Relationship between the Line Structured Light Vision Calibration Accuracy and Hardware Parameters

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Abstract. The line structured light vision has better robustness and higher measurement accuracy as an active vision measurement method, which is widely used in the measurement of component size and shape tolerance. The calibration is a key technology of vision measurement. The calibration accuracy is not only affected by the calibration algorithm, but the parameters of the hardware equipment also have an important impact on the final calibration accuracy. Based on the analysis of the calibration algorithm, this paper conducts a theoretical analysis on the selection of the main hardware parameters, and uses the orthogonal experiment method to determine the relationship between the equipment parameters and the calibration accuracy. In the experiments, the aperture has the greatest impact on the calibration accuracy among the main equipment parameters, and the calibration accuracy is the highest when the camera aperture is between F4-F8.

Keywords: Line Structured Light Vision, Vision System Calibration, Orthogonal Experiment

1. Introduction

Machine vision is a comprehensive cutting-edge technology, and it can cover almost all inspection industries. Compared with traditional measurement methods, its detection accuracy, speed and stability are greatly improved [1-3]. The structured light-based vision measurement technology is a major type of active vision measurement technology, which is based on optical triangulation. According to different structured light shapes, the line structured light vision technology has the advantages of low hardware cost, high measurement efficiency, and measurement accuracy, which are widely used in mechanical manufacturing.

Line structure visual calibration can be divided into camera calibration and line structured light plane equation solving. The camera calibration is a process of solving the parameters of the imaging model. The existing camera calibration methods include linear method, nonlinear method, and two-step calibration method. The two-step method combines the advantages of the linear method and the nonlinear method, and this method is widely used camera calibration method. At present, the
method of Tsai R Y [4], the method of Heikkila J [5] and the method of Zhang Zhengyou [6] are the most used two-step camera calibration methods.

The Tsai R Y method first solves most of the camera parameters by establishing linear equations, and then introduces radial distortion to obtain the remaining few camera parameters through nonlinear optimization. The calculation speed of this method is fast, but because the distortion model is relatively simple, it cannot solve the camera distortion problem well. First, this method solves most of the camera parameters by establishing linear equations, and then the remaining camera parameters are obtained by nonlinear optimization of radial distortion. Although the calculation speed of this method is fast, because the distortion model is relatively simple, it cannot solve the camera distortion problem well. Heikkila J’s method first uses the transformation relationship between a space point and the pixel point projected on the CCD to establish a linear method, and then introduces radial and tangential distortion optimization to obtain camera parameters. Zhang Zhengyou first obtains the initial calibration value according to the orthogonality of the vectors in the rotation matrix, and then introduces the distortion model to obtain the calibration parameters by iteratively solving the nonlinear equation. This method only needs a plane template to complete the calibration process, and the positional relationship between the template and the camera does not need to be known before calibration, so this method is widely used.

The light plane calibration [7-9] refers to the calibration of the light plane and the pose parameters of the camera on the basis of the camera parameters. Since the three-dimensional coordinates of the characteristic points on the light bar are obtained according to the light plane parameters, the calibration accuracy of the light plane directly affects the measurement accuracy of the line structured light system.

In 2000, Duan et al. [10] used a translation table and a sawtooth target to calculate the equation of the light. The method projects the light plane emitted by the laser onto the tooth-shaped target surface, and the calibration point is the bright spot formed by the intersection of the light plane and the tooth-shaped target. However, the installation of the calibration system is more complicated, and the number of calibration points is small, which affects the calibration accuracy. In 2005, Wei et al.[11-12] proposed a method of obtaining calibration points based on the double cross-ratio constant, but the calibration accuracy of this method depends on the processing accuracy of the three-dimensional target. The cost of calibration is higher.

Zhou Fuqiang et al. [13] completed the light plane calibration based on freely moving targets. This method first determines the relative positional relationship between the target and the camera through the spatial and pixel coordinates of the points on the target. The equation of the light plane is solved by repeat the above process. Because the calibration method is simple and suitable for on-site calibration, this method has been widely used.

Based on the analysis of camera calibration and light plane calibration algorithm, the impact of calibration accuracy is analyzed, and these main hardware parameters include camera aperture, line laser power and backlight power. The paper can be divided into the following steps: The Section 2 introduces the calibration algorithm; The Section 3 analyzes the influence of the aperture on the calibration accuracy, and designs the orthogonal test of the influence of the equipment parameters on the calibration accuracy; The Section 4 get the relationship between equipment parameters and calibration accuracy through orthogonal experiments, and obtains the most important factors. The last part summarizes the full text.

