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# Calibration of line structured light vision system based on camera's projective center

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**Abstract**: Based on the characteristics of line structured light sensor, a speedy method for the calibration was established. With the coplanar reference target, the spacial pose between camera and optical plane can be calibrated by using of the camera's projective center and the light's information in the camera's image surface. Without striction to the movement of the coplanar reference target and assistant adjustment equipment, this calibration method can be implemented. This method has been used and decreased the cost of calibration equipment, simplified the calibration procedure, improved calibration efficiency. Using experiment, the sensor can attain relative accuracy about 0.5%, which indicates the rationality and effectivity of this method.

**Key words**: line structured light sensor; vision system; coplanar reference target; calibration; light plane

## 1　Introduction

A vision measurement method based on line structured light[1], with the characteristic of simple structure, nice flexibility, fascinating speed, moderate precision and strong resistance to disturbance, is a developed non-touching technology, which has been widely applied in many fields such as high-speed online inspection, quality control and reverse engineering. However, the optical plane of the line structured light sensor, determined by the beam distribution of the light projector and light stripe software arithmetic, is imaginary and can not be easily detected by common instruments as other general mechanical planes. Consequently, it becomes really difficult to make sure of the relationship between the camera and the optical plane. In case of an access to the required precision, how to ascertain the position of the optical plane against the camera is the main focus in the process of calibration for vision inspection system.[1]

Currently, there are several popularly used methods for calibrating line structured light sensor, namely Mechanism Adjustment Method[2], Wire Drawing Scattering Method[3] and Zigzag Calibration Method[4]. Mechanism Adjustment Method is something like this: firstly, to place the optical plane at a certain position due to personal experience in addition to using some adjusting equipment, and then to attain the accurate localization with the help of ideal perspective model. The primary drawback of this method lies in its relatively low precision, involving too much manual adjustment. The principle of Wire Drawing Scattering Method can be described as follows: To project the optical plane to some filaments which are non-coplanar and to measure

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the world coordinates of the points by using corresponding instruments. By comparing the coordinates of the points in the image plane and in the world coordinate, we can calculate to obtain the spacial relationship between the camera and the optical plane. In this method, the scattering points themselves show the light intensity distribution, which causes the non-consistency between the points aimed by the instruments and the points extracted through the images. Moreover, the scattering ability of filaments and the actually measured surface are not equal, which induces that the calibrated optical plane and the measured optical plane are not identical. This unavoidably brings about error to the measurement. Zigzag Calibration Method also does not fit for online calibration in virtue of the fact that it calls for external supplementary equipment in order to make the optical plane vertical to a standard plane and what's more, the points are not easy to extract because the points used for calibration are few and the zigzag arris is apt to glisten.

Nowadays, another calibration method making use of cross ratio invariance[5] is improved. If we have known the exact coordinates of three points in a line at least, which are located in a three-dimensional reference target, we can attain the coordinate of the point of intersection formed between the line structured light stripe and the line. Nevertheless, this method requires no less than two mutual vertical planes in order to constitute a high precision three-dimensional reference target. As a result, the planes are shielded from one another and we can not acquire highly accurate images. Meanwhile, we can not obtain many points useful for calibration.

Considering the shortages mentioned above, this paper proposes a high-speed method for the calibration of line structured light sensor, in which we can calibrate the position parameter between the optical plane and the projective center of the camera, only using one coplanar reference target. This method calls for no additional adjustment equipment. Additionally, this method avoids the planes sheltering from each other, and dosen't face with the question of the inconsistence of the physical point and the gathering point. We can calculate equations of two non-superposition lines in optical plane and then attain the equation of the optical plane due to the information of the projective center and the light stripe on the camera's image surface. Thus, we can finally calibrate the relationship between the optical plane and the camera, and the calibration arithmetic is simplified.

## 2 Calibration of parameters

Concretely, calibration includes two parts: One is the calibrations of the camera's inner parameters[6]; the other is the calibrations of the spacial pose of the camera and optical plane.

