A Survey of Surface Reconstruction Techniques for Line Structured Light Systems

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Abstract. Reverse engineering has been widely used in industrial production, and surface reconstruction technology is the most important part of reverse engineering. Line structure measurement is a non-contact surface measurement method with high precision, low destructiveness, high data acquisition efficiency and strong anti-interference. This paper focuses on the measurement principle of line structured light, system calibration, strip center extraction and point cloud data processing and surface reconstruction. Finally, the existing surface reconstruction techniques that are widely used are summarized.

1. Introduction
In recent years, with the rapid development of computer technology and modern manufacturing technology, the shortcomings of traditional forward engineering design have attracted people's attention. Reverse engineering has the advantages of short manufacturing cycle, low cost and high efficiency. Surface reconstruction is the most important part of reverse engineering. It stimulates the research enthusiasm of researchers at home and abroad, and carries out a lot of research work around 3D measurement technology and surface reconstruction. Among them, three-dimensional measurement technology is divided into contact type (three coordinate measuring machine) and non-contact measurement, non-contact measurement has laser radar, industrial CT, stereo vision and structured light measurement technology [1]. Contact measurement can cause damage to the surface of the object due to direct contact between the probe and the measured object, and the applicable range is small [2]; Lidar and industrial CT have the disadvantages of low measurement accuracy and high cost [3]; the key technology of stereo vision is the matching problem of the corresponding points on the left and right, so the measurement range is limited [4]; the structured light has a certain precision, a non-contact of the applicable range of light measurement method.

Line structure light is the most widely studied type of structured light, and has the advantages of low system construction cost, non-destructiveness, high precision, high efficiency and large amount of information obtained, and is widely used. The main components of the line structure optical system are line structure light emitters and CCD cameras. The CCD camera collects three-dimensional information on the surface of the object to be measured, and uses the triangulation principle to obtain three-dimensional information. The key technologies of line structure scanning include: line structure light scanning system calibration, strip center extraction, 3D point cloud data preprocessing and surface reconstruction.
2. Measuring principle
The three-dimensional detection of line structure light is mainly based on the principle of triangular laser measurement. The objective is to solve the angle between the optical axis of the camera and the plane of light of the line structure and the coordinates of the center of the recorded light strip on the surface of the object under test. Image coordinate system change [5]. However, this method is very strict on the relative position between the camera and the line structure light generator. Any change in the relative position of the space in the measurement will cause the calibration data to change. Therefore, during the experimental measurement, the external calibration parameters are calibrated. Upon completion, the relative position and spatial position of the camera and laser generator must be the same [6].

![Fig.1 Schematic diagram of the principle of triangular laser measurement](image)

3. Camera internal and external parameter calibration
In this paper, Zhang Zhengyou's three-step method is used to obtain the camera's internal parameters and external parameters [7], as shown in Equation 1:

\[
A = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}, \quad R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, \quad T = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}^T \tag{1}
\]

In Equation 1, the camera's internal parameter matrix is \(f_x\), the camera's focal length is \(f_y\); \(c_x\) and \(c_y\) are reference points; the external parameter \(R\) is the rotation matrix; and \(T\) is the translation vector.

Using the image coordinates and spatial coordinates of \(n\) double template points, when \(2n > 8\), \(2n\) equations can be obtained, and the least squares method of the equation is solved, that is, the required \(h\) is obtained, and then \(H\) is obtained. The principle of solving the internal and external parameters of the camera through the homography matrix, as shown in Equation 2:

\[
\begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = \lambda A \begin{bmatrix} r_1 \\ r_2 \\ t \end{bmatrix} \tag{2}
\]

In Equation 2, \(\lambda\) is a scaling factor. \(R_1\) and \(r_2\) are unit orthogonal vectors, there are

\[
h_i^T A^{-T} A^{-1} h_2 = 0 \tag{3}
\]

\[
h_i^T A^{-T} A^{-1} h_1 = h_i^T A^{-T} h_2 \tag{4}
\]

