

A Simple Calibration Method of Structured Light Plane Parameters for Welding Robots

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Abstract: It is necessary to calibrate the structured light plane parameters in addition to the camera intrinsic parameters for structured light vision systems. Besides, structured light plane parameters calibration should be simple and practical on the premise of being accurate. In this paper, a simple calibration method of structured light plane parameters for welding robots is proposed. In the process of camera intrinsic parameters calibration, structured light plane parameters can be calibrated simultaneously. Two feature points on the laser stripe are extracted firstly. Then, another two feature points on the laser stripe are extracted while the robot moves from one calibrating position to another with constraints so that two misaligned laser stripes are generated. Then, the structured light plane parameters could be determined using four points on the structured light plane. What's more, special calibration objects and manual measurements are not required in this method. Therefore, it is a simple and practical calibration method. Finally, a calibration experiment and two vision measurement experiments are implemented. Experimental results show that the structured light plane calibration accuracy could meet the requirement of welding robot.

Key Words: Calibration, structured light, welding robot

1 Introduction

Structured light vision measurement is considered a promising visual measurement method due to its high accuracy, good real-time and anti-interference capability [1-2]. When the structured light visual sensing system is used as a three dimensional information measurement, there are two classes of methods [3]. The first class of methods is stereo-structured light vision, where the images of light stripe are acquired by two or more cameras simultaneously and the three dimensional (3-D) coordinates of feature points are calculated by stereo visual match method. This class of methods only needs to calibrate camera intrinsic parameters. It is not need to calibrate the structured light plane parameters. The other class of methods is monocular-structured light vision, which uses one camera and one laser to realize the 3-D measurement. Compared with the first method, it has several advantages such as lower cost and higher precision. According to the intrinsic and extrinsic parameters of camera model, we know that monocular vision lacks depth information. Thus, we need additional information from the structured light plane. It is necessary to calibrate the structured light plane parameters and the calibration accuracy has a direct impact on the 3-D measurement.

In regard to structured light plane calibration, many different researches have been proposed [3-8]. The calibration method could be divided into two categories based on the calibration objects. One method uses specific calibration objects, which has two defects. On the one hand, it is difficult to manufacture precise objects. On the other hand, from the objects it could only get a few feature points.

G. Xu et al. [4] proposed a method to calibrate the structured light plane based on cross-ratio invariance. A trapezoidal block and a wedge block targets were used to get feature points. The 3-D coordinates of feature points can be calculated precisely. The other method uses common planar objects or even does not use any object. D. Xu et al. [2] used the target plane and the distance between two points on the laser stripe to establish linear equations containing structured light plane parameters. Then the parameters of structured light plane could be solved by least mean square method. F. Zheng [5] used the intrinsic and extrinsic parameters of the camera to estimate parameters of the structured light plane. However, these methods need manual measurements to get coordinates of the feature points on the planar targets. F. Zhou et al. [6] proposed a novel approach that employed the invariance of a cross-ratio to construct an arbitrary number of calibration points on the light stripe plane by viewing a plane from unknown orientations. However, this method needs to know the local coordinates of more than three points on the features lines in advance. Z. Wang et al [7] proposed a method which did not need to calibrate the camera intrinsic, extrinsic parameters and structured light parameters. The 3D coordinates of points corresponding to the image points can be obtained through perspective projection model, cross-ratio invariability and vanishing points. Y.B. Zhang et al. [8] used a homography matrix between the image and light plane to achieve 3-D reconstructions. However, these methods require particular calibration objects.

