A Method of Welding Path Planning of Steel Mesh Based on Point Cloud for Welding Robot

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A method of welding path planning of steel mesh based on point cloud for welding robot

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Abstract At present, the operators needs to carry out complicated teaching and programming work on the welding path planning for the welding robot before welding the steel mesh. In this work, an automatic welding path planning method of steel mesh based on point cloud is proposed to simplify the complicated teaching and programming work in welding path planning. The point cloud model of steel mesh is obtained by three-dimensional vision structured light camera. Then we use the relevant point cloud processing algorithm to calculate the welding path of the steel mesh, and obtain the 3D information of the welding path for the welding localization of the robot welding process. Experimental results show that the method can accurately realize the welding path planning of the steel mesh and accomplish the welding task without teaching and programming before welding, which improves the production efficiency.

Keywords Without teaching and programming · 3D structured light camera · Steel mesh point cloud · Welding path planning

1 Introduction

With the rapid development of automation and robot technologies, the welding robots are widely applied into the welding environment to replace human work. The teaching-playback mode of welding robots still plays an important role in the current industrial production. However, the operator needs to carry out complicated teaching and programming work on the welding path of this mode of welding robot before welding. Meanwhile, this work has high requirements for the operator’s operation level and the accuracy. To conquer the above problems, many researchers study on weld extraction and welding planning using different sensors for different workpieces.

In the application and research of welding robot, the mainly used sensor include infrared sensors [1], RGB-D sensors [2,3] and vision sensors [4,5]. The vision sensors of welding robots could be divided into two-dimensional (2D) vision sensors and three-dimensional (3D) vision sensors. The use of 2D vision sensor in welding process mostly needs to cooperate with laser sensor. For example, Wang et al. [6] proposed a method of combining laser and vision sensor to identify V-shaped welds of oil pipelines through image processing, which can be used for subsequent trajectory planning. Xu et al. [7] designed a set of real-time welding seam tracking system based on laser and vision sensor, through an improved Canny algorithm to detect the edges of seam and pool, which could better overcome the deficiencies of the welding seam tracking control of the teaching-playback mode during welding process.

Compared with the 2D vision sensor, the 3D vision sensor can obtain 3D coordinate information of the workpiece and accurate completely the welding task. At present, Linear structured light vision sensors and

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stereo vision sensors are the commonly used 3D vision sensors in robot welding task. For the use of Linear structured light vision sensors, Zeng et al. [8] proposed a narrow butt 3D off-line welding path planning method based on a laser structured light sensor. Hou et al. [9] proposed non-instructional welding method of robotic gas metal arc welding (GMAW) based on laser structured light vision sensing system (LVSS), and experiments on V-grooves and fillet welds were performed. The 3D structured light could obtain the global information of the welding environment. However, the laser structured light vision could only obtain the local information. Therefore, the linear structured light is mostly used for the online identification and tracking of the weld seam. It is not suitable for the off-line 3D path planning of the welding robot.

To overcome the deficiency of linear structured light sensor and realize accurate and efficient off-line 3D path planning, using the stereo structured light sensor to generate point cloud and using the point cloud processing method to process it has become a new scheme to solve the path planning of welding robot without teaching and programming. Lei et al. [10] proposed a novel 3D path extraction method of weld seams based on point cloud, which could well serve for the 3D path teaching task before welding. Zhang et al. [11] proposed point cloud based approach to recognize working environment and locate welding initial position using laser stripe sensor.

Few researches hammer at automatic welding path planning method of welding robot under the condition of without teaching and programming. With the development of society and the infrastructure construction, structural parts, such as steel cage and steel mesh are widely used. At the same time, the welding of steel mesh faces scenes with many crossing points, which results in the cumbersome teaching process. Therefore, using the point cloud processing method to plan the welding path of steel mesh is an important part of solving the complex teaching and programming problems of welding robot before welding.

In this paper, an automatic welding path planning method of steel mesh based on point cloud is proposed, which realizes the welding path planning of welding robot without teaching and programming. Section 2 introduces the configuration of the experiment system; Section 3 illustrates the steps of point cloud preprocessing; Section 4 illustrates the step of welding path planning; Section 5 shows about the analysis of the experimental results, and finally, the conclusion and prospect of this paper are described.

2 Experiment platform configuration and framework

2.1 Experiment system

The robot welding system of the experimental platform is shown in Fig. 1. It consists of two parts: the welding execution system and the 3D vision system [12]. The welding execution system includes the welding torch, the wire feeder, the manipulator, the robot controller and the cross steel mesh, which is used to complete the welding of the intersections of steel mesh. The 3D vision system includes a 3D surface scanning structured light camera and an industrial personal computer (IPC), which is used to obtain the 3D information of the cross steel mesh in the camera field of vision.