2. Line Structured Light System Calibration
The calibration of line structured light vision system is mainly divided into camera calibration and light plane calibration. Camera calibration is to convert the two-dimensional pixel coordinates into three-dimensional space coordinates, and the light plane calibration is to obtain the parameters of the light plane equation.

2.1. Camera Calibration
As shown in Figure 1, four coordinate systems need to be established: pixel coordinate system \((O_{uv})\), Image coordinate system \((O_{xy})\), camera coordinate system \((O_CXCYCZC)\), world coordinate system \((O_WX_WY_WZ_W)\) in camera calibration.

![Figure 1. Coordinate system relationship in line structure vision system](image)

Camera imaging models are divided into linear models and nonlinear models. The two models are analyzed below:

(A) Linear model of camera imaging

The coordinate system setting of the camera calibration is shown in Figure 1. According to the positional relationship between the world coordinate system and the camera coordinate system, the camera coordinates of the space point \(P\) are:

\[
\begin{bmatrix}
X_C \\
Y_C \\
Z_C
\end{bmatrix} = \begin{bmatrix}
X_W \\
Y_W \\
Z_W
\end{bmatrix} + t
\]  

(1)

Where, \(t = (t_x, t_y, t_z)^T\) is a translation vector, \(R = R(\theta, \psi, \phi)\) is a \(3 \times 3\) orthogonal matrix, and is expressed as

\[
R(\theta, \psi, \phi) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \theta & -\sin \theta \\
0 & \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\cos \psi & 0 & \sin \psi \\
0 & \cos \phi & -\sin \phi \\
\sin \phi & 0 & \cos \phi
\end{bmatrix}
\]

(2)

As shown in Figure 2, \(dx\) and \(dy\) are the physical dimensions of the pixel unit on the imaging plane, \(\theta_0\) is the angle between the axis in the coordinate system. The relationship of pixel coordinates and the image coordinate system is

\[
\begin{bmatrix}
u \\
v \\
1
\end{bmatrix} = \begin{bmatrix}
1/d_x & -\cos \theta_0 & u_0 \\
0 & 1/(d_y \sin \theta_0) & v_0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_w \\
y_w \\
1
\end{bmatrix}
\]

(3)
Figure 2. The transformation relationship between image coordinates and pixel coordinates

According to the small hole imaging model, the transform between the camera coordinate system and the image plane can be expressed as:

\[
\begin{align*}
  x &= f \frac{X_c}{Z_c} \\
  y &= f \frac{Y_c}{Z_c}
\end{align*}
\]

For easy calculation, the plane of the calibration board is taken as the coordinate plane in the world coordinate system. Based on the equations (1)-(4), the relationship is:

\[
\begin{bmatrix}
  u \\
  v \\
  1
\end{bmatrix} =
\begin{bmatrix}
  0 & \alpha & \gamma & u_0 & 0 \\
  0 & \beta & \gamma & v_0 & 0 \\
  0 & 0 & 1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  X_w \\
  Y_w \\
  1
\end{bmatrix}
= 
\begin{bmatrix}
  R & t \\
  0 & 1
\end{bmatrix}
\begin{bmatrix}
  X_w \\
  Y_w \\
  1
\end{bmatrix}
\]

Where, \( \alpha = f/d_x \), \( \beta = f/d_y \sin \theta_0 \), \( \gamma = -f \cot \theta_0 /d_y \), \( r_1 \), \( r_2 \) are the first and second columns of the rotation matrix \( R \), \( R \) and \( t \) are the external parameters of the camera model, and the internal parameters of the camera model can be obtained:

\[
A =
\begin{bmatrix}
  \alpha & \gamma & u_0 \\
  0 & \beta & v_0 \\
  0 & 0 & 1
\end{bmatrix}
\]

(B) Non-linear model of camera imaging

The camera optical system has errors in the manufacturing and assembly process, it affects the image. This effect is called distortion, which includes radial distortion and tangential distortion. The total aberration model can be established:

\[
\begin{align*}
  \delta_x(x_u, y_u) &= x_u (k_1 \rho^2 + k_2 \rho^4) + 2p_1 x_u y_u + p_2 (3x_u^2 + y_u^2) \\
  \delta_y(x_u, y_u) &= y_u (k_1 \rho^2 + k_2 \rho^4) + p_1 (x_u^2 + 3y_u^2) + 2p_2 x_u y_u
\end{align*}
\]