The accuracy of the above calibration methods can be guaranteed, but the calibration process is complex. From the perspective of an industrial requirement, calibration should be simple and practical on the premise of being accurate [9]. In this paper, a simple calibration method of structured light plane parameters is proposed. Firstly, the laser source projects a structured light plane onto the planar grid target

* This work is supported by the National Natural Science Foundation of China under Grant 61305024, 61373337, 61573358, and by the Foundation for Innovative Research Groups of the National Natural Science Foundation of China under Grant 61421004.

forming a structured light stripe and the image of the stripe is captured by the CCD camera. Then, the image is processed and two feature points on the laser stripe are extracted. Another two feature points on the laser stripe are extracted on the same method while the robot moves from one calibrating position to another position with constraint so that two misaligned laser stripes are generated. Finally, the structured light plane parameters could be determined using four points on the structured light plane. In the process of the camera intrinsic parameters calibration, structured light plane parameters can be calibrated simultaneously. What's more, special calibration objects and manual measurements are not required in this method.

This paper is arranged as follows. Section II describes the calibration system. Section III describes the camera pinhole model. Section IV elaborates on the calibration process of structured light plane parameters. Section V provides a structured light plane experiment and two sets of vision measurement experiments. Finally, some conclusions are drawn in Section VI.

2 Calibration System

The calibration system is shown in Fig.1, which is composed of four parts: an industry robot, a CCD camera, a laser source, and a planar grid target. The CCD camera and the laser source are fixed at the robot end link. The planar grid target is placed on the workbench. The laser source projects a structured light plane onto the planar grid target forming a laser stripe that could be captured by the CCD camera. As shown in the Fig.1, the camera frame Σ_c is located at the camera center, and the world frame Σ_w is located on the planar grid target.

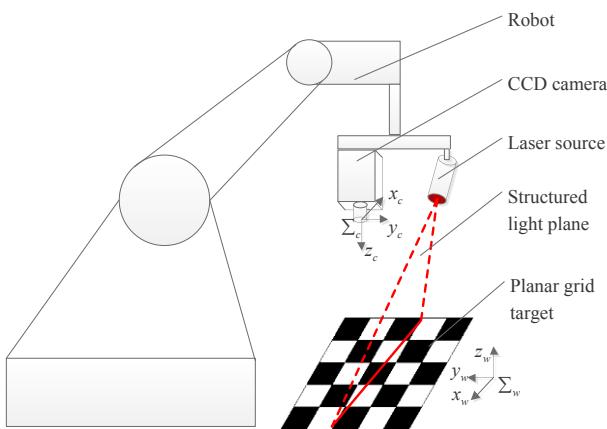


Fig. 1: The illustration of the calibration system

3 Camera Pinhole Model

In this paper, we adopt the camera pinhole model. According to the camera's perspective projection model [10], the fundamental equation of the pinhole model is expressed as (1).

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \frac{1}{z_c} \begin{bmatrix} k_x & 0 & u_0 \\ 0 & k_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \frac{1}{z_c} M_c \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \quad (1)$$

Where (u, v) are the coordinates of a point in an image, (u_0, v_0) are the coordinates of principal point of the camera, (k_x, k_y) are the magnification coefficients of X axis and Y axis respectively, (x_c, y_c, z_c) are the 3-D coordinates of a point in the camera coordinate system, M_c is the camera intrinsic parameters matrix.

In (1), the relationship between a point in the image frame and camera frame is conducted. The relationship between a point in the camera frame and the world frame is expressed as (2).

$$\begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = {}^c M_w \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} \quad (2)$$

Where (x_w, y_w, z_w) are coordinates of a point in the world frame, ${}^c M_w$ is the extrinsic parameters matrix which is the transformation matrix from the camera frame to the world frame consisting of a rotation matrix R and a translation matrix P .

According to X. Feng's study, Zhang's method has the best practicability and validity [11]. In this paper, we adopted Zhang's method to calibrate the intrinsic and extrinsic parameters.

4 Structured Light Calibration

Assume the equation of the structured light plane in camera coordinate system is

$$z = ax + by + c \quad (3)$$

The feature point's coordinates on the laser stripe in camera coordinate system can be calculated by combining (1) and (3), therefore

$$\begin{cases} z_c = ck_x k_y / (k_x k_y + ak_y(u_0 - u) + bk_x(v_0 - v)) \\ x_c = z_c(u - u_0) / k_x \\ y_c = z_c(v - v_0) / k_y \end{cases} \quad (4)$$

Calibrating structured light plane parameters is aimed at getting the value of a, b and c.