Fig. 1 The robot welding system

The manipulator used in the experimental platform is universal robots 5(UR5), and the 3D surface scanning industrial camera is chishine surface 120, as shown in Fig. 2. It should be noted that the installation position of 3D surface scanning structured light camera needs to ensure that the welding torch does not enter the field of vision of the camera. The characteristics of 3D surface scanning structured light camera are shown in Table 1.

2.2 Steel mesh model

In order to clearly introduce the method of planning the welding path of steel mesh, the steel mesh model used in this paper is shown in Fig. 3a. For the convenience of robot welding, there is a gap at the intersection of the upper and lower steel bars of the steel mesh model. The upper steel bars are supported by two fixed-size support plates on the left and right sides, and the relevant dimensions of the model are marked in the top view of the steel mesh with the main optical axis of the camera as the main viewing direction. Fig. 3b shows the size of the steel mesh from the top view.
Table 1 The characteristics of 3D surface scanning structured light camera

| Case | Parameter                  | Value                      |
|------|----------------------------|----------------------------|
| 1    | Working Principle          | Binocular Structured Light |
| 2    | Light Source               | Infrared laser             |
| 3    | Optimum Working Distance   | 500 ± 250 mm               |
| 4    | Maximum Working Distance   | 750                        |
| 5    | Field of View(FOV)         | $H52^\circ \times V31^\circ$ |
| 6    | Repeat Accuracy            | ±0.5 mm                    |
| 7    | Depth Map Resolution       | 1280×800@max 2fps; 640×400@max 8fps; 320×200@max 15fps; 800×600@max 16fps; 640×400@max 20fps |
| 8    | Color Resolution           | 2560×1600@20fps            |
| 9    | Point Cloud Output         | RGB-D                      |
| 10   | Shutter                    | 1/144s to 1/10s            |
| 11   | Gain                       | 1× to 16×                  |

2.3 System framework

During the process of welding path planning of steel mesh based on point cloud, move the manipulator to the steel mesh intersection position and adjust the camera field of view to the reasonable scope through the industrial robot controller. Simultaneously, we record the shooting points and generate the shooting path. Then form a point cloud image of the steel mesh through 3D surface scanning structured light camera at shooting point. The image is transferred into the IPC through the MicroB. Finally, the IPC obtains the welding path of the steel mesh within the vision of the 3D camera through the relevant point cloud processing method and sends the welding path to the robot controller. After the robot completes the welding task of the current shooting point according to the robot controller instructions and then continue the welding task of the next shooting point [13]. The specific operation process is shown in Fig. 4.

It should be noted that, since the shooting range of the 3D surface scanning industrial camera is the coverage range of the structured light, if the angle between the main optical axis of the camera and the plane of the steel mesh is too large or too small, as shown in Fig. 5a, the taken point cloud image will be the side surface of the steel bar, which will affect the accuracy of subsequent welding path planning of the steel mesh. Therefore, when recording the shooting point position, it is necessary to adjust the shooting posture of the camera to ensure that the plane between the main optical axis and the steel mesh is $90^\circ \pm 5^\circ$, as shown in Fig. 5b. The red area in the Fig. 5 is the area that the camera can capture. The position of the shooting point and the posture of the camera can be determined through adjustment based on the number of display points of the steel mesh intersection in the camera’s field of view.

3 Point cloud preprocessing

After the 3D surface structured light camera takes pictures of the steel mesh at the shooting point, it will form a point cloud of the steel mesh within the camera’s field of view at the shooting point. It is the initial point cloud of the steel mesh without any processing, as shown in Fig. 6. Compared with the preprocessed steel mesh point cloud, it has the characteristics of complex background, many irrelevant features and high density of point cloud. Therefore, in order to obtain a high-quality point cloud of the steel mesh, it is necessary to preprocess the initial point cloud.

3.1 Point cloud filtering

The initial steel mesh point cloud contains all the features in the camera’s field of view. In order to prevent the interference of irrelevant features on the welding path planning of the steel mesh and to reduce the number of points to increase the calculation speed, the initial steel mesh point cloud need filtering the irrelevant features using a pass-through filter. The principle of a pass-through filter is to perform a simple filtering along a specified dimension, that is, cut off values that are either inside or outside a given user range.
Fig. 3 The steel mesh model

Fig. 4 The specific operation process

The filtering of the initial point cloud in this method is mainly to remove the point cloud of the support platform. Therefore, there is no need to filter along the z-axis. According to the display of the steel mesh point cloud on the right of the Fig. 7, we can determine that the initial point cloud only needs to be filtered along the x-axis. The accepted interval values of x-axis are set to\((-10, 140)\), and the rest are all removed.

The filtering point cloud of the steel mesh using a pass-through filter is shown in Fig. 8. The number of points in the point cloud is reduced from 176843 to 110777.