### 2.1 Calibration of camera's inner parameters

The calibration of the camera's inner parameters can adopt several principles such as calibration of a camera using a single view of a coplanar set of points[7], calibration of a camera using a single view of a non-coplanar set of points[8] and calibration of a camera using self-calibration technology[9]. Considering the practical application background of the sensor: the object distance of the camera is about 400 ~ 450 mm, the angle of the field of view of the camera is about 8° and the effective depth of field is about 50 mm. In the condition mentioned above, it is suitable to adopt calibration of a camera using a single view of a non-coplanar set of points.

In the calibration of the camera's inner parameters, if the lens is a wide-angle lens, it should consider radial distortion, tangential distortion and thin prism distortion; And if it is a simple lens, radial distortion can completely describe the nonlinear distortion. If more complex distortion parameters are considered, the solution of the equation would be instability. In this experiment, we choose *Watec* 902*H* camera, its angle of the field is 7.37°. This belongs to simple camera, so in the calibration, we only consider the radial distortion.

Adopting the calibration of a camera using a single view of a non-coplanar set of points, the structure of the non-coplanar three-dimensional target shows in Fig. 1.

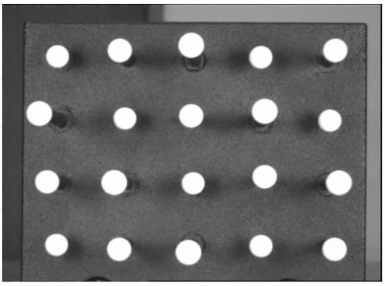

Fig. 1 Non-coplanar three-dimensional target used in calibration

According to the calibration of a camera using a single view of a non-coplanar set of points, these parameters need to be calibrated: the effective focus $f$ of the camera; the image plane center's coordinate $Cx$, $Cy$; image scale factor $Sx$ and distortion coefficient $K$. The result of the calibration is shown in Tab. 1.

**Tab. 1 Calibration result of camera's inner parameters**

| $f$ | $Cx$ | $Cy$ | $Sx$ | $K$ |
|---|---|---|---|---|
| 28.6885 | 359.33 | 318.41 | 1.018 | 0.0001658 |

## 2.2 Calibration of sensor

### 2.2.1 The theory of calibration

The calibration principle of this article, a speedy method for the calibration of line structured light sensor based on coplanar reference target, has been put forward, and includes seven steps as follows:

(1) A standard coplanar reference target, composed of several circular holes, is located in a plane with outstanding flatness. Measure the spacial relationship between each circular hole by coordinate measuring machine as reference appraisal parameters;

(2) Place the coplanar reference target in the structured light sensor's spacial measurement range;

(3) According to the known spacial relationship between the circular holes in the target and the screen coordinate of the circular holes, we can obtain the coplanar reference target's plane equation in the camera coordinate system;

(4) In the sensor's measurement range, the light projector projects light beam on the coplanar reference target plane, and the light beam intersects target plane at a straight-line. In virtue of the light stripe imaged on the camera's image surface, we can obtain the information of this light stripe;

(5) According to the camera's projective center and the light stripe imaged on the camera's image surface, a plane is confirmed. This plane intersects the target plane at a straight-line. Then a linear equation in the optical plane can be obtained;

(6) In the sensor's spacial measurement range, the target is moved to random position without restriction. Afterwards, shoot the second image. In virtue of the light stripe imaged on the camera's image surface, we can obtain the information of the second light stripe, also can obtain the second linear equation in the optical plane;

(7) According to the two straight-lines which are not matched together in the optical plane, the equation of optical plane can be obtained. Finally, we can calibrate the relationship between the optical plane and the camera.

And then, combining the calibration sketch, the process of the sensor's calibration is explained further detailedly.

As shown in Fig. 2, a standard coplanar reference target, composed of several circular holes, is located in the sensor's spacial measurement range.

