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

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Research Article

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

Posted Date: April 7th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-379414/v1>

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on July 15th, 2021. See the published version at <https://doi.org/10.1007/s00170-021-07601-6>.

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

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Received: date / Accepted: date

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

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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

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.

Fig. 2 3D Surface scanning industrial camera of Chishine Surface 120

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 @ Maximum Frame Rate	1280×800 @max 2fps; 640×400 @max 8fps; 320×200 @max 15fps;
8	Color Resolution	2560×1600 @20fps
9	Point Cloud Output	RGB-D
10	Shutter	1/142s to 1/10s
11	Gain	$1 \times$ to $16 \times$

2.3 System framework

During the process of welding path planning of steel mesh based on point cloud, move the manipulator to 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 $\{P_i|P_1, P_2, \dots, P_n\}$ 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 and record 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

we use the graphic display method to determine the filtering range. The 3D coordinate system of the point cloud is based on the camera position with the coordinate origin (0,0,0). Therefore, we display the steel mesh point cloud in this coordinate system through the software, and determine the filtering range of irrelevant features point cloud according to the display area of the point cloud on the x,y and z axes.

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

Fig. 5 The diagram of 3D camera shooting posture

Fig. 6 The initial point cloud of the steel mesh

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

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

object in the program. The second step is to define the model type. In this experiment, the model type is defined as a plane model (SACMODEL_PLANE) because the placement of the steel mesh is a plane. Plane model contains four parameters, shown in Table 2, which determine the plane $ax + by + cz + d = 0$. The plane is obtained by using the Random Sample Consensus (RANSAC) method (SAC_RANSAC) as the robust estimator of choice. 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.

The selection of the distance threshold uses the graphic display method to display the filtered steel mesh point

Table 2 The specific meaning of the parameters in plane model

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

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.

Fig. 9 The filtered steel mesh point cloud display along z-axis in the camera coordinate system **Fig. 10** The steel mesh point cloud after background point cloud removal

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 The specific meaning of the parameters in line model

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

Fig. 11 The point cloud after the segmentation display in the camera x-o-y coordinate system

Fig. 12 The Point cloud after clustering

steel bar point cloud. On this basis, we Obtain the welding point coordinates of the steel mesh, finally realizes the welding path planning of the steel mesh.

It should be noted that the straight line fitting based on SVD method is suitable for independent steel bar point cloud. However, [14]the straight line fitting based on RANSAC method is suitable for clustering and segmentation of steel mesh point cloud. The main differences are listed as follows:

1)The RANSAC method principle is shown on the left side of Fig. 13, which determines a line by two points on the basis of all sample points, and obtain the line model based on interior points by setting the distance threshold. The algorithm is simple and the calculation speed is fast. However the straight line obtained by the fitting must pass through two of the sample points. It slightly reduces the fitting accuracy.

2)The SVD method principle is shown on the right side of Fig. 13, which determines the line based on sample points in the way of minimizing the distance between all sample points and the fitting line. The fitting process does not need pass through any sample point, leading to a high-accurate fitting results.

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 the 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.

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.

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.

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.

$$\begin{cases} \bar{x} = \frac{\sum_{i=1}^n x_i}{n} \\ \bar{y} = \frac{\sum_{i=1}^n y_i}{n} \\ \bar{z} = \frac{\sum_{i=1}^n z_i}{n} \end{cases} \quad (1)$$

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

$$A = \begin{bmatrix} x_1 - \bar{x} & y_1 - \bar{y} & z_1 - \bar{z} \\ x_2 - \bar{x} & y_2 - \bar{y} & z_2 - \bar{z} \\ x_3 - \bar{x} & y_3 - \bar{y} & z_3 - \bar{z} \\ \vdots & \vdots & \vdots \\ x_n - \bar{x} & y_n - \bar{y} & z_n - \bar{z} \end{bmatrix} \quad (2)$$

The singular value decomposition of matrix A is performed by

$$\begin{aligned} A^T A &= (V S^T U^T) U S V^T = V S^T (U^T U) S V^T \\ &= V (S^T S) V^T = V \begin{bmatrix} \sigma_{\max}^2 & & \\ & \ddots & \\ & & \sigma_{\min}^2 \end{bmatrix} V^T \end{aligned} \quad (3)$$

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 3×3 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_l, y_l, z_l) 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.

$$\begin{cases} x_l = \bar{x} + V_d(1,1) \times t \\ y_l = \bar{y} + V_d(1,2) \times t \\ z_l = \bar{z} + V_d(1,3) \times t \end{cases} \quad (4)$$

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 t_1 and t_2 [15]. Finally, we bring t_1 and t_2 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 t_1 and t_2 . 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)