Where, \( \rho = \sqrt{(x_u^2 + y_u^2)} \), \( k_1, k_2, p_1, p_2 \) are the radial and tangential distortion coefficients, respectively. The relationship between ideal image coordinates and actual image coordinates of a space point is:

\[
\begin{align*}
  x_d &= x_u + \delta_x(x_u, y_u) \\
  y_d &= y_u + \delta_y(x_u, y_u)
\end{align*}
\]

2.2. Line Structure Light Calibration

The line structure light calibration is to determine the position relationship between the light plane and the camera, that is, the process of obtaining the parameters of the light plane equation.
The line structure light calibration is shown in Figure 3, where $l$ is the light stripe projected by the light plane on the flat target, and $P$ is the center point of the light strip $l$. Several images of the target can be obtained by rotating the flat target. Set the camera coordinates of the center point of the $i$-th light bar on the $j$-th light bar image is $(C_{ij}^x, C_{ij}^y, C_{ij}^z)$. The equation of the light plane is:

$$b_1X + b_2Y + b_3Z - 1 = 0$$  \hspace{1cm} (9)

Substitute the camera coordinates of the light stripe center point into equation (9) and write it in matrix form:

$$
\begin{bmatrix}
X_{C1}^i & Y_{C1}^i & Z_{C1}^i \\
\vdots & \vdots & \vdots \\
X_{Cj}^i & Y_{Cj}^i & Z_{Cj}^i \\
\vdots & \vdots & \vdots \\
X_{CK}^i & Y_{CK}^i & Z_{CK}^i
\end{bmatrix}
\begin{bmatrix}
b_1 \\
b_2 \\
b_3
\end{bmatrix} = 
\begin{bmatrix}
1 \\
1 \\
1 \\
1 \\
1
\end{bmatrix}
$$  \hspace{1cm} (10)

In the equation, $N$ is the number of light stripe images obtained by rotating the target, and $K$ is the number of center points on each light stripe. Solve the overdetermined equations by the least square method:

$$
\begin{bmatrix}
b_1 \\
b_2 \\
b_3
\end{bmatrix} = 
\begin{bmatrix}
\sum_{j=1}^N \sum_{i=1}^K X_{Cj}^{i2} & \sum_{j=1}^N \sum_{i=1}^K X_{Cj}^{iy} & \sum_{j=1}^N \sum_{i=1}^K X_{Cj}^{iz} \\
\sum_{j=1}^N \sum_{i=1}^K Y_{Cj}^{i2} & \sum_{j=1}^N \sum_{i=1}^K Y_{Cj}^{iy} & \sum_{j=1}^N \sum_{i=1}^K Y_{Cj}^{iz} \\
\sum_{j=1}^N \sum_{i=1}^K Z_{Cj}^{i2} & \sum_{j=1}^N \sum_{i=1}^K Z_{Cj}^{iy} & \sum_{j=1}^N \sum_{i=1}^K Z_{Cj}^{iz}
\end{bmatrix}^{-1} \begin{bmatrix}
\sum_{j=1}^N \sum_{i=1}^K X_{Cj}^{i} \\
\sum_{j=1}^N \sum_{i=1}^K Y_{Cj}^{i} \\
\sum_{j=1}^N \sum_{i=1}^K Z_{Cj}^{i}
\end{bmatrix}
$$  \hspace{1cm} (11)

The light plane equation coefficients $b_1$, $b_2$, $b_3$ can be obtained by (11)

3. Orthogonal Experimental Design of Line Structure Calibration

According to the process of capturing images from the camera, the aperture size of the lens, the power of the parallel light source, and the power of the laser have the greatest impact on the image quality. Therefore, the above three hardware parameters are used as test factors to analyze the impact of the three test factors on the calibration accuracy. The above three experimental factors are interrelated during the calibration process, so the influence of the three factors on the experiment is considered at the same time in the paper, and the optimal combination of the three factors is found by comparing the calibration residuals. The experiment is to find the optimal combination of equipment parameters, when traversing all parameter combinations according to the conventional method, the experiment volume will be very large and it is not convenient to analyze the test results. For example, when the
number of lens aperture, backlight power, and laser power each test factor takes three values, the number of tests is 27 sets. In order to simplify the test process, the orthogonal test method is adopted. Orthogonal experimental design can not only make reasonable arrangements for experiments, select representative parameter combinations for experiments, but also scientifically analyze and process experimental results. Here we need to introduce the basic concepts in several orthogonal experiments:

1) Test index ($y_i$), a characteristic quantity used to measure the effect of the test. In this experiment, the space distance from point to plane is selected as the test index, and the distance can be got by Equation (12).

$$F = \frac{1}{N} \sum_{i=1}^{N} b_i X_i + b_i Y_i + b_i Z_i - 1$$ (12)

$N$ is the total number of points of the light stripe.