In the welding of steel mesh with many intersections, it is impossible to display all the intersections in the camera’s field of view at the same time. Therefore, it is necessary to record the shooting point and camera pose for multi-point shooting. Since, the shooting distance and posture basically remain unchanged, this filtering parameter can be used in subsequent shooting, which is determined in the first shooting. If the steel mesh point cloud is shown as Fig. 8 without any support platform or other irrelevant features point cloud, the next step of point cloud plane segmentation can be operated directly without using point cloud filtering.

3.2 Background point cloud removal

After point cloud filtering, irrelevant features in the steel mesh point cloud have been removed, and only the steel mesh point cloud and the background point cloud are retained. At this time, the independent steel mesh point cloud can be obtained by removing the background point cloud through point cloud segmentation. In this experiment, the placement of the steel mesh is a plane. The background plane point cloud is removed by the plane point cloud segmentation algorithm in the point cloud library.

When using the point cloud segmentation algorithm in the point cloud library, the first step is to create an
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The angle between the main optical axis and the steel mesh plane (95° < α < 85°)

Steel bar 1
Steel mesh plane

The angle between the main optical axis and the steel mesh plane (85° < α < 95°)

Steel bar 1
Steel mesh plane

**Fig. 5** The diagram of 3D camera shooting posture

**Fig. 6** The initial point cloud of the steel mesh

**Fig. 7** The determination of the filtering range by the graphic display method

**Fig. 8** The filtering point cloud of the steel mesh using a Pass-Through filter

The selection of the distance threshold uses the graphic display method to display the filtered steel mesh point cloud and outlier point cloud. The reason for choosing the RANSAC method is based on RANSAC’s simplicity. Finally, the plane model point cloud and outlier point cloud are classified by setting the distance threshold. All points with a distance less than the threshold are regarded as interior points, and others are regarded as outlier points. The retention of internal or outlier points can be achieved through the setting program.
Table 2

| Parameter   | Meaning                                      |
|-------------|----------------------------------------------|
| normal\_x  | the x coordinate of the plane’s normal       |
| normal\_y  | the y coordinate of the plane’s normal       |
| normal\_z  | the z coordinate of the plane’s normal       |
| d           | the fourth Hessian component of the plane’s equation |

The specific meaning of the parameters in plane model.

cloud along z-axis in the camera coordinate system. According to the point cloud along the z-axis in Fig. 9, it can be found that the thickness of the background plane point cloud is about 6mm, so set the distance threshold to 6 and keep the outlier point cloud. It should be noted that the background point cloud has the same thickness when shooting at each shooting point. Therefore, the distance threshold can be reused. The steel mesh point cloud after background point cloud removal is shown in Fig. 10.

3.3 Independent steel bar point cloud acquisition

In the process of welding path planning of steel mesh, it is necessary to carry out linear fitting of steel bar point cloud and other operations. Therefore, point clouds belonging to the same steel bar can be grouped into same a class to form an independent steel bar point cloud by point cloud clustering method, which can facilitate subsequent operation.

The method of steel bars point cloud clustering is similar to the point cloud plane segmentation. After creating the object, the first step is to define the model type as a linear model(SACMODEL\_LINE). The linear model contains six parameters, shown in Table 3, which jointly determine the straight line. The straight line is also obtained using the RANSAC method (SAC\_RANSAC) as the robust estimator of choice. Finally, the interior point and outlier point are determined by setting the distance threshold.

Table 3

| Parameter      | Meaning                                           |
|----------------|---------------------------------------------------|
| point\_on\_line.x  | the x coordinate of a point on the line           |
| point\_on\_line.y  | the y coordinate of the plane’s normal            |
| point\_on\_line.z  | the z coordinate of the plane’s normal            |
| line\_direction.x  | the x coordinate of a line’s direction            |
| line\_direction.y  | the y coordinate of a line’s direction            |
| line\_direction.z  | the z coordinate of a line’s direction            |

According to the point cloud after the segmentation in the camera x-O-y coordinate system in Fig. 11, it can be seen that the diameter of the steel bar is about 10mm. Compared with the actual size 9.8mm, it can be determined that the maximum distance from a point in the same bar to the straight line fitted by the RANSAC method will not exceed 10mm. Hence, the the distance threshold is set to 10, to ensure that all points belonging to the same steel bar are regarded as interior points. Through program setting, the interior points of each line are reserved and stored separately to obtain four independent steel bar point clouds.

Clustered points cloud are shown in Fig. 12, where four colors represent four clustered steel bars.