From the above formula, two constraints of the internal parameter matrix can be obtained. \(A^{-T} A^{-1}\) describes the absolute quadratic curve image, the expanded form is
\[ A^{-T}A^{-1} = \begin{bmatrix}
\frac{1}{\alpha^2} & -\frac{\gamma}{\alpha^2 \beta} & -\frac{\nu_0 \gamma - \mu_0 \beta}{\alpha^2 \beta} \\
-\frac{\gamma}{\alpha^2 \beta} & \frac{\gamma^2}{\alpha^2 \beta^2} + \frac{1}{\beta^2} & -\frac{\gamma (\nu_0 \gamma - \mu_0 \beta)}{\alpha^2 \beta^2} - \frac{\nu_0}{\beta^2} \\
-\frac{\nu_0 \gamma - \mu_0 \beta}{\alpha^2 \beta} & -\frac{\gamma (\nu_0 \gamma - \mu_0 \beta)}{\alpha^2 \beta^2} - \frac{\nu_0}{\beta^2} & \frac{(\nu_0 \gamma - \mu_0 \beta)^2}{\alpha^2 \beta^2} + 1 - \frac{\nu_0^2}{\beta^2}
\end{bmatrix} \]

(5)

\[ B = A^{-T}A^{-1} = \begin{bmatrix}
B_{11} & B_{12} & B_{13} \\
B_{21} & B_{22} & B_{23} \\
B_{31} & B_{32} & B_{33}
\end{bmatrix} \]

(6)

The B matrix is a symmetric matrix, so a 6-dimensional vector is defined as Equation 7.

\[ b = \begin{bmatrix}
B_{11} & B_{12} & B_{13} & B_{21} & B_{22} & B_{23} \\
B_{31} & B_{32} & B_{33}
\end{bmatrix}^T \]

(7)

Let H's ith column vector be \( h_i = \begin{bmatrix}
h_{i1} & h_{i2} & h_{i3}
\end{bmatrix} \), so

\[ h_i^T B h = V_i^T b \]

(8)

In Equation 8

\[ V_i = \begin{bmatrix}
h_{i1}^T & h_{i2}^T & h_{i3}^T
\end{bmatrix} \]

(9)

The constraints of the above internal parameters can be written as the equation of b:

\[ \begin{bmatrix}
V_{i2}^T \\
V_{i1}^T - V_{i2}^T
\end{bmatrix} B = 0 \]

(10)

If there are more than two images to be processed, the equations between the equations can be combined to obtain the linear equation \( V^T b = 0 \). Therefore, the value of the parameter \( b \) can be solved, and the value of the inner parameter matrix A can be obtained.

4. Light plane calibration

Calibration of the light plane pose can be obtained by taking two strip images. The left and right cameras need four sets of different strip images, the left camera captures two sets of images, and the left and right cameras capture two sets of high and low images\(^8\). Two images are taken on each plane, one from the shooting calibration plate and one from the light strip.

5. Motion posture calibration

The calibration procedure for completing the pose is only necessary to capture two calibration plate images at different moving positions. The displacement of the mobile platform in the world coordinate system is obtained by solving the movement of the position of the calibration plate. After completing the first calibration plate image acquisition, we need to collect the second image after the calibration plate moves enough steps to improve the calibration accuracy. Since the pose of the object on the measuring platform is only translated without rotation, the single-step moving pose can be obtained by dividing the translation vector \( \begin{bmatrix} x, y, z \end{bmatrix} \) of the calibration plate by the number of steps.

6. Strip center extraction

The extraction of the coordinates of the center point of the light strip is one of the focuses of the three-dimensional reconstruction technique based on the triangular laser measurement method, and the speed and accuracy of the obtained three-dimensional point cloud data of the object are affected by it.
The extraction of the center of the line structure light strip is a very important link, especially in the online structure light point cloud data three-dimensional reconstruction system, the quality of the strip center extraction is crucial to the acquisition of the 3D point cloud data. The higher the precision of the center point extraction of the light bar, the higher the accuracy of the object 3D point cloud data.

