Planning the Torch Orientation of Planar Lap Joint in Robotic Welding

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Abstract. The torch orientation plays an important role in welding a lap joint. This paper proposes a torch orientation planning method for planar lap joint. In this method, the seam coordinates are firstly generated based on the visual servoing approach. The rotation matrix describing the torch orientation is calculated at each seam point according to the geometrical contains of the torch, which is set according to welding conditions and the arrangement of the workpiece. The rotation angle increments used to adjust the torch orientation is then calculated. A curve seam was used to validate this method. The robot movement experiments prove the torch can be automatically adjusted to the desired orientation when the robot moves the torch along the seam using the generated seam coordinates.

1 Introduction

At present, large numbers of industry robots have been used in the automation of arc welding process. However, most of them works in the mode of "teach and playback". They must be taught the welding path in advance as well as welding parameters and work sequence. The teach process is time-consuming especial for curve lap joint, because the varied torch orientation is required. In order to develop the intelligent robot, it is necessary that the welding system can autonomously plan the welding path which includes the torch orientation as well as its position.

The visual sensor has been applied for seam tracking because it has non-contact sensing capability and it can provide abundant information. However, in many studies [1-4], the obtained visual information was mainly used to correct the weld path which was manually taught or off-line programming based on CAD data prior to welding.

In this paper, a torch orientation calculating method for planar lap joint is proposed. The seam coordinates is automatically generated based on the visual servoing approach. The rotation matrix describing the torch orientation is constructed at each seam point according to the geometrical contains of the torch. Then, the rotation angle increments used to adjust the torch orientation is calculated.

2 System Description

The constructed experimental system, which is shown in Fig.1, mainly consists of three parts: the RH6 robot system, the sensor device and the master computer. The

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RH6 robot system is a six-axis industry robot, developed by Shenyang institute of automation, Chinese academy of sciences. The sensor device is composed of a tilted CCD camera and its supporting system. The master computer is a Pentium III PC, which runs the image processing and tracking control program and acts as the man-machine interface to the system.

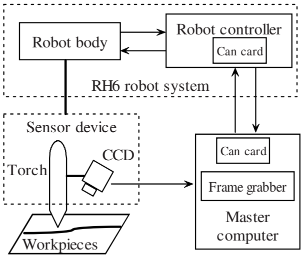


Fig. 1. Diagram of the experimental system

The master computer communicates with the robot controller using CAN (Controller Area Network) bus. The RH6 robot has its controller with the interface for accepting incremental pose from the master computer and for sending the current pose of the robot body to the master computer. The control cycle of the robot controller is 16ms.

3 Generation of the Seam Coordinates

The workpiece with lap joint is fixed on a horizontal worktable. In order to generate the seam coordinates, the system tracks the seam based on visual servoing method before welding. During seam tracking, the torch axis remains vertical so as to easily obtain the seam position based on the local seam image. When welding, the torch is automatically adjusted to the desired orientation according to the generated seam coordinates and the welding conditions.

The method of generating the seam coordinates is briefly explained here, and the similar method used for the butt-plane seam is discussed in [5]. The local seam image captured by the camera is transferred to the memory of the master computer with the frame grabber. The master computer processes the image and extracts the seam errors circularly. With the information of seam errors, the master computer sends motion increments to the robot controller, and then the robot moves the end-effector along the seam path. At the same time, the master computer reads the current pose of the robot from the robot controller, corrects these data with the current seam errors, and then records them to generate the seam coordinates in the base frame. The recorded coordinate point is called seam point.

4 Planning of Welding Torch Orientation

As shown in the Fig.2, both the position and the orientation of the torch can be represented by the tool frame {T}. The origin of {T} is at the tip of the torch, which is usually called Tool Center Point (TCP), and the principal directions of {T} is given by three orthogonal unit vectors with the following convention:

- the approach vector **a** is collinear with the axial line of the torch and is the direction of approach;
- the orientation vector **o** is coplanar with the vector **a** and the vector **v**, a unit vector of the welding direction, while its **v**-component vector has the same direction with **v**;
- the normal vector **n** is given by the cross product of the vectors **o** and **a**.

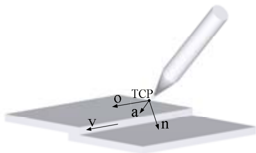


Fig. 2. Definition of Tool Center Point (TCP) and the tool frame {T}

4.1 Geometrical Constraints of the Torch Orientation

When welding a planar lap joint, the geometrical constrains of the torch orientation are shown in Fig.3. The angle θ is the included angle between the plane Π_1, decided by the electrode axis and the tangent line of the local seam, and horizontal plane Π_2 including the tangent line of the local seam. The angle ψ is the included angle between electrode axis and the line perpendicular to the tangent line of the seam in the plane Π_1. The angles θ and ψ are the acute angles.

