Welding Seam Detection and Tracking Based on Laser Vision for Robotic Arc Welding

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Abstract. The welding robots are widely employed in the manufacturing field. In order to measure up to the developing need of automation and intelligent production, real-time welding process sensing and controlling are necessary, in which the welding seam detection and tracking is the representative task. Among the kinds of sensors applied in the robotic welding process, vision sensors is one of the most widely used for automatic welding seam tracking and quality control in robotic arc welding. This paper is to present a new framework and the data process algorithm of the sensor. A novel two-step calibration approach is proposed in this paper based on the “Calibration toolbox in Matlab”, the proposed approach acquires the laser light plane by project the linear stripe on the calibration pattern plate during camera calibration process. Experiment result indicates that the fitting error of the detected 3D point data of the weld groove is less than 0.1mm. The tracking error in robotic welding process is no more than 0.2mm. Which is acceptable for robotic welding system.

1. Introduction
Currently, the welding robots are widely employed in the manufacturing field. The traditional teaching and play back working mode are no more suitable for the rapid rhythm of production and the flexible manufacturing process. [1-3] In order to measure up to the developing need of automation and intelligent production, real-time welding process sensing and controlling are necessary, in which the welding seam detection and tracking is the representative task. [4-8]

The chief tasks for seam detection and tracking have been found to be weld starting and end point detection, weld edge detection, joint width measurement and weld path position determination with respect to robot co-ordinate frame. [9] Among the kinds of sensors applied in the robotic welding process, vision sensors is one of the most widely used for automatic welding seam tracking and quality control in robotic arc welding. [6, 10] Currently, vision sensors applied in welding system can be divided into active vision principle with light source and passive vision principle under natural light. [1] Sehun Rhee employed a laser vision sensor to determine the position and orientation of the welding torch and to automatically generate the robotic welding path. However, the geometric model cannot be established by the obtained range data alone, the CAD data is necessary as well. As the distortion of the parts and welding seam, it is hard to accomplish the accurate seam tracking. Wenjun Shao [8] proposed a novel welding seam detection method for butt joint of thin metal plate laser
welding. The vision sensor he used consisted of three laser stripes projector, among which two red laser stripes are used to measure the three-dimensional profile of the weld face and one green laser stripe is used to measure the edge and the centerline of the welding seam. But the dimension of the proposed sensor is too big that maybe not very practical in the industrial field. Ke Zhang designed a weld path autonomous programming system based on laser structure light to realize complex weld of large workpiece. The 3D modeling deviation of the welding seam curve is less than 0.4mm. [11] As the general require of the accuracy class for welding seam detection and tracking is about half of the wire dimension, this result can reach the minimum requirement for the gas metal arc welding process when the dimension of the welding consumables is less than 1.0mm. But it is not good enough to service for the more precise application such as laser welding and plasma arc welding.

As to improve the accuracy and intelligence of the welding seam detection and tracking, as well as the application practicability of the sensor, this proposed paper designed a small size integrated welding seam detection and tracking sensor based on laser vision, which can get accuracy 3D information of the welding seam in real time.

The aim of this paper is to present a new framework and the data process algorithm of the sensor. First, the configuration and structure of the sensor is introduced in section 2. Then, the calibration approach of the sensor is studied in section 3. Finally, the feature point extraction method of the welding seam and its accuracy is analyzed in section 4.

2. Configuration and Structure of the Sensor

2.1. Configuration of the sensor

The present sensor in this paper is designed by our research team, which is made up of an industrial camera and a linear stripe light laser projector. The configuration information of the sensor is shown in the Table 1.

| Part Name | Camera | Laser Projector |
|-----------|--------|-----------------|
| Model     | MER-201-25GM | Model | LS-650 |
| Dimension | 38.3×29×29mm | Dimension | Φ15×68mm |
| Working Distance | 110mm | Working distance | 100—150mm |
| Focal length | 12mm | Power | 50mW |
| Sight field | 50×50mm | Wave length | 658nm |
| Resolution | 1628 (H)×1236 (V) | Stripe width | 0.3mm |
| Frame rate | 25fps@1628×1236 | Pixel size | 4.4×4.4μm |

