

3.2 Global Calibration for MVS

Figure 2 shows the arrangement of MVS system. V_iCF (i = 1,2,3) represented the coordinate system corresponding to each camera respectively. GCS was established in V_1CF, and transformed V_2CF, V_3CF to V1CF coordinate system respectively to complete the global calibration of MVS.

The key to the conversion between two coordinate systems is to obtain the [R, t] matrix that represents a relative positional relationship [9]. Take the solving of [R_{21}, t_{21}] between the local coordinate system V_2CF and the global coordinate system V_1CF as an example, then illustrated the idea of global calibration.

As shown in Fig. 2, the point P on the Light-receiving surface was marked (X_{P1}, Y_{P1}) in the camera 1, and marked (x_{P2}, y_{P2}, z_{P2}) in the camera 2, then the two coordinate must meet (8).

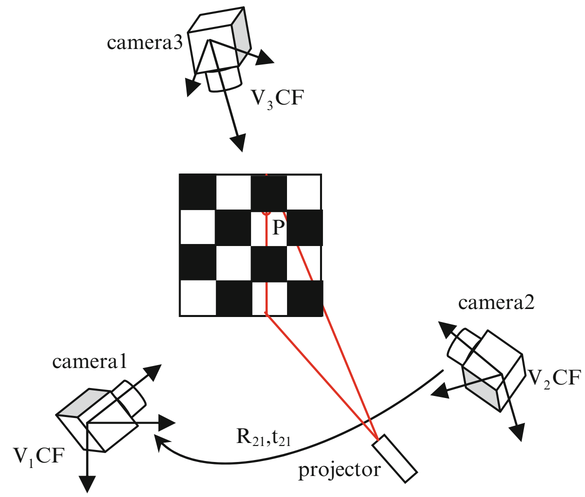

Fig. 2 The arrangement of MVS system

$$\rho \begin{bmatrix} X_{P1} \\ Y_{P1} \\ 1 \end{bmatrix} = A_1[R_{21}, t_{21}] \begin{bmatrix} x_{P2} \\ y_{P2} \\ z_{P2} \\ 1 \end{bmatrix} \quad (8)$$

The matrix A_1 represents the intrinsic parameters matrix of camera 1. $[R_{21}, t_{21}]$ represents the transformation from V_2CF to V_1CF. According to (8), if we get a series of image points in the camera1 and world points in the camera 2, we can obtain the outside parameter matrix $[R_{21}, t_{21}]$.

The following steps are used to complete global calibration:

1. According to Section 2, the positional relationship between the camera 2 and the light plane as shown in Fig. 2 can be determined.
2. Obtain the feature points in light plane by the chessboard. And camera 1 and 2 capture the images at the same time. Calculate the image coordinates (X_{P1}, Y_{P1}) of the feature point P in the camera 1.
3. Calculate the image coordinates (X_{P2}, Y_{P2}) of the feature point P in camera2.
4. According to the calibration results in step 1, calculate the world coordinates (x_{P2}, y_{P2}, z_{P2}) of the feature point P in the camera 2.
5. According to the size of the chessboard, we can get multiple image plane coordinates in camera1and world coordinates in camera 2 at each position. Then by freely moving the target, we can get enough image coordinate points in camera1 and world coordinate points in camera 2. Put the coordinates into (8), using the L-M optimization algorithm [10], we can obtain $[R_{21}, t_{21}]$.Other V_iFC (i = 3,4, ...) coordinate system can be transformed directly or indirectly through the above method. That is the global calibration method we proposed.

4 Experiment Result

The calibration results are shown as follows:
Camera 1: Intrinsic Matrx A_1

$$A_1 = \begin{bmatrix} 1605.638 & 0 & 640.945 \\ 0 & 1616.061 & 509.606 \\ 0 & 0 & 1 \end{bmatrix}$$

The radial and tangent distortion coefficients:
k_1 = -9.77 × 10-2, p_1 = 5.20 × 10-2, k_2 = 1.29 × 10-3, p_2 = -2.67 × 10-3
Camer 2: Intrinsic Matrx A_2

$$A_2 = \begin{bmatrix} 1607.821 & 0 & 674.013 \\ 0 & 1617.634 & 495.395 \\ 0 & 0 & 1 \end{bmatrix}$$

The radial and tangent distortion coefficients
k_1 = -8.65 × 10-2, p_1 = 4.13 × 10-2, k_2 = -2.17 × 10-3, p_2 = 1.16 × 10-3
Camer 3: Intrinsic Matrx A_3

$$A_3 = \begin{bmatrix} 1608.240 & 0 & 592.927 \\ 0 & 1618.168 & 477.667 \\ 0 & 0 & 1 \end{bmatrix}$$