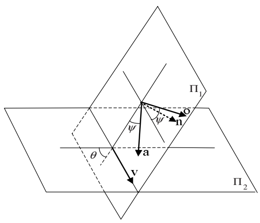


Fig. 3. Geometrical constraints of the torch orientation

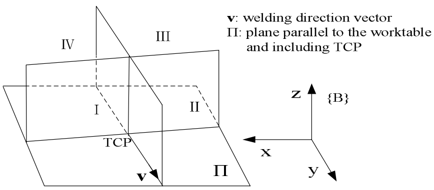


Fig. 4. Octants used to specify the torch orientation

In order to conveniently specify the torch orientation, we label four regions (the upper four octants) in the three dimensional space as shown in Fig.4.

4.2 Construction of Rotation Matrix ${}^{B}_{T}R$

4.2.1 Calculation of Trajectory Tangent Vector

The local seam trajectory is estimated by least square curve fitting to a 2nd degree polynomial curve of the following form:

$$y = a_0 + a_1 x + a_2 x^2 \tag{1}$$

Then, the slope k at point (x_i, y_i) is calculated by:

$$k = y'\big|_{x_i} = a_1 + 2a_2 x_i \tag{2}$$

The corresponding tangent vector $\mathbf{s}$ at this point is in the following form:

$$\mathbf{s} = [1\ k\ 0]^T \tag{3}$$

When the robot moves the torch according to the generated seam points, the torch orientation corresponding to the next seam point is calculated. For each seam point except for the last 5 ones, the 2nd degree polynomial curve fitting of the current point and the following 5 ones is performed to calculate the slope k at this point. The slopes at the last 6 seam points are calculated at every point using the last 2nd degree polynomial curve.

4.2.2 Construction of Intermediate Rotation Matrix ${}^{B}_{T'}R$

The orientation vector $\mathbf{o}$ becomes $\mathbf{o'}$, the approach vector $\mathbf{a}$ becomes $\mathbf{a'}$ when angle ψ is equal to zero. We denote the intermediate frame with its principal directions given by $\mathbf{n}$, $\mathbf{a'}$ and $\mathbf{o'}$ as $\{T'\}$.

The unit vector $\mathbf{o'}$ can be calculated by normalization of the vector $\mathbf{s}$ and correction the sign of its elements because the vector $\mathbf{o'}$ is parallel to the vector $\mathbf{s}$.

$$\mathbf{o'} = \begin{bmatrix} o'_x & o'_y & o'_z \end{bmatrix}^T = \begin{bmatrix} \dfrac{k}{|k|\sqrt{1+k^2}} & \dfrac{|k|}{\sqrt{1+k^2}} & 0 \end{bmatrix}^T \tag{4}$$

Suppose the direction vector of the line including the normal vector $\mathbf{n}$ is $\mathbf{n_1}$ and its three elements are A, B and C, respectively. According to the definition of the tool frame {T}, $\mathbf{n_1}$ is the normal vector of the plane Π_1. Since the plane Π_2 is horizontal, its normal vector $\mathbf{n_2}$ may be set to $\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$.

According to the including angle between the plane Π_1 and the plane Π_2 is θ and the vector $\mathbf{n_1}$ is perpendicular to the tangent line of the local seam, we can obtain the following equations set:

$$\begin{cases} A + kB = 0 \\ \dfrac{|C|}{\sqrt{A^2 + B^2 + C^2}} = \cos\theta \end{cases} \tag{5}$$

Given $\dfrac{|C|}{\cos\theta} = 1$, we can get its solutions. They give four unit vectors that the normal vector **n** could be. By selecting the correct sign of its every element according to the actual torch orientation, we can obtain two solutions of vector **n** corresponding to two cases:

When the torch is in II or III octants,

$$\mathbf{n} = \begin{bmatrix} n_x & n_y & n_z \end{bmatrix}^T = \begin{bmatrix} -\dfrac{\sin\theta|k|}{\sqrt{1+k^2}} & \dfrac{\sin\theta|k|}{k\sqrt{1+k^2}} & -\cos\theta \end{bmatrix}^T \tag{6}$$

When the torch is in II or III octants,

$$\mathbf{n} = \begin{bmatrix} n_x & n_y & n_z \end{bmatrix}^T = \begin{bmatrix} -\dfrac{\sin\theta|k|}{\sqrt{1+k^2}} & \dfrac{\sin\theta|k|}{k\sqrt{1+k^2}} & \cos\theta \end{bmatrix}^T \tag{7}$$

The approach vector $\mathbf{a'}$ is given by the cross product of the vectors **n** and $\mathbf{o'}$,

$$\mathbf{a'} = \mathbf{n} \times \mathbf{o'} \tag{8}$$

By now, we have constructed the rotation matrix ${}^{B}_{T'}R$ of the following form, which describes the orientation of the intermediate frame $\{T'\}$ relative to the base frame {B}.

$${}^{B}_{T'}R = \begin{bmatrix} \mathbf{n} & \mathbf{o}' & \mathbf{a}' \end{bmatrix} \tag{9}$$

4.2.3 Calculation of Rotation Matrix ${}^{B}_{T}R$

Suppose $\gamma = \psi$ if the torch in II or III octants, and $\gamma = -\psi$ if the torch in III or IVoctants. Then the intermediate frame $\{T'\}$ will become the tool frame {T} by rotating the angle γ about the vector **n**. Therefore, the rotation matrix ${}^{B}_{T}R$, giving the torch orientation relative to {B}, can be calculated by the following equation:

$${}^{B}_{T}R = {}^{B}_{T'}R\,{}^{T'}_{T}R \tag{10}$$

where ${}^{T'}_{T}R = R_n(\gamma)$.