4 Steps of welding path planning

Through the point cloud preprocessing operation, the steel mesh point cloud is divided into independent
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Fig. 11 The point cloud after the segmentation display in the camera x-o-y coordinate system

Fig. 12 The Point cloud after clustering

Fig. 13 The Principle of straight line fitting based on RANSAC method and SVD method

The purpose of clustering and segmentation of steel mesh point cloud is to obtain independent steel bars point cloud. This process has low requirements on the accuracy of the straight line fitting method and high requirements on the fitting speed. Therefore, the straight line fitting based on RANSAC method is selected. However, the purpose of fitting the line of independent steel bar point cloud is to achieve the welding path planning. This process has high requirements on the accuracy of the straight line fitting method, where the straight line fitting based on SVD method is selected.

4.1 The point cloud filtering based on radius outlier removal

As shown in Fig. 14, when the angle between the main optical axis of the 3D camera and the plane of the steel mesh is $90^\circ \pm 5^\circ$, the captured point cloud is the upper half of each steel bar, and the density of the point cloud is gradually sparse along the z-axis. At this point, SVD method is used to carry out linear fitting for each steel bar point cloud. According to the principle of the SVD method, the fitted straight line is located between the central axis and the upper surface of the reinforcing bar point cloud.

Fig. 14 Three views of the steel mesh point cloud

From the top view of the cross steel bar point cloud shown in Fig. 15, it can be seen that the common vertical line of the cross steel bars point cloud is from the straight line fitted by the upper surface point cloud of the lower steel bar to the straight line fitted by the upper surface point cloud of the upper steel bar. In order to facilitate the accurate solution of the common vertical line, it is necessary to constrain the fitting line of the steel bar point cloud to locate on its upper surface. Therefore, we need to remove the sparse points on both
sides of the steel by point cloud filtering based on radius outlier removal. The remaining point cloud on the upper surface of the steel bar are taken as the sample point of the fitting line.

![Steel bar and fitted line](image1)

**Fig. 15** The top view of the cross steel bar point cloud

According to the principle of radius outlier removal in Fig. 16, calculate the number of other points within the radius $d$ of each point. When the number of other points within the radius is less than the set number, the point will be removed.

![Radius outlier removal principle](image2)

**Fig. 16** The principle of radius outlier removal

After repeated debugging in this experiment, the search radius is set to 2.5 and the number of points is set to 12. The point cloud after filtering based on radius outlier removal is shown in Fig. 17.

![Three views of point cloud after filtering](image3)

**Fig. 17** Three views of the point cloud after filtering based on radius outlier removal

### 4.2 The straight line fitting based on SVD method

The idea of fitting a space line based on SVD method is straightforward, that is, minimizing to minimize the distance from all sample points to the straight line. Firstly, we calculate the arithmetic average of all sample points coordinates $(\bar{x}, \bar{y}, \bar{z})$ according to Eq. 1. The straight line must pass through the position of the arithmetic average of all sample points coordinates.

$$
\left\{
\begin{aligned}
\bar{x} &= \frac{1}{n} \sum_{i=1}^{n} x_i \\
\bar{y} &= \frac{1}{n} \sum_{i=1}^{n} y_i \\
\bar{z} &= \frac{1}{n} \sum_{i=1}^{n} z_i
\end{aligned}
\right.
$$

(1)

The difference matrix $A$ between the coordinates of each sample point and the arithmetic average of all sample points coordinates $(\bar{x}, \bar{y}, \bar{z})$ is calculated by

$$
A = 
\begin{bmatrix}
x_1 - \bar{x} & y_1 - \bar{y} & z_1 - \bar{z} \\
x_2 - \bar{x} & y_2 - \bar{y} & z_2 - \bar{z} \\
x_3 - \bar{x} & y_3 - \bar{y} & z_3 - \bar{z} \\
\vdots & \vdots & \vdots \\
x_n - \bar{x} & y_n - \bar{y} & z_n - \bar{z}
\end{bmatrix}
$$

(2)

The singular value decomposition of matrix $A$ is performed by

$$
A^T A = (VS^T U)^T U S V^T = V S^T (U^T U) S V^T = V (S^T S) V^T = V \begin{bmatrix} \sigma_{max}^2 & \cdots \\ \cdots & \sigma_{min}^2 \end{bmatrix} V^T
$$

(3)

$U$ is an $n \times n$ orthogonal matrix, $S$ is a square matrix composed of $r$ singular values from large to small along the arranged diagonally, and $r$ is the rank of matrix $A$. $V$ is a $3 \times 3$ singular vector matrix arranged from large to small along the column direction. The direction of the obtained straight line is the same as the singular vector corresponding to the maximum singular value. Therefore, the first column of the $V$ matrix is selected as the direction of the fitted straight line, and the singular vector matrix with three rows and one column is expressed as $V_d$.