There are many methods for extracting the center point of a light bar. The gray center of gravity method, the curve interpolation method, the Gaussian curve fitting method and the direction template method are the main methods for extracting the coordinates of the center point of the light bar. In this paper, the traditional gray center of gravity method is used to complete the extraction of the center point of the light bar.

The working principle of the gray center of gravity method is to first establish an ROI of interest area. When the line structure light hits the surface of the object to be measured, there will also be some light strips appearing in the field of view outside the object to be measured. There are some interference points at the center point, and these strips do not need us. We only need to hit the image of the strip on the object to be measured, so we must determine the range of the ROI. Then, the threshold segmentation method is used to determine a threshold value so that we can extract the gray center of gravity of the light bar in the ROI region. When calculating the gray center of gravity, the light bar is calculated in one column and one column. The calculated gray center of gravity is the center of the light bar. Point coordinates. Suppose a threshold value is determined. When the gray value of the image is smaller, the portion is divided. When the gray value of the image is larger, the gray value is subtracted from the threshold.

7. Experimental result

In this paper, the calibration method of the camera is Zhang Zhengyou calibration method [6]. The calibration plate adopts the plane target with the shape of a dot. Without considering the radial distortion model, the picture of each calibration plate needs to cover the four corners. The camera has collected Twelve sheets of the calibration picture and extract the center pixel coordinates of the dot. The camera pose, the light plane pose, and the moving pose are calibrated separately. The calibration results are shown in Table 1, Table 2 and Table 3.

| Table 1. Camera pose parameters |
| Camera calibration data | Camera pose |
|---------------------------|-------------|
| f (mm) | 8.43726 | X(mm) | 3.00574 |
| Kappa | -1593.08 | Y(mm) | -7.62398 |
| dx | 7.37427 | Z(mm) | 185.612 |
| dy | 7.400 | X direction rotation (degrees) | 1.51494 |
| u0 | 317.441 | Y direction rotation (degrees) | 353.294 |
| v0 | 227.753 | Z direction rotation (degrees) | 358.768 |
Table 2. Optical plane pose parameters

| Light plane pose parameter |       |
|---------------------------|-------|
| X-axis translation (mm)   | 0.00822097 |
| Y-axis translation (mm)   | 0.0178083  |
| Z axis translation (mm)   | -0.0126762 |
| X direction rotation angle (degrees) | 118.552  |
| Y direction rotation angle (degrees) | 301.539  |
| Z direction rotation angle (degrees) | 302.556  |

Table 3. Sports pose parameters

| Moving pose parameter |       |
|-----------------------|-------|
| X-axis translation (mm) | -0.000299632 |
| Y-axis translation (mm) | 2.25086e-005 |
| Z axis translation (mm) | -3.51802e-006 |
| X direction rotation angle (degrees) | 0  |
| Y direction rotation angle (degrees) | 0  |
| Z direction rotation angle (degrees) | 0  |

8. Application prospect

The surface reconstruction of 3D data point cloud mainly includes parametric surface reconstruction and topological relation surface reconstruction. Parametric surface reconstruction includes curved Bezier surface, B-spline surface, NURBS surface, etc. Topological relational surface reconstruction has A-shape modeling algorithm, Split-and-merge algorithm, r-regular modeling algorithm, self-applying distance function Modular algorithm, etc.

With the application of computer technology and 3D modeling technology in more and more fields, the development of 3D modeling technology has been made. The line structure has the advantages of low cost, no damage, high precision, high efficiency, and large amount of information obtained. The reconstruction of line structure light and surface has been applied to industry after years of
development. At the same time, there are still some problems to be solved, which require the research of various researchers to better realize the more efficient production of industry.

9. Conclusions
In this paper, the measuring principle, system calibration and strip center extraction theory of the non-contact measuring line structured light system are introduced. The camera internal and external parameters calibration, light plane calibration and moving pose calibration of the line structured light system are carried out through experiments, and the calibration data are obtained successfully. Finally, three-dimensional point cloud surface reconstruction is carried out. The technology and prospects are introduced, which can be used for reference for scholars to study the technology of line structured light and surface reconstruction in the future.

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