4.1 Image Acquisition

The image is acquired when camera parameters are calibrated. At first, the checkerboard is placed on the workbench. At this position, the image is captured by the camera as shown in Fig. 2(a). Then, the structured light is turned on and the image of the chessboard with the light stripe at the same pose is captured as shown in Fig. 2(b).

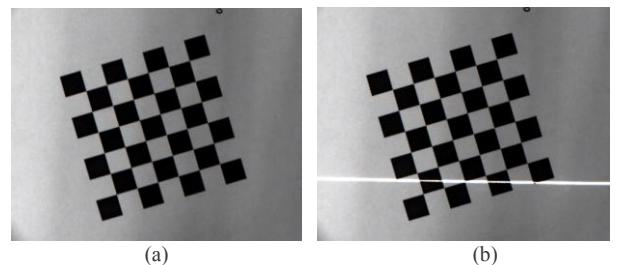


Fig. 2: The first set of chessboard image

We change the position and orientation of the chessboard

under some constraints that chessboard rotates around the X axis or Y axis of the camera coordinates system so that two misaligned laser stripes are generated. Then, we repeat the above step. Two images are captured as shown on the Fig. 3.

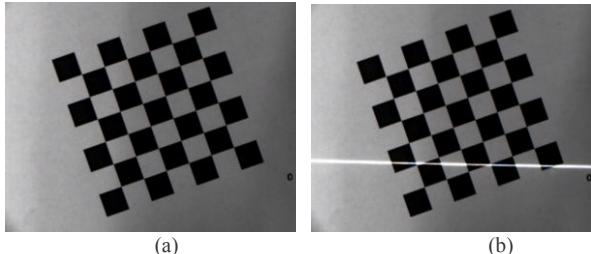


Fig. 3: The second set of chessboard image

4.2 Image Processing

1) ROI computation: Since the laser stripe is approximately parallel with the u-axis of the image, the ROI can be computed by projecting the gray value onto v-axis. The projection operation is carried out as follows, and the projection result is shown in Fig. 4.

$$J_v(i) = \sum_{j=1}^w I(i, j) \quad (i = 1, 2, \dots, h) \quad (5)$$

Where $J_v(i)$ is the projection of i-th row of pixels on v-axis, and w and h are the width and height of the image respectively.

The ROI of the laser stripe in the image is computed as follows:

$$\begin{cases} [x_{\min}, x_{\max}] = [1, w] \\ [y_{\min}, y_{\max}] = [v_c - \Delta y, v_c + \Delta y] \end{cases} \quad (6)$$

Where $[x_{\min}, x_{\max}]$ and $[y_{\min}, y_{\max}]$ are the x-range and y-range of the ROI of the laser stripe, Δy is the threshold value for computing the y-range, and v_c is the row index with greatest projection.

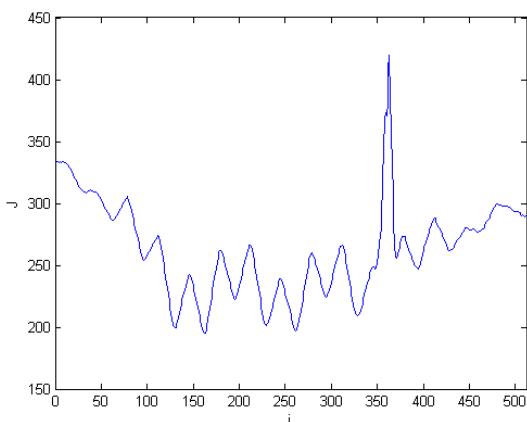


Fig. 4: The projection of gray value

2) adaptive thresholding: The row of pixels with the laser stripe has the greatest projection value. Therefore, the adaptive threshold value for segmenting the laser stripe from the image is computed as follows:

$$t = k \frac{\max\{J_v(i)\}}{w} \quad (7)$$

Where t is the threshold value for the laser stripe, and k is proportionality coefficient.