We can define a straight line by the known direction and one point. The coordinates $(x_1, y_1, z_1)$ of all points on this straight line satisfy Eq. 4. $t$ is the relation variable between the point coordinates on the straight line and the arithmetic average of all sample point coordinates.

$$
\left\{
\begin{aligned}
x_1 &= \bar{x} + V_d (1,1) \times t \\
y_1 &= \bar{y} + V_d (1,2) \times t \\
z_1 &= \bar{z} + V_d (1,3) \times t
\end{aligned}
\right.
$$

(4)

The length of the fitting line can be determined according to Eq. 4. The direction of the steel bar is divided into two types: extending along the x-axis and
extending along the y-axis. When the steel bar extending along the x-axis, firstly, we select the x coordinate of the outermost points on both ends of the steel bar point cloud extension direction as the x coordinate on the two endpoints of the fitting line. Then we bring the x coordinate of each endpoint into the x coordinate expression in Eq. 4, and find the corresponding t of this endpoint, which are t1 and t2 [15]. Finally, we bring t1 and t2 into the expression of y coordinate and z coordinate in Eq. 4. At this point, we can determine the coordinates of the two endpoints and length of the fitting line. The relation variable t corresponding to all the points between the two endpoints of the line are all the numbers between t1 and t2. The length of the fitting straight line of the steel bar point cloud extending along the y-axis is solved in the same way as extending along the x-axis. The straight line fitting based on SVD method is shown in Fig. 18.

Fig. 18 Three views of the straight line fitting based on SVD method

4.3 Find the common vertical line

After obtaining the fitting straight line of the steel bar point cloud, we need to find the common vertical line of the fitting line. As shown in Fig. 19, the fitting straight lines of steel bar 1 and steel bar 3 are AB and CD. The common vertical line of AB and CD is PQ. M is the foot point of AB and N is the foot point of CD.

Fig. 19 The Schematic diagram of finding the common vertical line

We can calculate the four points coordinates of A \((x_a, y_a, z_a)\), B \((x_b, y_b, z_b)\), C \((x_c, y_c, z_c)\) and D \((x_d, y_d, z_d)\) according to Eq. 4. The relationship between straight line AM and AB, CN and CD is

\[
\begin{align*}
\overrightarrow{AM} &= k_1 \overrightarrow{AB} = k_1 (x_b - x_a, y_b - y_a, z_b - z_a) \\
\overrightarrow{CN} &= k_2 \overrightarrow{CD} = k_2 (x_d - x_c, y_d - y_c, z_d - z_c) \\
\end{align*}
\]

By solving Eq. 5, it can be known that the coordinates of foot point M \((x_m, y_m, z_m)\) and foot point N \((x_n, y_n, z_n)\) are expressed as

\[
\begin{align*}
(x_m, y_m, z_m) &= (k_1 (x_b - x_a) + x_a, k_1 (y_b - y_a) + y_a, k_1 (z_b - z_a) + z_a) \\
(x_n, y_n, z_n) &= (k_2 (x_d - x_c) + x_c, k_2 (y_d - y_c) + y_c, k_2 (z_d - z_c) + z_c) \\
\end{align*}
\]

Substituting Eq. 6 into Eq. 7, we can obtain k1 and k2 according to Eq. 7 which denotes the inner product of two perpendicular vectors is 0. Therefore, we can obtain the coordinates of the foot point M and the foot point N.

\[
\begin{align*}
\overrightarrow{AB} \cdot \overrightarrow{MN} &= 0 \\
\overrightarrow{CD} \cdot \overrightarrow{NM} &= 0 \\
\end{align*}
\]

Through the foot points M and N, we can determine a straight line, which is the common vertical line of the straight lines AB and CD. The coordinates of the points between MN on the common vertical line conform to Eq. 8, and l is the relation variable. The common vertical line of the fitting line is shown in Fig. 20.

\[
\begin{align*}
x_{mn} &= l \times (x_n - x_m) + x_m \\
y_{mn} &= l \times (y_n - y_m) + y_m \quad (0 \leq l \leq 1) \\
z_{mn} &= l \times (z_n - z_m) + z_m \\
\end{align*}
\]
4.4 Find the gap width of crossed steel bars

The welding path planning needs to be determined according to the gap width of crossed steel bars. When the gap width is less than 2mm, the steel mesh welding adopts spot welding. When the gap width is greater than 2mm, the steel mesh welding adopts are welding. Therefore, before determining the welding path, we should calculate the gap width of the crossed steel bars on first.

After obtaining the coordinates of the two endpoints of the common vertical line MN, we can get the length of the common vertical line MN according to

$$D_{mn} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2}$$

(9)

The length of the common vertical line MN refers to the distance between the upper surface of the lower steel bar and the upper surface of the upper steel bar. Therefore, we can get the gap width between the crossed bars by subtracting the diameter $d_{up}$ of the upper steel bar from the length $d_{up}$ of the common vertical line MN. The upper steel bar diameter has been accurately measured before welding.

$$D_{FN} = D_{MN} - d_{up}$$

(10)

After getting the gap width of the crossed steel bars, we began to plan the welding path. As shown in Fig. 21, point $P$ is the midpoint of the gap between the upper and lower steel bars, point $E_1$ is obtained by offsetting point $P$ along the NC direction by the distance of the upper steel bar radius, and the length of is $PE_1$ the radius $d_{up}/2$ of the upper steel bar.