2.2. Structure of the sensor

The working situation of the robotic welding system is shown in Figure 1. There are both the outside welding seam and the inside welding seam, in order to improve the accessibility of the robot manipulator, the auxiliary tools such as the welding seam detection and tracking sensor should be mall size integrated.
There are three structure type of the welding seam sensors based on laser vision, (a) the perpendicular projecting-oblique receiving structure, (b) the oblique projecting- perpendicular receiving structure and (c) the oblique projecting- oblique receiving structure, as shown in Figure 2. The coordination transformation of type (a) structure is simple, but the capture image is apt to be disturbed by the welding arc. The solver of the depth information of type (b) structure is complex, while it is relatively accurate. The type (c) structure can provided the highest accuracy, but its dimension the largest as well [12].

In order to reduce the dimension of the sensor, this paper design the sensor structure follow type (b). The included angle between the camera optical axis and the laser projector axis is 25°. The shell of the
sensor is made of aluminum to reduce the weight. The designed sensor installed on the experiment platform is shown in figure 3.

Figure 3. The present welding seam sensor.

3. Calibration
Calibration of the sensor is the most significant issue before it is applied for welding seam detection and tracking. The calibration algorithm is proposed in this paper, which include to steps, firstly, camera calibration and secondly, light plane calibration.

3.1. Camera calibration
The principle model of the sensor is described in Figure 4, point P is assumed as a point on the detected surface, its coordinates in the world coordination system is \((X_w, Y_w, Z_w)\), the coordinates of image point in the image coordination system is \((u, v)\), then there will exist a function satisfied:

\[
\begin{bmatrix}
X_w \\
Y_w \\
Z_w \\
\end{bmatrix} = \begin{bmatrix}
m_0 & m_1 & m_2 \\
m_3 & m_4 & m_5 \\
m_6 & m_7 & m_8 \\
\end{bmatrix} \begin{bmatrix}
u \\
v \\
1 \\
\end{bmatrix}
\]  

(1)

The above relationship in formula (1) can be described in homogeneous matrix:

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

(2)

where \((u_0, v_0)\) is the principal point of the camera, \(\alpha\) and \(\beta\) is the scale factors of \(u\) and \(v\) axes in image coordinate, and \(\gamma\) is the parameter that describe the skew of the two image axes. \(u_0, v_0, \alpha, \beta\) and \(\gamma\) are the intrinsic parameters, while \((R, t)\) denotes the rotation and translation from the world coordinate system to the camera coordinate system.
The camera calibration is conducted using the “Calibration toolbox in Matlab”, it assumes that the 2D calibration plate in the $X_wO_wY_w$ of the world coordinate system, that is $Z_w=0$. The calibration results of intrinsic parameters are:

$$\alpha = 1/1284.821; \beta = 1/1287.780; \gamma = 0; u_0 = 542.223; v_0 = 604.964;$$

3.2. Light plane calibration

It is obvious that there is a sector light plane between the projector and the projected linear stripe, the light plane $\Omega$ in camera coordination system can be described as:

$$Z = aX + bY + c$$

(3)

It is mentioned above that the $(R, t)$ denotes the rotation and translation from the world coordinate system to the camera coordinate system. The linear stripe is project to the calibration pattern plate during the camera calibration process, and the stripe is captured by CCD as a line segment on the calibration pattern plate, shown as figure 5. Although the moving parameters of the plane target in space cannot be determined, because the laser vision sensor is fixed in the calibration process, all the linear light stripes in the captured image are belong to the plane $\Omega$. 

Figure 4. Principle model of the sensor.

Figure 5. The laser stripe on the calibration pattern plate.
We can get the two-dimension pixel coordination of the light stripes, and there three-dimension coordination in the world coordinate system can be solved by:

\[
\begin{bmatrix}
\frac{X_{Wi}}{s_i} \\
\frac{Y_{Wi}}{s_i} \\
1
\end{bmatrix} = \begin{bmatrix} r_{i1} & r_{i2} & t_i \end{bmatrix}^{-1} K^{-1}_i \begin{bmatrix} u_i \\
v_i \\
1
\end{bmatrix}
\]

(4)