When calibrating, firstly, put the coplanar reference target in position *i*, and the target is shot on the camera's image surface, at the mean time the circular holes' information in the image surface can be got. According to the known spacial relationship between the circular holes on the target and the screen coordinate of the circular holes, we can obtain the coplanar reference target's plane equation in the camera coordinate system (in position *i*). Simultaneously, the light projector P projects a light beam in the coplanar reference target (the real line shown in position *i*). Based on this real line imaged on the image surface and the camera's projective center, a plane can be confirmed. This plane intersects the coplanar reference target at a line (the real line showed in position *i*). According to the plane equations of this two intersected planes, the real line's equation can be defined; Secondly, in the sensor's spacial measurement range, under the condition of keeping the relative position of the light projector P and camera C immovability, the target is moved to random position *ii* without restriction. As step one, we can obtain the coplanar reference target's plane equation (position *ii*) and the linear equation of the projection on the coplanar reference target (the dashed line showed in position *ii*). Finally, according to the linear equation of projection in position *i* and the linear equation of projection in position *ii*, the optical plane's equation can be defined. Consequently, the relative position relationship between optical plane and the camera can be obtained and the calibration is implemented.

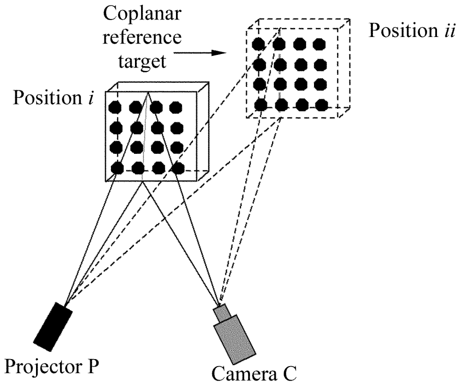

Fig. 2 Calibration of line structured light sensor

### 2.2.2 Procedure of calibration

The calibration process of line structured light sensor is shown in Fig. 3. $o_c x_c y_c z_c$ is camera coordinate system, $o_i x_i y_i z_i$ is the coordinate system established in the coplanar reference target, $o_{ii} x_{ii} y_{ii} z_{ii}$ is the coordinate system established in the coplanar reference target which has been moved to another position, $o_s x_s y_s z_s$ is the measurement coordinate; $o_c$ is the camera's projective center, $\pi_c$ is image plane, $\pi_s$ is optical plane, $\pi_i$ is the coplanar reference target's plane, $\pi_{ii}$ is the coplanar reference target's plane which has been moved to another position; $\pi_{ab}$ is the plane which is defined by the projective center $o_c$ and the straight linear $a_i b_i$, $\pi_{cd}$ is the plane which defined by the projective center $o_c$ and the straight linear $c_i d_i$; the point P is the light projector; the straight lines $A_i B_i$, $C_i D_i$, projected by the light projector P, are on planes $\pi_i$ and $\pi_{ii}$ respectively. The straight lines $a_i b_i$, $c_i d_i$ on image plane are the images of the straight lines $A_i B_i$ *and* $C_i D_i$.

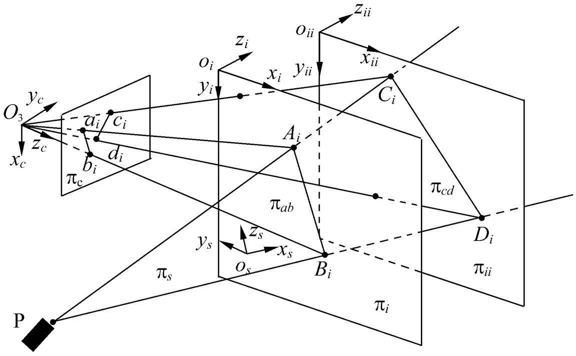

Fig. 3 Calibration process picture of line structured light sensor

According to the coordinates of circle holes' centers on the target, we can obtain the plane equation of plane $\pi_i$: $A_i x + B_i y + C_i z = D_i$; By means of image processing, the linear equation of straight line $a_ib_i$ on the camera's image surface can be defined: $y=k_{ab}x+b_{ab}$; And then we can define the plane equation of plane $\pi_{ab}$: $A_{ab}x+B_{ab}y+C_{ab}z=D_{ab}$ by the known point $o_c$ and the linear equation $y=k_{ab}x+b_{ab}$. For the straight line $A_iB_i$ is the intersection of plane $\pi_{ab}$ and plane $\pi_I$, we can define the linear equation of straight line $A_iB_i$ ($y=k_{AB}x+b_{AB}$) by simultaneous equations (1).