3) Skeleton thinning: In this paper, we adopt the fast parallel thinning algorithm presented in [12] to get the skeleton of the laser stripe. This algorithm consists of two steps, one is aimed at deleting the southeast boundary points and northwest corner points, and the other one is aimed at deleting the northwest boundary points and the southeast corner points.

In the first step, the point P_1 is deleted if it satisfies the following conditions:

- (a) $2 \leq B(P_1) \leq 6$
- (b) $A(P_1) = 1$
- (c) $P_2 P_4 P_6 = 0$
- (d) $P_4 P_6 P_8 = 0$

where $P_i (i = 1, 2, \dots, 9)$ is shown in Fig. 5, $p_i = 0$ or 1, $B(P_1) = P_2 + P_3 + \dots + P_8 + P_9$, $A(P_1)$ is the number of 01 alternate mode in the ordered set $P_2, P_3, \dots, P_8, P_9$.

In the second step, the same operations are carried out except that only conditions c and d are changed, as follows:

- (c') $P_2 P_4 P_8 = 0$
- (d') $P_2 P_6 P_8 = 0$

P_9	P_2	P_3
P_8	P_9	P_4
P_7	P_6	P_5

Fig. 5: The pattern of P_i

4) Feature extraction: The intersections of a quarter and three quarters vertical lines of the image and the laser stripe are defined as the feature points of the laser stripe. Therefore, the laser stripe line must be first extracted.

Least square line fitting technique is adopted here to extract the feature line based on the thinned skeleton. Suppose the laser stripe line is

$$y = kx + b \quad (8)$$

Where k and b are the slope and intercept of the feature line respectively.

The least square line fitting process is as follows:

$$\left\{ \begin{array}{l} \tilde{k} = \frac{\sum_{i=1}^n x_i y_i - n \bar{x} \bar{y}}{\sum_{i=1}^n x_i^2 - n \bar{x}^2} \\ \tilde{b} = \bar{y} - \tilde{k} \bar{x} \end{array} \right. \quad (9)$$

Where \tilde{k} and \tilde{b} are the parameters of fitted feature lines, $(x_i, y_i) (i = 1, 2, \dots, n)$ are the inner points, n is their number, and (\bar{x}, \bar{y}) are the average coordinates of the inner points.

The image feature points are computed as follows:

$$\begin{cases} X_1 = 0.25w \\ Y_1 = 0.25w\tilde{k} + \tilde{b} \end{cases} \quad (10)$$

$$\begin{cases} X_2 = 0.75w \\ Y_2 = 0.75w\tilde{k} + \tilde{b} \end{cases} \quad (11)$$

Where (X_1, Y_1) are the coordinates of the first feature point of the laser stripe and (X_2, Y_2) are the coordinates of the second feature point of the laser stripe. The completed image processing procedure and feature extraction result is shown in Fig. 6.

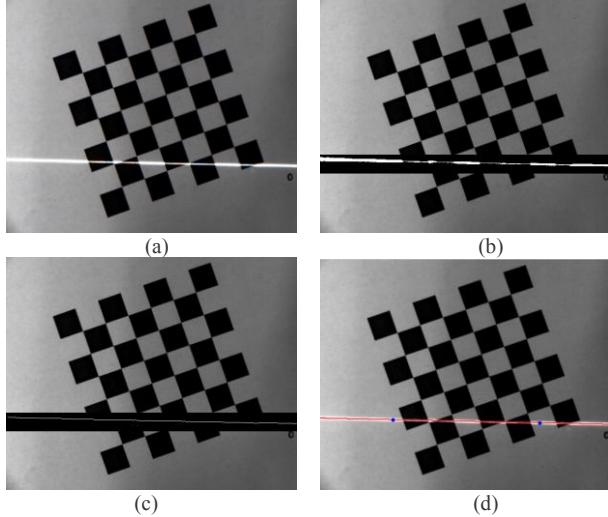


Fig. 6: The procedure of image processing. a Original image. b ROI and adaptive thresholding of laser stripe. c Thinned laser stripe. d The extracted feature lines and feature points

