Welding Gun Inclination Detection and Curved Fillet Weld Joint Tracking

An investigation was conducted to detect the welding gun deviation and inclination simultaneously based on the welding current for the control of a mobile robot to track curved fillet welds

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ABSTRACT

It is important to adjust the welding gun’s inclination during automatic curved-joint tracking of arc welding. In this paper, a novel method is proposed to detect the deviation and inclination of the welding gun based on the arc currents acquired by a high-speed rotational arc sensor. It uses a least-squares method to fit the arc currents to a plane in three dimensions. The deviation and inclination of the welding gun are projected to two orthogonal planes so that they can be decoupled and thus can be calculated separately. A mobile welding robotic system was developed, which consists of a differential driving vehicle and a cross-slider manipulator. A fuzzy controller was designed to control the robot path and to extend the horizontal slider based on the measurements.

In this research, a novel method was developed that fits the arc currents to a plane in three dimensions using a least-squares fitting method. The deviation of the welding gun was obtained through calculating the intersection line slope of the fitting plane with the Y-Z plane, and the inclination was calculated through the intersection line slope of the fitting plane with the X-Z plane.

A wheeled mobile robot consisting of a differential driving vehicle and a cross-slider manipulator was developed. A rotational arc sensor was used for measuring the deviation and inclination of the welding gun. A fuzzy controller was designed to control the robot path and to extend the horizontal slider based on the measurements.

Dynamic Model of the Rotational Arc Sensor

Figure 1 shows the equivalent circuit of a gas metal arc welding (GMAW) system. The output voltage of the welding power source can be calculated by

\[ U(t) = U_e(t) + U_a(t) \]  

(1)

where \( U_e \) and \( U_a \) are the voltages of the wire extension and the welding arc, respectively. The arc voltage can be expressed as

\[ U_a(t) = k_a H_a(t) + k_p I(t) + U_c \]  

(2)

where \( k_a \) is the potential gradient across the arc column, \( k_p \) is the equivalent resistance of the cathode and anode spots, and \( U_c \) is a constant in the welding model.

The voltage of the wire extension \( U_e(t) \) can be written as

\[ U_e(t) = k_e H_e(t) I(t) \]  

(3)

where \( k_e \) is the electrical resistance per unit length of the wire extension, and
He(t) is the length of the wire extension. For GMAW, a melting model was developed by Lesnewich (Ref. 11) in which the wire-melting rate is

\[ V_m(t) = k_m I(t) + k_\eta H(t) I^2(t) + C_m \]

(4)

where \( k_\eta \) can be regarded as the influence of resistance heating on the melting rate, \( k_m \) is the influence of arc heating on the melting rate, and \( C_m \) is a constant. If we assume that the working range of the arc sensor is within a small area around the quiescent point, the small-signal theory is justifiable for analysis, and \( H(t)I(t) \) and \( H(t)I^2(t) \) can be linearized according to a first-order Taylor series. Based on the assumption, Equations 3 and 4 can be linearized as

\[ U_e(t) = k_l I(t) + k_i H(t) + C_1 \]

(5)

\[ V_m(t) = k_c I(t) + k_r H(t) + C_2 \]

(6)

Assuming \( I(t) \) in the quiescent point is \( I_0 \) and \( H(t) \) is \( H_0 \), we have \( k_l = k_c H_0 \), \( k_i = k_r H_0 \). \( k_c = k_m + 2k_\eta H_0 \) and \( k_r = k_\eta I_0 \). \( C_1 \) and \( C_2 \) are constants.

The relationship of wire feed rate and the wire-melting rate is

\[ \frac{dH(t)}{dt} + V_m(t) - V_f(t) = \frac{dH(t)}{dt} \]

(7)

where \( V_f(t) \) is the wire feed rate.