![Fig. 21 The schematic diagram of welding path planning](image)

Point is located on the common vertical line MN, so the coordinate of point $P$ conforms to Eq. 8. At this time, we could find $l$ corresponding to point $P$ according to Eq. 11, and then bring it into Eq. 8 to find the coordinate of point $P (x_p, y_p, z_p)$

$$l_P = \frac{d_{up} + D_{FN}/2}{D_{MN}}$$

(11)

The coordinates of point $E_1 (x_{E1}, y_{E1}, z_{E1})$ can be calculated according to Eq. 12. It denotes the coordinates of two parallel vectors are proportional to each other.

$$\frac{x_{E1} - x} {x_c - x_m} = \frac{y_{E1} - y} {y_c - y_m} = \frac{z_{E1} - z} {z_c - z_m}$$

(12)

According to Eq. 12, the relationship between $y_{E1}$ and $x_{E1}, z_{E1}$ and $E_1$ can be summarized as

$$\begin{cases}
    y_{E1} = \frac{(x_{E1} - x) \times (y_c - y_m)}{x_c - x_m} + y_p \\
    z_{E1} = \frac{(x_{E1} - x) \times (z_c - z_m)}{x_c - x_m} + z_p
\end{cases}$$

(13)

Substituting Eq. 13 into the $PE_1$ distance calculation Eq. 14, we can get the $x$ coordinate $x_{E1}$ of point $E_1$.

$$|PE_1| = d_{up}/2$$

$$= \sqrt{(x_{E1} - x_p)^2 + (y_{E1} - y_p)^2 + (z_{E1} - z_p)^2}$$

(14)

Substituting $x_{E1}$ into Eq. 12, we can get the proportional relationship, and then acquire the coordinate $(x_{E1}, y_{E1}, z_{E1})$ of point $E_1$.

Point $F_1$ is obtained by offsetting point $P$ along the MB direction by the distance of the lower steel bar radius. The way of calculating the coordinates of point $F_1$ is the same as point $E_1$. Similar to Eq. 12, we can get

$$\begin{cases}
    y_{F1} = \frac{(x_{F1} - x_p) \times (y_c - y_m)}{x_h - x_m} + y_p \\
    z_{F1} = \frac{(x_{F1} - x_p) \times (z_c - z_m)}{x_h - x_m} + z_p
\end{cases}$$

(15)

Substituting Eq. 15 into the $PF_1$ distance calculation Eq. 16, we can get the $x$ coordinate $x_{F1}$ of point $F_1$.

$$|PF_1| = d_{down}/2$$

$$= \sqrt{(x_{F1} - x_p)^2 + (y_{F1} - y_p)^2 + (z_{F1} - z_p)^2}$$

(16)

Point $G_1$ is obtained by offsetting point $P$ along the NC direction by the distance of the upper steel
bar radius and then along the \( \overrightarrow{MB} \) direction by the distance of the lower steel bar radius. We can get Eq. 17 according to \( E_1G_1 \) is parallel to \( PF_1 \) and has the same length. Then, the coordinates \((x_{G1}, y_{G1}, z_{G1})\) of point \( G_1 \) can be obtained by Eq. 17. Similarly, we can get the coordinates of point \( F_2 \) and point \( H_2 \).

\[
\frac{x_{G1} - x_{E1}}{x_{F1} - x_P} = \frac{y_{G1} - y_{E1}}{y_{F1} - y_P} = \frac{z_{G1} - z_{E1}}{z_{F1} - z_P} = 1
\] (17)

4.5 Welding path planning

The final step is to plan the welding path, which can be divided into the following two situations.

1) When the gap width \( D_{FN} \) between crossed bars is less than 2mm, the steel mesh welding adopts spot welding, and the welding point of the welding torch is \( E_1 \).

2) When the gap width \( D_{FN} \) between crossed bars is greater than 2mm, the steel mesh welding adopts arc welding. The initial point of the welding path is \( H_1 \). Then the welding torch passes through point \( E_1 \) along the direction of \( \overrightarrow{H_1G_1} \) in a straight line and finally reaches the endpoint \( G_1 \) of the welding path to accomplish the primary welding [16]. If the gap width \( D_{FN} \) between crossed bars is too large, it is necessary to weld the welding path several times according to the actual situation. For example, after completing a welding task, the welding torch reaches point \( G_1 \), then the welding torch passes through point \( E_1 \) along the direction of \( \overrightarrow{G_1H} \) in a straight line, and finally reaches the endpoint \( H_1 \) and complete the secondary welding. Actual welding times, can be set freely according to the gap width \( D_{FN} \). The positions of welding points required for welding path planning are shown in Fig. 22.