4.3 Parameters Computation

From the previous steps, two feature points in each image are derived. According to (1), we can get

$$\begin{cases} u = k_x x_c / z_c + u_0 \\ v = k_x y_c / z_c + v_0 \end{cases} \quad (12)$$

It is clear that z_w of the feature points in the chessboard is zero. Thus, according to (2), we can get

$$a_x(x_c - p_x) + a_y(y_c - p_y) + a_z(z_c - p_z) = 0 \quad (13)$$

Thus, the z-coordinates of the feature points in the camera frame can be calculated by (14).

$$z_c = \frac{a_x p_x + a_y p_y + a_z p_z}{(u - u_0) a_x / k_x + (v - v_0) a_y / k_y + a_z} \quad (14)$$

The x-coordinates and y-coordinates of the feature points in the camera frame can be calculated by (4) and (14).

From the above steps, we can get coordinates of four feature points in the camera frame. Thus, the number of points is sufficient for the calculation. Least square fitting technique is used here to get the structured light plane parameters. The least square fitting process is as follows:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i \\ \sum x_i & \sum y_i & n \end{bmatrix}^{-1} \begin{bmatrix} \sum x_i z_i \\ \sum y_i z_i \\ \sum z_i \end{bmatrix} \quad (15)$$

5 Experiment on The Structured Light Vision Measurement

5.1 Experiment on the Structured Light Plane Parameters Calibration

As shown in Fig. 7, the structured light plane parameters calibration experiment system consists of a 6-dof MOTOMAN UP6 robot; a CCD camera HV1351UM-M, the image acquired by the camera is 640×512 pixels; a red light semiconductor laser source, the power of the laser diode is 5mW, the wave length is 650 nm; a planar grid target, the size of the grid is 10×10 mm². The CCD camera and the laser source are fixed at the robot end link.

Through calibration, the CCD camera intrinsic and extrinsic parameters are shown as follows:

$$M_c = \begin{bmatrix} 1575.9153 & 0 & 320.0159 \\ 0 & 1576.9231 & 247.7847 \\ 0 & 0 & 1 \end{bmatrix}$$

$${}^c M_{w1} = \begin{bmatrix} -0.9593 & 0.2819 & 0.0146 & 15.3560 \\ 0.2820 & 0.9594 & 0.0021 & -27.8703 \\ -0.0134 & 0.0061 & -0.9999 & 332.8000 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^c M_{w2} = \begin{bmatrix} -0.3277 & -0.9439 & 0.0417 & 34.7498 \\ -0.9447 & 0.3281 & 0.0023 & 14.6916 \\ -0.0159 & -0.0386 & -0.9991 & 301.7768 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

${}^c M_{w1}$ and ${}^c M_{w2}$ represent the extrinsic parameters matrix of chessboard at location 1 and 2 respectively.

The estimated parameters of the structured light plane are as follows:

$$a = -0.0696, b = 4.5914, c = 202.1216$$

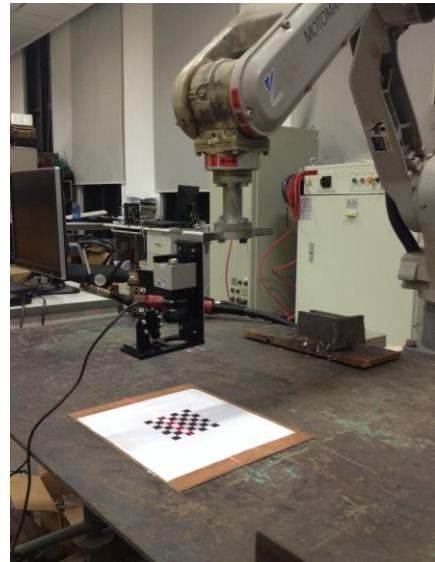


Fig. 7: The experiment scene of the structured light plane parameters calibration.