Fig. 20 Three views of the common vertical line of the fitting line

according to Eq. 4. The relationship between straight line AM and AB , CN and CD is

$$\begin{cases} \overrightarrow{AM} = k_1 \overrightarrow{AB} = k_1 (x_b - x_a, y_b - y_a, z_b - z_a) \\ \overrightarrow{CN} = k_2 \overrightarrow{CD} = k_2 (x_d - x_c, y_d - y_c, z_d - z_c) \end{cases} \quad (5)$$

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

$$\begin{cases} (x_m, y_m, z_m) = \\ (k_1 (x_b - x_a) + x_a, k_1 (y_b - y_a) + y_a, k_1 (z_b - z_a) + z_a) \\ (x_n, y_n, z_n) = \\ (k_2 (x_d - x_c) + x_c, k_2 (y_d - y_c) + y_c, k_2 (z_d - z_c) + z_c) \end{cases} \quad (6)$$

Substituting Eq. 6 into Eq. 7, we can obtain k_1 and k_2 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 .

$$\begin{cases} \overrightarrow{AB} \cdot \overrightarrow{MN} = 0 \\ \overrightarrow{CD} \cdot \overrightarrow{NM} = 0 \end{cases} \quad (7)$$

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.

$$\begin{cases} x_{mn} = l \times (x_n - x_m) + x_m \\ y_{mn} = l \times (y_n - y_m) + y_m \\ z_{mn} = l \times (z_n - z_m) + z_m \end{cases} \quad (0 \leq l \leq 1) \quad (8)$$

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 arc 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

$$D_{mn} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2} \quad (9)$$

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.

$$D_{FN} = D_{MN} - d_{up} \quad (10)$$

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 $\overrightarrow{NC}$ direction by the distance of the upper steel bar radius, and the length of is $\overrightarrow{PE_1}$ the radius $d_{up}/2$ of the upper steel bar.

Fig. 21 The schematic diagram of welding path planning

Point P 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 $p(x_p, y_p, z_p)$

$$l_P = \frac{d_{up} + D_{FN}/2}{D_{MN}} \quad (11)$$

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.

$$\frac{x_{E1} - x_p}{x_c - x_n} = \frac{y_{E1} - y_p}{y_c - y_n} = \frac{z_{E1} - z_p}{z_c - z_n} \quad (12)$$

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

$$\begin{cases} y_{E1} = \left[\frac{(x_{E1} - x_p) \times (y_c - y_n)}{x_c - x_n} \right] + y_p \\ z_{E1} = \left[\frac{(x_{E1} - x_p) \times (z_c - z_n)}{x_c - x_n} \right] + z_p \end{cases} \quad (13)$$

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

$$\begin{aligned} |\overrightarrow{PE_1}| &= d_{up}/2 \\ &= \sqrt{(x_{E1} - x_p)^2 + (y_{E1} - y_p)^2 + (z_{E1} - z_p)^2} \end{aligned} \quad (14)$$

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 $\overrightarrow{MB}$ 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

$$\begin{cases} y_{F1} = \left[\frac{(x_{F1} - x_p) \times (y_b - y_m)}{x_b - x_m} \right] + y_p \\ z_{F1} = \left[\frac{(x_{F1} - x_p) \times (z_b - z_m)}{x_b - x_m} \right] + z_p \end{cases} \quad (15)$$

Substituting Eq. 15 into the $\overrightarrow{PF_1}$ distance calculation Eq. 16, we can get the x coordinate x_{F1} of point F_1 . Then, bring x_{F1} into vector parallel formula, we can get the coordinate (x_{F1}, y_{F1}, z_{F1}) of point F_1 .

$$\begin{aligned} |\overrightarrow{PF_1}| &= d_{down}/2 \\ &= \sqrt{(x_{F1} - x_p)^2 + (y_{F1} - y_p)^2 + (z_{F1} - z_p)^2} \end{aligned} \quad (16)$$

Point G_1 is obtained by offsetting point P along the $\overrightarrow{NC}$ 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 $\overrightarrow{E_1G_1}$ is parallel to $\overrightarrow{PF_1}$ and has the same length. Then, the coordinates $(x_{G_1}, y_{G_1}, z_{G_1})$ of point G_1 can be obtained by Eq. 17. Similarly, we can get the coordinates of point F_2 and point H_2 .

$$\frac{x_{G_1} - x_{E_1}}{x_{F_1} - x_P} = \frac{y_{G_1} - y_{E_1}}{y_{F_1} - y_P} = \frac{z_{G_1} - z_{E_1}}{z_{F_1} - z_P} = 1 \quad (17)$$

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 $\overrightarrow{G_1H_1}$ in a straight line, and finally reaches the endpoint H_1 and to 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

Fig. 22 The positions of welding points required for welding path planning

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.

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

Table 7 The welding point coordinates required for the four welding positions

Welding positions	Points	x	y	z
1	H_1	120.63	-55.97	384.34
	G_1	110.86	-55.96	385.06
	E_1	115.74	-55.97	384.70
2	H_1	57.87	24.51	381.91
	G_1	48.12	25.18	382.56
	E_1	52.93	24.85	382.24
3	H_1	57.22	-55.90	389.11
	G_1	47.45	-55.89	389.83
	E_1	52.33	-55.90	389.47
4	H_1	120.21	20.19	377.60
	G_1	110.45	20.86	378.25
	E_1	115.33	20.52	377.92

welding torch to the position of the welding point [19]. The principle of hand-eye calibration in this experiment is shown in Fig. 23.