The calibration result of the camera is used to solve the three-dimension coordinate of the points in the camera coordinate on each stripe by the following equation (because we assume the calibration plate in \(X_wO_wY_w\), the three-dimension point coordination in the world coordinate system is written in the form \((X_w, Y_w, 0)\)):

\[
\begin{bmatrix}
X_c \\
Y_c \\
Z_c
\end{bmatrix} = R \begin{bmatrix} X_w \\
Y_w \\
Z_w
\end{bmatrix} + T
\]

(5)

Assume that the points \(X_i (i = 1, 2, ..., n)\), \(n\) is the number of camera capture position) is the elements of point set \(M\). The structured light plane equation can be solved by fitting the points in the point set \(M\):

\[
0.013875X_c - 0.0012984Y_c - 0.0038244Z_c + 1 = 0
\]

(6)

3.3. Accuracy analysis

Take a butt specimen with a 60°V groove as example, shown in figure 6, this paper investigated the accuracy of the sensor.

![Figure 6. The butt specimen with a 60°V groove.](image)

The detected 3D point data of the weld groove is shown in figure 7. It is indicated that fitting error is less than 0.1mm.
Figure 7. The fitting result of detected 3D point data.

4. Welding Seam Detection and Tracking

Because the linear light stripe projected by the sensor has a certain distance before the welding torch (called forward-looking distance), the extracted 3D points information are not used immediately in the tracking process, but can only be used when the welding gun running close to the point. Therefore, it is necessary to store the collected tracking points information and provide one by one for use when necessary. In this paper, the circular queue structure is used to store the tracking points data. The T6 matrix is read in real time by the robot controller, and then the coordinates of the tracked point in the robot base coordinate system are obtained by equation (5), and the coordinates are stored in the established cycle queue.

\[
\begin{bmatrix}
  x_w \\
  y_w \\
  z_w
\end{bmatrix} = T6 \cdot TOOL \cdot \begin{bmatrix}
  x_t \\
  y_t \\
  z_t
\end{bmatrix}
\]

(7)

Where T6 is rotation translation matrix of the sixth joint coordinate system, TOOL is the rotation translation matrix from the sixth joint coordinate system to the welding gun tool coordinate system.

4.1. Welding seam detection and tracking process

The flow chart of welding seam detection and tracking process is shown in figure 8.

Figure 8. The flow chart of welding seam detection and tracking process.
Firstly, the robot is made to move in a uniform speed along the general direction of the weld (this direction is defined as the x-axis direction of the robot base coordinate system in this experiment). When the welding seam is detected by the laser stripe, the feature point is recorded as the beginning of the weld, and then the following tracking points are successively stored in the circular queue.

The stage before the welding torch reaches the initial point of the weld is the detection stage. In this stage, the position and attitude of the welding torch should be adjusted in real time, so that the root of the weld is always in the center of the laser stripe, and the tip of the torch is aligned with the initial point of tracking. The stage when the welding torch reaches the initial point and the welding process starts, is the tracking stage, the strategy in this stage is to control the welding torch to run along the welding seam. At the same time, the sensor continues to collect data, and sends the data to the robot controller and store them in the loop queue.

4.2. Experiment
In this paper, the v-butt weld with the thickness of 8mm has been tested. The values of each parameter in the tracking process are shown in table II:

| Parameter in the tracking process |
|----------------------------------|
| Step Length | Travel Speed | Groove Angle | Image Process Time |
| 0.05mm       | 5mm/s        | 60°          | 20ms               |

The tracking path of the linear welding seam is shown in figure 9. It is indicated that the tracking error is no more than 0.2mm.

![Tracking Path and Error](image)

**Figure 9.** The tracking path of the linear welding seam.

5. Conclusion
Vision sensors is one of the most widely used for automatic welding seam tracking and quality control in robotic arc welding. The present paper designs a welding seam detection and tracking sensor based on laser vision.

1. A novel two-step calibration approach is proposed in this paper based on the “Calibration toolbox in Matlab”, the proposed approach acquires the laser light plane by project the linear stripe on the calibration pattern plate during camera calibration process.

2. The fitting error of the detected 3D point data of the weld groove is less than 0.1mm.

3. The tracking error in robotic welding process is no more than 0.2mm.

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