5.2 Structured light vision measurement experiment on planar target

Table 1: The feature points' coordinate measurement data and accuracy evaluation

No.	Image coordinate		coordinate(camera frame)			Distance	coordinate(target frame)			Distance	ΔD (mm)
	u(pixel)	v(pixel)	X(mm)	Y(mm)	Z(mm)		X(mm)	Y(mm)	Z(mm)		
1	176	380	-30.35	27.84	332.07		54.05	0.00	0.00		
2	224	380	-20.16	27.75	330.91	10.25	52.15	10.00	0.00	10.18	-0.07
3	272	381	-10.10	27.99	331.34	10.08	50.38	20.00	0.00	10.16	0.08
4	321	382	0.21	28.24	331.75	10.31	48.38	30.00	0.00	10.20	-0.11
5	369	382	10.28	28.14	330.60	10.13	46.42	40.00	0.00	10.19	0.06
6	416	383	20.37	28.38	331.03	10.11	44.62	50.00	0.00	10.16	0.05

As shown in Fig.8, the structured light plane fall onto the planar target forming a structured light stripe. It is obvious that the structured light stripe is intersected with each square and six intersections on the stripe line can be chosen as feature points.

According to (4), the 3-D coordinates of each feature point on the laser stripe line in the camera frame can be calculated based on the structured light plane calibration results. The distance based on the structured light vision measurement model and the distance based on intrinsic and extrinsic parameters of camera is 0.0746, and the root mean square (RMS) is 0.0780 mm.

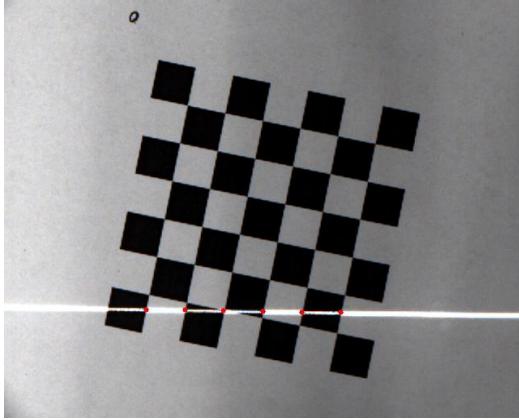


Fig. 8: The structured light stripe on a planar target

5.3 Structured light vision measurement experiment on multiple V-shape target

The structured light plane falls onto the multiple V-shape target, forming a deformed laser stripe, as shown in Fig. 9.

Along a section of the multiple V-shape target, deformed laser stripe is captured 6 times. It is obvious that the 3-D coordinates of each feature point on the deformed laser stripe in the camera frame can be calculated based on the structured light plane calibration results.

As shown in Table 2, Points A_1 , A_2 , A_3 and Points C_1 , C_2 , C_3 stand for the outer edge points along the multiple V-shape target, and points B_1 , B_2 , B_3 stand for the bottom edge points along the multiple V-shape target. The coordinates of feature points on the laser stripe are given in the base frame of the welding robot.

The 3-D spatial data diagram is shown in Fig.10, where the symbol ‘o’ stands for two outer edge points of the multiple V-shape target and the symbol “*” stands for the bottom edge points of the multiple V-shape target. In regard to the multiple V-shape target, the heights between two outer edges and the bottom edge are fixed. From this point, the

root mean error is 0.096 mm. Thus, the calibration method proposed in this paper can meet the precision requirement of welding robot.