4.3 Calculation of Orientation Increment

The orientation increment is calculated using the differential vector equation as follows:

$$\begin{bmatrix} \Delta R_x & \Delta R_y & \Delta R_z \end{bmatrix}^T = \begin{bmatrix} \dfrac{1}{2}(\mathbf{n}_c \times \mathbf{n}_d + \mathbf{o}_c \times \mathbf{o}_d + \mathbf{a}_c \times \mathbf{a}_d) \end{bmatrix} \tag{11}$$

where $\Delta R_x, \Delta R_y, \Delta R_z$ are the rotation angle increments of the tool frame around the axes x, y, z of the base frame respectively, the vectors $\mathbf{n}_c, \mathbf{o}_c$ and $\mathbf{a}_c$ describe the current torch orientation, obtained by reading the torch pose form the robot controller, and the vectors $\mathbf{n}_d, \mathbf{o}_d$ and $\mathbf{a}_d$ describe the desired torch orientation at the next seam point. The rotation angle increments are used to control the robot to adjust the torch orientation by the master computer.

5 Experimental Results

A planar curve seam, shown in Fig.5, was chosen to validate the calculation of the torch orientation. Accordingly, the reciprocal of the slope is calculated at each seam point (Fig.6(a)). Then, the median filter was adopted to remove the noise data (Fig.6(b)).

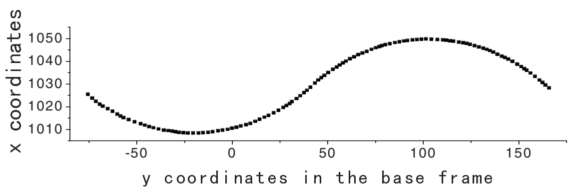
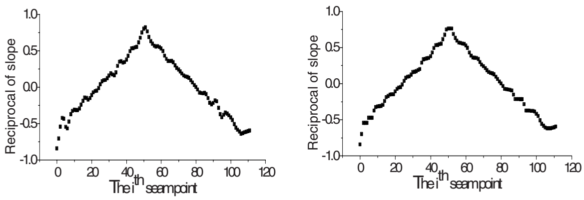


Fig. 5. The seam coordinates in the base frame (after smoothing)



(a) raw data (b) after median filtering

Fig. 6. Reciprocal of slope

When the robot moves the torch along the seam based on the generated seam points, the torch orientation at the next seam point is calculated and the torch is adjusted to this orientation according to the calculated rotation angle increments. The robot movement experiments prove the torch can be adjusted to the desired orientation at every seam point. The calculation data at the first 6 seam point are given in Table 1. Here, the torch orientation is in IV octant, the angle ψ is equal to 15 degree, and the angle θ is equal to 60 degree.

Table 1. The calculation data at the first 6 seam point

Seam point		Current torch orientation						Rotation angle increments		
x	y	o_x	o_y	o_z	a_x	a_y	a_z	ΔR_x	ΔR_y	ΔR_z
1025.42	-75.59	0.2371	0.9714	-0.0099	0.1031	-0.0353	-0.9941	-4.231	28.683	21.966
1023.72	-73.36	-0.1783	0.9789	-0.0999	-0.3546	-0.1587	-0.9215	2.762	4.544	-2.020
1022.35	-71.46	-0.1491	0.9880	-0.0394	-0.4313	-0.1009	-0.8966	1.524	2.315	-4.513
1021.10	-69.46	-0.0718	0.9974	-0.0085	-0.4728	-0.0416	-0.8802	0.468	1.502	-1.967
1020.25	-67.78	-0.0376	0.9993	0.0011	-0.4968	-0.0177	-0.8677	0.166	0.896	-0.879
1019.15	-65.19	-0.0222	0.9997	0.0045	-0.5105	-0.0075	-0.8599	0.242	0.366	-2.231

6 Conclusions

In this paper, the torch orientation calculating method for the planar lap joint is proposed. The seam coordinates used to calculate the seam tangent is generated based on the visual servoing. The rotation matrix describing the torch orientation is calculated at each seam point according to the geometrical contains of the torch The rotation angle increments used to adjust the torch orientation is then calculated. The actual robot experiments show that the torch can be automatically adjusted to the desired orientation when the robot moves the torch along the seam using the generated seam coordinates.

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