2) Test factors, it indicate possible reasons for the test indicators, and usually indicated by capital letters A, B, C. In this experiment, the test factors are lens aperture number (A), backlight power (B), laser power (C).

3) Test level, the various states of test factors or different values taken during the test.

4) Treatment combination, the test point formed by the level combination of all test factors.

The test level is set according to the parameters of the hardware equipment. In the designed experiment, the test factors are divided into 8 levels, and Table 1 is the factor level table.

**Table 1.** Calibration experiment level table

| factors | (1) A/F | (2) B/W | (3) C/mW |
|---|---|---|---|
| level | Lens aperture number | Power source | Laser power |
| 1 | 1.4 | 6.5 | 10 |
| 2 | 2 | 7 | 15 |
| 3 | 2.8 | 7.5 | 20 |
| 4 | 4 | 8 | - |
| 5 | 5.6 | 8.5 | - |
| 6 | 8 | 9 | - |
| 7 | 11 | 9.5 | - |
| 8 | 16 | 10 | - |

4. Experiment and Result Analysis

4.1. Calibration Process of Vision System

The experimental equipment is shown in Figure 4, which mainly include: computer, camera, optical lens, line laser, high-precision calibration board, backlight, etc. As shown in Figure 5, this paper designed a special target for optical plane calibration, and the external parameters of the plane target can be obtained through the calibration board.

**Figure 4.** Experimental site diagram

**Figure 5.** Plane target

The experiment of calibration includes camera and light plane calibration. First, the images of the calibration board in different poses are collected by changing the pose of the calibration board, and the internal parameters and distortion coefficient of the camera can be obtained according to the sub-pixel
coordinates of the corner points. Figure 6 shows the different positions of the calibration board in space.

Then, the images of the plane targets are collected at 6 different positions, and the sub-pixel coordinates of the corner points of the calibration plate on the plane target and the center point of the light stripe are detect. Based on the corner points and the center of the light stripe, the parameters of the light plane equation can be calculated. The spatial position of the light stripes are shown in Figure 7.

4.2. Experimental Results and Analysis

According to the orthogonal experiment designed in Part 3, the lens aperture number, backlight power, and laser power are selected with different parameters of the three hardware indicators to complete the line structure cursor setting experiment, and the calibration accuracy is evaluated according to the equation (12). When the lens aperture is very large, the brightness of the backlight is selected very small, the quality of the calibration image taken and the calibration accuracy will be very poor. Therefore, when the aperture number is selected to be a larger value, the backlight source should be selected with a larger power. According to the standard orthogonal table, the experiment is divided into three orthogonal tables, namely Table 2, Table 3 and Table 4. The experiment results are analyzed in the orthogonal test table by the range analysis method. \( y_{jk} \) is the sum of the test indexes of the \( j \)-th factor at the \( k \) level in the table; \( M(y_{jk}) \) is the average value of \( y_{jk} \), which can determine the optimal level of factor \( j \). The expression of \( R_j \) is:

\[
R_j = \max \left[ M(y_{j1}), M(y_{j2}), \cdots \right] - \min \left[ M(y_{j1}), M(y_{j2}), \cdots \right]
\]

(13)

, and it reflects the influence degree of factor \( j \) on the test index.
Table 2. Experimental results and analysis (Aperture value: F1.4, F2, F2.8)

| No  | Lens aperture number (A) | Power source (B) | Laser power (C) | $y_i$ |
|-----|--------------------------|------------------|-----------------|-------|
| 1   | 1.4                      | 6.5              | 10              | 0.506 |
| 2   | 1.4                      | 7                | 15              | 0.135 |
| 3   | 1.4                      | 7.5              | 20              | 0.269 |
| 4   | 2                        | 6.5              | 20              | 0.166 |
| 5   | 2                        | 7                | 15              | 0.13  |
| 6   | 2                        | 7.5              | 10              | 0.113 |
| 7   | 2.8                      | 6.5              | 15              | 0.061 |
| 8   | 2.8                      | 7                | 20              | 0.110 |
| 9   | 2.8                      | 7.5              | 10              | 0.059 |