5 Experiments and results

After obtaining the welding path of the steel mesh, we verify the feasibility, efficiency and accuracy of the welding path planning method of steel mesh based on point cloud through error analysis, method efficiency and welding platform experiment results.

5.1 Method error analysis

The error analysis is to verify whether the welding path planning method of the steel mesh based on point cloud meets the welding accuracy requirements, and to validate its feasibility. Through the welding path planning, we determine the coordinates of the points required for the welding path planning. We use the relevant points to calculate the gap width of the crossed steel bars, then compare with the actual gap width of the crossed steel bars and calculate its error [17]. Finally, we determine the feasibility of the welding path planning method of the steel mesh based on point cloud according to this error. In this experiment, there are four crossed steel bars in the view field of the 3D camera, generating four welding positions. Through the calculation of the point cloud taken by the 3D camera, the coordinates of the two endpoints of the gap between crossed steel bars at four welding positions are calculated as shown in Table 4.

![Fig. 22 The positions of welding points required for welding path planning](image)

Table 4 The coordinates of the two endpoints of the gap at four welding positions

| Welding positions | Points | x   | y   | z       |
|-------------------|--------|-----|-----|---------|
| 1                 | F      | 115.603 | -51.223 | 382.744 |
|                   | N      | 115.828 | -50.952 | 385.781 |
| 2                 | F      | 52.914  | 29.583 | 380.185 |
|                   | N      | 53.151  | 29.870 | 383.414 |
| 3                 | F      | 52.254  | -51.159 | 387.428 |
|                   | N      | 52.492  | -50.873 | 390.644 |
| 4                 | F      | 115.194 | 25.2727 | 376.003 |
|                   | N      | 115.412 | 25.5382 | 378.973 |

According to the coordinates of the two endpoints of the gap, we get the gap width and error of the four welding positions. The results are shown in Table 5. Through the comparison between the calculated gap width of the crossed bars and the actual gap width, it can be found that the maximum error is 0.75mm, the minimum error is 0.49mm, and the average error is 0.635mm. According to Table 1, the repeatability of the camera is ±0.5 mm [18]. Taking into account the shooting error of the
3D camera, it can be concluded that the error between the calculated gap width and the actual gap width of the crossed steel bars meets the accuracy requirements. Therefore, the welding path planning method of the steel mesh based on point cloud is feasible, which meets the welding accuracy requirements.

### Table 5 The gap width and error of the four welding positions

| Welding positions | The calculated gap width (mm) | The actual gap width (mm) | Error (mm) |
|-------------------|-------------------------------|---------------------------|------------|
| 1                 | 3.06                          | 2.5                       | 0.56       |
| 2                 | 3.25                          | 2.5                       | 0.75       |
| 3                 | 3.24                          | 2.5                       | 0.74       |
| 4                 | 2.99                          | 2.5                       | 0.49       |

### 5.2 Method efficiency analysis

Running time is a key factor to reflect the method performance. Because there are large number of shooting points in industrial field, there are certain requirements for the time of point cloud generation and welding path planning for each shooting. Through many experiments, we record the total time for the welding path planning at four welding positions, as shown in Table 6.

### Table 6 The total time for the welding path planning at four welding positions

| Case | Step                        | Running time (ms) |
|------|-----------------------------|-------------------|
| 1    | 3D camera shooting to form a point cloud | 52                |
| 2    | Path planning               | 2875              |
| 3    | The whole process           | 2927              |

The process of welding path planning at four welding positions in this method takes about 3s. Therefore, the efficiency of this method can fully adapt to the needs of industrial production.

### 5.3 Welding platform experiment results analysis

Table 7 summarizes the results of the welding point coordinates required for the four welding positions in the 3D camera field of view obtained by the welding path planning method based on point cloud.

The welding robot needs to carry out reasonable and accurate hand-eye calibration experiments to realize the accurate positioning of the front end of the welding torch to the position of the welding point [19]. The principle of hand-eye calibration in this experiment is shown in Fig. 23.

![Eye-in-Hand calibration](image)

#### Fig. 23 The principle of Eye-in-Hand calibration

In the eye-in-hand calibration method, Eq. 18 is applicable to any two postures of the robot in the process of moving.

\[
Base T_{End2} \times End2 T_{Camera2} \times Camera2 T_{Object} = Base T_{End1} \times End1 T_{Camera1} \times Camera1 T_{Object}
\]  

(18)

According to the Eq. 18, the external matrix \(End T_{Camera}\) with the smallest error is selected as follows after multiple calibrations.

\[
End T_{Camera} = \begin{bmatrix}
0.9997 & 0.0221 & -0.0051 & -40.7215 \\
-0.0221 & 0.9996 & 0.0147 & 115.4470 \\
0.0054 & -0.0146 & 0.9999 & -126.3277 \\
0.0000 & 0.0000 & 0.0000 & 1.0000
\end{bmatrix}
\]

(19)

We record the shooting posture (-272.08, 647.67, 419.28, -174.76, 3.37, 20.09) of the 3D camera. According to the shooting posture and the external matrix, we acquire...
the coordinates of the front end of welding torch cor-
responding to the welding points at four welding posi-
tions in the robot base coordinate system. The results
are shown in Table 8.