The radial and tangent distortion coefficients:
k_1 = -8.67 × 10-2, p_1 = 8.60 × 10-2, k_2 = -9.17 × 10-3, p_2 = -9.72 × 10-3
The equation of the light plane1 under coordinate V_2CF:

$$x\text{-}0.017y - 0.588z + 293.375 = 0$$

The equation of the light plane2 under coordinate V_3CF:

$$x\text{-}0.002y - 0.692z - 324.375 = 0$$

The Rotation and Translation Matrix [R_{21},t_{21}]from V_2CF to V_1CF is:

$$[R_{21}, \mathrm{t}_{21}] = \begin{bmatrix} 0.561 & -0.0015 & -0.828 & 427.411 \\ -0.002 & 1 & -0.003 & -7.136 \\ 0.829 & 0.004 & 0.561 & 228.762 \end{bmatrix}$$

The Rotation and Translation Matrix [*R31*, *t31*] from V3CF to V1CF is:

Table 1 Calibration precision between camer 1 and camera 2

Feature point P	P's image coordinate in camera 1 (pixel)		P's image coordinate from camera 2 to camera 1 (pixel)		Δx	Δy
	X	Y	X'	Y'		
1	477.048	853.892	476.847	854.808	0.201	−0.916
2	462.476	771.734	462.458	772.521	0.018	−0.787
3	462.208	689.678	462.214	690.271	−0.006	−0.593
4	461.942	607.334	461.970	607.752	−0.028	−0.418
5	461.674	525.060	461.726	525.253	−0.052	−0.193
6	461.407	443.111	461.481	442.970	−0.074	0.141
7	461.141	361.185	461.237	360.679	−0.096	0.506
8	460.874	279.586	460.993	278.536	−0.119	1.05
9	479.034	198.497	478.889	196.850	0.145	1.647
10	478.785	844.717	478.634	845.857	0.151	−1.14
Average error					0.014	−0.070

Table 2 Calibration precision between camer 1 and camera 3

Feature point P	P's image coordinate in camera1(pixel)		P's image coordinate from camera 3 to camera 1 (pixel)		Δx	Δy
	X	Y	X'	Y'		
1	618.832	711.188	617.965	710.689	0.867	0.499
2	619.108	636.875	618.386	636.039	0.722	0.836
3	619.385	562.212	618.809	561.259	0.576	0.953
4	619.663	487.515	619.23	486.732	0.433	0.783
5	619.94	412.923	619.649	412.466	0.291	0.457
6	620.217	338.214	620.068	338.241	0.149	0.027
7	620.495	263.548	620.486	264.323	0.009	0.775
8	620.771	189.235	620.9	189.309	0.129	0.074
9	669.176	775.666	668.73	775.679	0.446	0.013
10	669.475	704.014	669.116	703.525	0.359	0.489
Average error					0.398	0.476

$$[R_{31}, t_{31}] = \begin{bmatrix} 0.303 & 0.002 & 0.953 & 427.411 \\ 0.026 & 1 & -0.011 & -11.486 \\ -0.953 & 0.028 & 0.302 & 319.533 \end{bmatrix}$$

An experiment to verify the accuracy of the calibration result is designed. Feature point P on light plane is selected. Camera 1 and 2 capture P at the same time. We can get P's image coordinate (X_{P1}, Y_{P1}) in camera 1.and P's world coordinate(x_{P2}, y_{P2}, z_{P2}) in camera 2 can be calculated according to the calibration result above. Equation (8) can make it possible to translate the coordinate (x_{P2}, y_{P2}, z_{P2}) to camera 1's image coordinate (X_{P1}', Y_{P1}'). The D-value between (X_{P1}, Y_{P1}) and (X_{P1}', Y_{P1}') could illustrate the precision of the calibration result. And the results are shown in Tables 1 and 2.

Ten feature points are obtained from light plane1 and 2. Calibration precision between camer1 and camera 2: the average reproject error in coordinate x is 0.014 pixel and -0.07 pixel in coordinate y. Calibration precision between camer 1 and camera 3: the average reproject error in coordinate x is 0.398 pixel and 0.476 pixel in coordinate y. The results of the experiment show that the method proposed above is feasible as well as high-precision.

5 Conclusions

The novel global calibration method for MVS proposed in this paper, which involved a structured light and plane target, provides a good accuracy. The method makes use of the uniqueness of the feature point to calculate the rotation and translations matrix between MVS. It is easy to use on-site with limited space. The target is easy to make with low-cost. What's more, the real experiment results show a good performance of the proposed methods.

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