For $y_{j1}$, $y_{j2}$, and $y_{j3}$, we have:

$y_{j1} = 0.91$, $y_{j2} = 0.409$, $y_{j3} = 0.23$

$M(y_{j1}) = 0.303$, $M(y_{j2}) = 0.136$, $M(y_{j3}) = 0.077$

$R_j = 0.226$, $y_{j4} = 0.207$, $y_{j5} = 0.163$, $y_{j6} = 0.269$

$M(y_{j4}) = 0.069$, $M(y_{j5}) = 0.054$, $M(y_{j6}) = 0.09$

$R_j = 0.036$, $y_{j7} = 0.036$

Optimal level: $A_3B_2C_2$

Optimal combination: $A>B=C$

Table 3. Experimental results and analysis (Aperture value: F4, F5.6, F8)

| No  | Lens aperture number (A) | Power source (B) | Laser power (C) | $y_i$ |
|-----|--------------------------|------------------|-----------------|-------|
| 1   | 4                        | 8                | 10              | 0.067 |
| 2   | 4                        | 8.5              | 15              | 0.081 |
| 3   | 4                        | 9                | 20              | 0.059 |
| 4   | 5.6                      | 8                | 20              | 0.064 |
| 5   | 5.6                      | 8.5              | 15              | 0.047 |
| 6   | 5.6                      | 9                | 10              | 0.052 |
| 7   | 8                        | 8                | 15              | 0.148 |
| 8   | 8                        | 8.5              | 20              | 0.053 |
| 9   | 8                        | 9                | 10              | 0.068 |

For $y_{j4}$, $y_{j5}$, and $y_{j6}$, we have:

$y_{j4} = 0.207$, $y_{j5} = 0.163$, $y_{j6} = 0.269$

$M(y_{j4}) = 0.069$, $M(y_{j5}) = 0.054$, $M(y_{j6}) = 0.09$

$R_j = 0.036$, $y_{j7} = 0.036$

Optimal level: $A_5B_6C_3$

Optimal combination: $A>B=C$

Optimal combination: $A_5B_6C_3$
Table 4. Experimental results and analysis (Aperture value: F11, F16)

| No | Factor | (1) A/F | (2) B/W | (3) C/mW | $y_i$ |
|----|--------|---------|---------|----------|-------|
|    | Lens aperture number | Power source | Laser power |         |       |
| 1  | 11     | 9.5     | 20      | 0.103    |       |
| 2  | 11     | 10      | 15      | 0.127    |       |
| 3  | 16     | 9.5     | 15      | 0.132    |       |
| 4  | 16     | 10      | 20      | 0.091    |       |
| $y_{j7}$ | 0.23 | 0.235 | 0.259 |       |       |
| $y_{j8}$ | 0.223 | 0.218 | 0.194 |       |       |
| $M(y_{j7})$ | 0.115 | 0.1175 | 0.13 |       |       |
| $M(y_{j8})$ | 0.112 | 0.109 | 0.097 |       |       |
| $R_j$ | 0.003 | 0.009 | 0.033 |       |       |
| Optimal level | $A_8$ | $B_8$ | $C_3$ |       |       |
| Optimal combination | $A_8B_8C_3$ |       |       |       |       |

Through the analysis of the experimental data of the three orthogonal tables, $(A_1B_2C_2)$, $(A_2B_4C_3)$, and $(A_4B_2C_3)$ are the three optimal combinations corresponding to Table 2, Table 3, and Table 4 respectively, and the lens aperture value has the greatest influence factor. When the aperture value is between F4-F8, the calibration accuracy of the line structured light system is significantly higher than other data sets. Therefore, the camera lens aperture value should be a value between F4 and F8.

5. Conclusion
The calibration of the linear structured light system is an important part of the vision system, and the accuracy of the system calibration directly affects the accuracy of the vision measurement. Based on the analysis of the calibration process, the paper compares the impact of the camera's aperture value, laser power, and backlight power on the accuracy of the line structure calibration. The number of comparison groups is optimized through orthogonal experiments. According to the results of experiments, it is shown that the aperture value has the greatest impact on the calibration accuracy, and when the aperture value is between F4 and F8, the calibration of the linear structured light system has the highest accuracy.

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