Table 8 The coordinates of the front of welding torch cor-
responding to the welding points acquired by hand-eye cali-
bration

| Welding positions | Points | x       | y       | z      |
|-------------------|--------|---------|---------|--------|
| 1                 | G₁     | -210.68 | 628.92  | 151.06 |
|                   | E₁     | -206.11 | 630.68  | 151.11 |
|                   | H₁     | -230.77 | 534.64  | 151.21 |
| 2                 | G₁     | -239.65 | 530.49  | 151.11 |
|                   | E₁     | -235.21 | 532.57  | 151.16 |
|                   | H₁     | -260.85 | 609.55  | 150.35 |
| 3                 | G₁     | -270.00 | 600.02  | 150.24 |
|                   | E₁     | -265.42 | 607.78  | 150.29 |
|                   | H₁     | -174.02 | 561.12  | 151.97 |
| 4                 | G₁     | -182.90 | 556.98  | 151.87 |
|                   | E₁     | -178.46 | 559.05  | 151.92 |

we acquire the coordinates of the front end of weld-
ing torch corresponding to the welding points at four
welding positions in the robot base coordinate system
by manual teaching. The results are shown in Table 9.

Table 9 The coordinates of the front of welding torch corre-
sponding to the welding points acquired by manual teaching

| Welding positions | Points | x       | y       | z      |
|-------------------|--------|---------|---------|--------|
| 1                 | H₁     | -200.93 | 632.11  | 150.93 |
|                   | G₁     | -210.02 | 628.75  | 151.20 |
|                   | E₁     | -205.71 | 630.65  | 150.97 |
|                   | H₁     | -230.5  | 534.41  | 150.73 |
| 2                 | G₁     | -239.41 | 530.29  | 151.40 |
|                   | E₁     | -235.28 | 532.22  | 152.55 |
|                   | H₁     | -260.44 | 609.32  | 150.13 |
| 3                 | G₁     | -269.65 | 605.83  | 149.98 |
|                   | E₁     | -265.46 | 607.40  | 150.18 |
|                   | H₁     | -174.08 | 560.7   | 152.21 |
| 4                 | G₁     | -182.48 | 556.69  | 152.09 |
|                   | E₁     | -178.48 | 558.52  | 151.38 |

After reasonable planning of the robot posture, the
coordinates of the welding point in Table 8 are sent
to the welding robot through the controller. Then the
welding robot drives the front end of the welding torch
to accurately find the welding point and execute the
welding task according to the planned welding path.

Finally, we analyze the error of the corresponding
welding points coordinates in Table 8 and Table 9. Fig.
24a, 24b, and 24c respectively show the x, y, and z axes
errors between the welding points coordinates acquired
by the article method and manual teaching, which the
error is within ±0.6 mm. Fig. 24d shows the distance
error between the welding points acquired by the article
method and manual teaching, which the error is within
1 mm.

Through the actual operation of the experiments
and the error analysis, we found that all the errors are
not more than 1 mm and within the allowable reasonable
range, which does not affect the welding effect. It is
verified that the method in this paper can realize the ac-
curacy of welding path planning without teaching and
programming.

6 Conclusion

This paper studies a method of welding path plan-
ing of steel mesh based on point cloud for welding
robot, which lays the foundation for the accurate plan-
ing of the steel mesh welding path and independent
welding while eliminating the complicated teaching and
programming work in welding path planning. The main
contributions of this paper are summarized as follows.

1) The application of the 3D surface scanning struc-
tured light camera to the industrial welding scene can
quickly and conveniently obtain the point cloud of the
workpiece, which improves the welding efficiency.

2) This method solved the complicated teaching and
programming problem of the welding robot before weld-
ing the steel mesh. Through the combination of point
cloud library and mathematical theory, we can accu-

complete the welding task without teaching and program-
ming before welding.

3) We verify the feasibility, efficiency and accuracy of the welding path planning method of steel mesh based on point cloud through analysis of method er-
ror, method efficiency and welding platform experiment results.

In the future work, we will improve and complete our work. Meanwhile, the proposed method also has some weaknesses. For example, the proposed method in this article is only suitable for the steel mesh work-
pieces. We will improve our method to adapt to differ-
ent welding scenarios.

Declarations

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Consent to Participate Not applicable.

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