$$\begin{cases} A_ix+B_iy+C_iz=D_i \\ A_{ab}x+B_{ab}y+C_{ab}z=D_{ab}, \end{cases} \tag{1}$$

Then in the sensor's spacial measurement range, moved the target to random position $\pi_{ii}$ without restriction. In the same manner, we can obtain the plane equation of plane $\pi_{ii}$ ($A_{ii}x+B_{ii}y+C_{ii}z=D_{ii}$) and the plane equation of plane $\pi_{\mathrm{cd}}$ ($A_{cd}x+B_{cd}y+C_{cd}z=D_{cd}$).

$$\begin{cases} A_{ii}x+B_{ii}y+C_{ii}z=D_i \\ A_{cd}x+B_{cd}y+C_{cd}z=D_{cd}, \end{cases} \tag{2}$$

For the straight line $C_iD_i$ is the intersection of plane $\pi_{cd}$ and plane $\pi_{ii}$, we can define the linear equation of straight line $C_iD_i$ ($y=k_{CD}x+b_{CD}$) by simultaneous equations (2).

According to linear equations of straight line $A_iB_i$ and $C_iD_i$:

$$\begin{cases} y=k_{AB}x+b_{AB} \\ y=k_{CD}x+b_{CD}, \end{cases} \tag{3}$$

We can define the plane equation of plane $\pi_s$: $A_sx+B_sy+C_sz=D_s$. Consequently, we have finally calibrated the relationship between the optical plane and the camera.

## 3 Experiment and error analysis

The experiment consists of two steps and the first one is the calibration of the sensor, from which we can attain the plane equation of the optical plane in the camera coordinate system. Consequently, we can obtain the relative position of the optical plane against the camera. We execute all the measurement experiments under the condition that the sensor has been calibrated already.

### 3.1 Calibration of the sensor

We designed a two-dimensional coplanar reference target used in the experiment, as described in Fig. 4, It is characterized by twelve circular holes arranged in three lines and the centre of each circular hole as latent point. By moving the reference target in the measurement field of the line structured light sensor without restriction, we have got two images of the coplanar reference target shot by the camera, shown in Fig. 4 and Fig. 5.

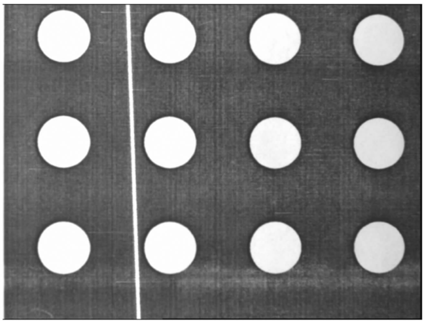

Fig. 4 Coplanar reference target in position *i*

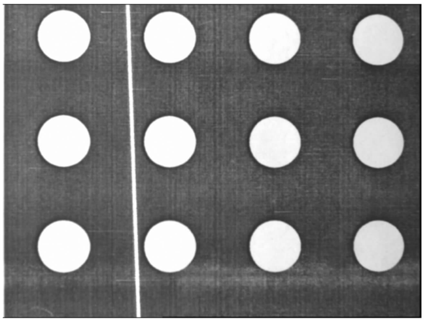

Fig. 5 Coplanar reference target in position *ii*

We can attain the plane equations of the coplanar reference target in position *i* and *ii* respectively, according to the coordinates of the circles′ centers in the images. After getting all the equations said above, we finally calculate the equation of the optical plane in the camera coordinate system with the help of two light information in the images.

Assuming a plane equation can be described as $Ax+By+Cz=D$ and We can see the parameters in Tab. 2.

**Tab. 2 Three plane equations' parameters**

| | $A$ | $B$ | $C$ | $D$ |
|---|---|---|---|---|
| Position *i* | −0.088158 | −0.10047 | 0.99103 | 462.181 |
| Position *ii* | −0.10920 | −0.11259 | 0.98762 | 431.270 |
| Optical plane | 0.89893 | 0.007579 | 0.43802 | 194.270 |

### 3.2 Measurement experiment

We also designed a measurement templet, as shown in Fig. 6. Firstly, we drew four parallel lines in the templet and the distances between each parallel line are measured by three-dimensional coordinate measuring system, and then we portrayed crossing hairs in order to make sure that the light is vertical to the parallel lines we first drew. The image acquired in this measurement experiment is described in Fig. 6.