From Equations 1, 2, 5, and 6, we can get

\[ \frac{dU_e(t)}{dt} = \frac{dU_a(t)}{dt} + \frac{dU_a(t)}{dt} \]

(8)

\[ \frac{dU_a(t)}{dt} = k_a \frac{dH(t)}{dt} + k_p I(t) \]

(9)

\[ \frac{dU_a(t)}{dt} = k_i \frac{dH(t)}{dt} + k_i H(t) \]

(10)

\[ \frac{dV_m(t)}{dt} = k_m \frac{dH(t)}{dt} + k_r H(t) \]

(11)

Using Laplace transform for Equations 7–11, we have

\[ U(s) = U_e(s) + U_a(s) \]

(12)

\[ U_a(s) = k_a H_a(s) + k_p I(s) \]

(13)

\[ U_e(s) = k_i H_a(s) + k_i I(s) \]

(14)

\[ V_m(s) = k_c I(s) + k_r H(s) \]

(15)

\[ sH(s) + V_m(s) - V_f(s) = sH_a(s) \]

(16)

\[ P(s) \]

denotes the dynamic model of the welding power source and is written as

\[ P(s) = P_0 \]

(17)

Based on Equations 12–17, Pan (Ref. 12) developed the transfer function from \( H(s) \) to \( I(s) \) as

\[ G(s) = \frac{I(s)}{H(s)} = \frac{k_p}{1 - k_N P(s)} \]

(18)

where \( k_N = k_k k_l - k_k k_h = k_k c - k_k \overline{k} N - k_k k_h \overline{k} m \). When the welding power source has the hard output characteristic, its transform function can be written as

\[ P(s) = P_0 \]

(19)

So the transfer function of the arc sensor becomes a first-order model and can be written as
Rotational Arc Sensor Structure and Identification of the Arc Sensor System

The construction of the rotational arc sensor is shown in Fig. 2. A hollow shaft motor is used as the main body of the rotational welding gun, and the electrically conducting tube is inserted with a tilt through the hollow shaft. The upper self-aligning bearing is used as a hinge for the electrically conducting tube, which is fixed on the upper end of the shell. The balance block is installed in the lower part of the electrically conducting tube. The eccentricity of the bottom of the electrically conducting tube can be adjusted by changing the position of the balance block. Thus, the welding electrode rotates on the line that generates a cone when the armature of the motor rotates. An optical encoder is mounted to the end of the motor. On the optical encoder circumference, there are 64 shallow slots and one deep slot. Two optocouplers that are fixed in the upper part of the arc sensor shell correspond to shallow slots and deep slot, respectively. The signal from the deep slot is used to detect the start point of each rotation cycle, and the signal from the shallow slot is used as a trig source for the out-trigger of DAQ, so there are 64 discrete sampled current values in one rotation cycle. The welding current is measured by a Hall-effect current sensor and acquired by a plug-in DAQ board.

From the above descriptions, we know that the dynamic model for the rotational arc sensors can be regarded as a first-order model, but we do not know the actual numerical value of the parameters, which is important for calculating the deviation and inclination of the welding gun. So it is necessary to identify the arc sensor system. Because the ratio of the output and input amplitudes and the phase difference between them change with the change of the input-signal frequency when a sinusoidal exciting signal is fed into a system, the rule by which these parameters change represents the dynamic properties of the system. To get the dynamic characteristic of the rotational arc sensor system, an experiment was designed as shown in Fig. 3. The welding gun was installed with its axis inclined 45 deg to the horizontal steel plate. Then the welding gun height varies according to a sinusoidal waveform while the gun rotates.

Suppose that the arc rotation frequency is \( \omega \), the rotation radius is \( r \), then the contact tip-to-workpiece distance \( H \) can be computed as

\[
H = r \sin(\omega t + \beta_0) + H_0
\]  

where \( \beta_0 \) is the welding gun angle position when \( t = 0 \), and \( H_0 \) is the average height of the welding gun. The parameters for welding experiments are shown in Table 1. The experimental results are shown in Table 2, which indicates the change of the welding gun height.

Based on the experimental results from Table 2, the Bode diagram of the sensor system is plotted as Fig. 4.