Fig. 9: The experiment scene of the structured light vision measurement on multiple V-shape target

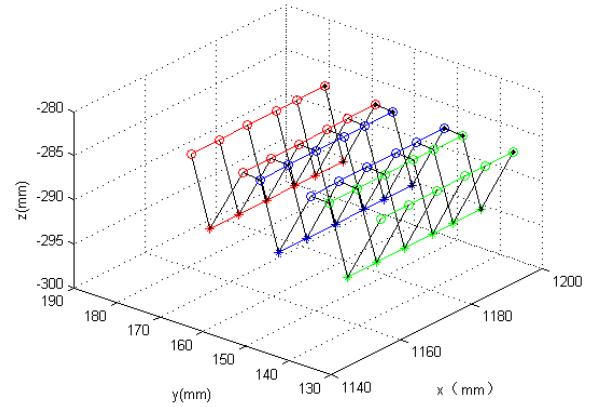


Fig. 10: The 3-D spatial data diagram of multiple V-shape target.

6 Conclusion

In this paper, a simple calibration method of structured light plane parameters for welding robots is proposed. The image is processed and two feature points on the laser stripe are extracted firstly. Then, another two feature points on the laser stripe are extracted while the robot moves from one calibrating position to another with constraints so that two

Table 2: The structured light vision measurement experiment on multiple V-shape target

No		A1	B1	C1	A2	B2	C2	A3	B3	C3
1	X(mm)	1199.97.	1197.99	1199.75	1199.64	1197.72	1199.48	1199.38	1197.44	1199.22
	Y(mm)	180.97	174.98	168.80	164.69	158.67	152.68	148.36	142.33	136.16
	Z(mm)	-287.69	-294.81	-287.72	-287.85	-294.77	-287.66	-287.76	-394.73	-287.54
2	X(mm)	1192.05	1190.07	1191.83	1191.72	1189.80	1191.56	1191.46	1189.52	1191.30
	Y(mm)	180.98	174.99	168.82	164.70	158.69	152.70	148.38	142.35	136.18
	Z(mm)	-287.70	-294.82	-287.73	-287.86	-294.79	-287.66	-287.77	-294.74	-287.55
3	X(mm)	1186.16	1184.189	1185.94	1185.84	1183.91	1185.68	1185.57	1183.64	1185.42
	Y(mm)	180.93	174.94	168.76	164.64	158.63	152.64	148.32	142.29	136.12
	Z(mm)	-287.68	-294.80	-287.72	-287.84	-294.76	-287.65	-287.75	-294.72	-287.53
4	X(mm)	1178.07	1176.10	1177.85	1177.75	1175.82	1177.59	1177.48	1175.55	1177.33
	Y(mm)	180.92	174.93	168.76	164.64	158.62	152.63	148.31	142.28	136.11
	Z(mm)	-287.72	-294.84	-287.75	-287.88	-294.80	-287.68	-287.79	-294.76	-287.57
5	X(mm)	1170.06	1168.09	1169.84	1169.74	1167.81	1169.58	1169.47	1167.54	1169.32
	Y(mm)	180.87	174.89	168.71	164.59	158.58	152.59	148.27	142.24	136.07
	Z(mm)	-287.72	-294.84	-287.75	-287.88	-294.80	-287.68	-287.79	-294.76	-287.57
6	X(mm)	1162.01	1160.03	1161.79	1161.68	1159.76	1161.52	1161.44	1159.48	1161.26
	Y(mm)	180.83	174.84	168.66	164.55	158.53	152.54	148.22	142.19	136.02
	Z(mm)	-287.73	-294.84	-287.76	-287.88	-294.80	-287.69	-287.80	-294.76	-287.58

misaligned laser stripes are generated. Then, the structured light plane parameters could be determined using four points on the structured light plane. What's more, particular calibration objects and manual measurements are not required in this method. In the process of the camera intrinsic parameters calibration, structured light plane parameters can be calibrated simultaneously. Finally, a calibration experiment and two vision measurement experiments are implemented. Experimental results show that the structured light plane calibration accuracy could meet the requirement of welding robot. In the future, we plan to make research on welding seam tracking using calibration results.

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