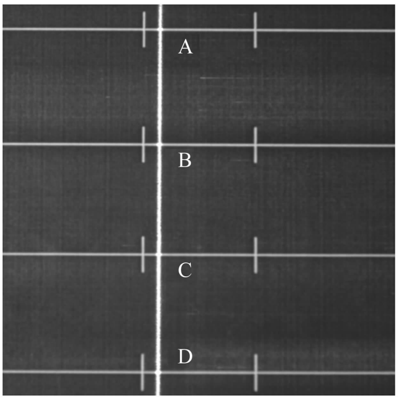

Fig. 6 Collected image by measurement experiment

The light intersects the four parallel lines at points $A$, $B$, $C$, $D$ respectively. The process of the measurement experiment can be stated as follows. Firstly, we measure the coordinate of these four points in the sensor coordinate, using the line structured light sensor that had been calibrated, we can see the results in Tab. 3. Secondly, took the distance of adjacent datum points as the appraise parameters; Finally compared the distance of the datum points which the sensor measured to the corresponding reference distance, the measurement deviation was obtained. The correlative results are shown in Tab. 4.

**Tab. 3 Coordinates of datum points (measured by the sensor)**

| | $x$ | $y$ | $z$ | Distance between adjacent points |
|---|---|---|---|---|
| $A$ | −4.50 | −39.43 | 453.43 | |
| $B$ | −6.04 | −19.24 | 456.34 | 20.41 |
| $C$ | −7.43 | −0.37 | 458.76 | 19.08 |
| $D$ | −8.88 | 19.91 | 461.54 | 20.51 |

Referencess distance $D$ is the distance of adjacent datum points which was measured by three-coordinate measuring machine; Measurement distance $D'$ is the distance of adjacent datum points which was measured by line structured light sensor. Deviation $\Delta$ is the difference between measurement distance $D'$ and reference distance $D$.

**Tab. 4 Measurement deviations**

| | $D$ | $D'$ | $\Delta$ |
|---|---|---|---|
| 1 | 20.517 | 20.41 | −0.107 |
| 2 | 18.985 | 19.08 | 0.095 |
| 3 | 20.493 | 20.51 | 0.017 |

From the measurement deviations in the Tab. 4, it indicates that the sensor can attain relative accuracy about 0.5%. The experiment results indicate that the calibration method which this article brings forward is reasonable and rational. And the experiment results have reached anticipation.

### 3.3 Error analysis

Theoretically, the measurement precision of the sensor can be prior to 0.3% due to the parameter of the camera. However, this can not be achieved because of the following reasons that we can hardly avoid in actual measure.

(1)Optical plane error

We consider the optical plane as an absolute plane in geometry and the light on the plane is well-proportioned, but both of them are impossible actually. Consequently, the measurement accuracy is introduced.

(2) Image processing error

Right now the experiment is proving, and haven't profoundly analyzed the arithmetic and the precision of the image processing. So the error of the image processing is an important factor of measurement error.

(3)Target error

The autologous reference accuracy of the target directly affects the calibrated accuracy of the camera and the sensor. So the target using in the experiment needs to be improved.

(4) Measurement light error

We can not make sure that the projection of the light is absolutely vertical to the parallel lines given by us(shows in Fig. 6). We call this non-verticality error.

## 4 Conclusion

In summary, this paper proposes a high-speed method for the calibration of line structured light sensor, whose overall process can be generalized in the following descriptions. A plane, determined by the projective center of the camera and the light information on the camera's image plane, intersects the coplanar reference target at a line. Likewise, we can obtain another line if we remove the coplanar reference target in the sensor's spacial measurement range without any restriction. And then we can calculate the optical plane according to these two non-superposition lines. As a consequence, we finally know the position relationship between the optical plane and the camera. This method requires no other additional adjustment equipment and has ascendant characteristics of high speed and efficiency. What's more, we can greatly reduce the cost of the equipment, simplify the calibration process and extend the application field of structured light sensor.

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