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.

$${}^{Base}T_{End2} \times {}^{End2}T_{Camera2} \times {}^{Camera2}T_{Object} = {}^{Base}T_{End1} \times {}^{End1}T_{Camera1} \times {}^{Camera1}T_{Object} \quad (18)$$

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

$${}^{End}T_{Camera} = \begin{bmatrix} 0.9997 & 0.0221 & -0.0051 & -40.7215 \\ -0.0221 & 0.9996 & 0.0147 & 115.4470 \\ 0.0054 & -0.0146 & 0.9999 & -126.3277 \\ 0.0000 & 0.0000 & 0.0000 & 1.0000 \end{bmatrix} \quad (19)$$

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 corresponding to the welding points at four welding positions in the robot base coordinate system. The results are shown in Table 8.

Table 8 The coordinates of the front of welding torch corresponding to the welding points acquired by hand-eye calibration

Welding positions	Points	x	y	z
1	H_1	-201.54	632.45	151.17
	G_1	-210.68	628.92	151.06
2	E_1	-206.11	630.68	151.11
	H_1	-230.77	534.64	151.21
	G_1	-239.65	530.49	151.11
3	E_1	-235.21	532.57	151.16
	H_1	-260.85	609.55	150.35
	G_1	-270.00	606.02	150.24
4	E_1	-265.42	607.78	150.29
	H_1	-174.02	561.12	151.97
	G_1	-182.90	556.98	151.87
	E_1	-178.46	559.05	151.92

we acquire the coordinates of the front end of welding 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 corresponding to the welding points acquired by manual teaching

Welding positions	Points	x	y	z
1	H_1	-200.93	632.11	150.93
	G_1	-210.02	628.75	151.20
	E_1	-205.7	630.65	150.97
2	H_1	-230.5	534.41	150.73
	G_1	-239.41	530.29	151.40
	E_1	-235.28	532.22	151.55
3	H_1	-260.44	609.32	150.13
	G_1	-269.65	605.83	149.98
	E_1	-265.46	607.40	150.18
4	H_1	-174.08	560.7	152.21
	G_1	-182.48	556.69	152.09
	E_1	-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

Fig. 24 The error analysis between the welding point coordinates acquired by the article method and manual teaching.

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 1mm.

Through the actual operation of the experiments and the error analysis, we found that all the errors are not more than 1mm 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 accuracy of welding path planning without teaching and programming.

6 Conclusion

This paper studies a method of welding path planning of steel mesh based on point cloud for welding robot, which lays the foundation for the accurate planning 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 structured 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 welding the steel mesh. Through the combination of point cloud library and mathematical theory, we can accurately plan the welding path of the steel mesh and com-

plete the welding task without teaching and programming 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 error, 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 workpieces. We will improve our method to adapt to different welding scenarios.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Authors Contributions Yusen Geng was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

Funding The authors gratefully thank the research funding the Shandong Provincial Key Research and Development Program (Major Scientific and Technological Innovation Project) under Grant No. 2019JZZY010441.

Competing Interests The authors declare that they have no conflict of interest.

Availability of data and materials Not applicable.

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Figures

Figure 1

The robot welding system

Figure 2

3D Surface scanning industrial camera of Chishine Surface 120

Figure 3

The steel mesh model

Figure 4

The specic operation process

Figure 5

The diagram of 3D camera shooting posture

Figure 6

The initial point cloud of the steel mesh

Figure 7

The determination of the ltering range by the graphic display method

Figure 8

The Itering point cloud of the steel mesh using a Pass-Through Iter

The thickness of the background point cloud is about 6 mm

Figure 9

The Itered steel mesh point cloud display along z-axis in the camera coordinate system

Figure 10

The steel mesh point cloud after background point cloud removal

Figure 11

The point cloud after the segmentation display in the camera x-o-y coordinate system

Figure 12

The Point cloud after clustering

Figure 13

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

Front view

Top view

Side view

Figure 14

Three views of the steel mesh point cloud

Figure 15

The top view of the cross steel bar point cloud

Figure 16

The principle of radius outlier removal

Figure 17

Three views of the point cloud after ltering based on radius outlier removal

Figure 18

Three views of the straight line tting based on SVD method

Figure 19

The Schematic diagram of nding the common vertical line

Figure 20

Three views of the common vertical line of the tting line

Figure 21

The schematic diagram of welding path planning

Figure 22

The positions of welding points required for welding path planning

Figure 23

The principle of Eye-in-Hand calibration

Figure 24

The error analysis between the welding point coordinates acquired by the article method and manual teaching.