From Fig. 4A, it can be seen that the zero frequency is \( f_1 = 3.2 \) Hz, the pole frequency is \( f_2 = 11.35 \) Hz, and the gain is \( k = -\text{ant log}(13.8/24.8) = -3.60 \), where the gain is negative since the angular phase differences are about 180 deg from Fig. 4B. So the first-order transfer function of the sensor system is

\[
G(s) = \frac{-3.60 - 1 + 0.0497s}{1 + 0.014s}
\]  

Filtering of Welding Current Signals

Because the welding current signals are often disturbed by outside noises, a hybrid filtering method is proposed in this paper. The flow chart of this filtering method is shown as Fig. 5. First, the welding current is filtered by the mean filtering method.
Then it is filtered by the space neighborhood median filtering method and the mean filtering method in turn. Finally, the last signal is obtained by use of the soft threshold wavelet filtering method. The wavelet used in this paper is four order Daubechies wavelet. The principle of the space neighborhood median filtering method is shown as Fig. 6.

Every row of data in Fig. 6 is the data sampled in one revolution of the arc (64 points per revolution). In each column, the data were sampled during different rotations of the arc, but they are at the same position of the arc in relation to the groove. Region B is the neighborhood in space, and region C is the neighborhood in time. The effect of filtering depends on the number of data in the neighborhood window. If it takes more points to filter in the direction of the row, it would result in a large phase delay. Because the welding gun is moving in the course of welding, the contact tip-to-workpiece distance is not the same at the same angular position in different cycles. It would cause a large error if it takes more points to filter in the direction of the column. So nine points were taken as a neighborhood window, and the value of the window’s center was calculated as

\[ a'(i,j) = \text{Median}(a(i,j)) \]

where A is the neighborhood window, and Median denotes the median filtering method.

To validate the hybrid filtering method, a series of experiments were done. The parameters for the welding experiments are also shown in Table 1, and the arc rotational frequency was 20 Hz. Because the welding gun inclines 45 deg to the workpiece, the contact-to-workpiece distance changed as a sinusoidal waveform. Based on the dynamic model of the rotational arc sensor, the welding current signals would also change as a sinusoidal waveform. The experimental results are shown in Fig. 7.

From Fig. 7, we can see that the original signal has many short-circuiting currents that appear as sharp pikes, which are regarded as interference. After being filtered by the proposed method, the short-circuiting current was suppressed completely. The waveform of the signal is approximately sinusoidal.

**Mathematical Model of Welding Gun Height when Tracking a V-Groove**

As shown in Fig. 8, the angle \( \theta \) between the axis of the welding gun and the normal of the workpiece is known as the inclination angle. Along the direction of welding, the inclination is a backward incline when the top is behind the end of welding gun (as the \( \theta \) shown in Fig. 8), otherwise, it is a forward incline. The error between welding gun and the symmetrical line of weld groove is known as deviation and recorded as \( e \). Suppose the angle between weld groove and horizontal plane is \( \beta \), the arc rotation radius is \( r \), the rotation period is \( 2T \), the rotation angle speed is \( \omega = \arcsin(e/r) \), and the arc is in the left of the groove when \( t = 0 \). Then in one rotational cycle, the welding gun height can be computed as Equation 24.

\[
H(t) = \begin{cases} 
T & \text{for } 0 \leq t < \frac{T}{2} \\
T - 2T & \text{for } \frac{T}{2} \leq t \leq T \\
\frac{3\pi}{2} + \frac{2T}{\omega} - \frac{2\pi}{\omega} + \frac{2\pi}{\omega} & \text{for } T \leq t \leq 2T \\
0 & \text{otherwise}
\end{cases}
\]

Suppose \( \beta = 45 \text{ deg}, r = 3 \text{ mm}, \text{ and } Hc = 25 \text{ mm} \). \( H(t) \) can be shown as in Fig. 9.

Based on Equation 24, we can get the heights of the welding gun from welding currents acquired from the rotational arc sensor. From Fig. 9, it can be seen that the heights both in interval \([0, 32]\) and \([0, 64]\) are symmetrical when \( e = 0 \) and \( \theta = 0 \).
While the heights in interval \([0, 32]\) are not symmetrical when \(e = -1.5\) and \(\theta = 0\), but the heights in \([0, 64]\) are symmetrical. So the symmetry of heights in interval \([0, 32]\) reflects the deviation of the welding gun and the symmetry of heights in interval \([0, 64]\) reflects the inclination. This method is called the interval integral method.

Although the interval integral method is simple and easy, the symmetry of heights is destroyed when both \(e \neq 0\) and \(\theta \neq 0\) due to the coupling of welding gun deviations and inclinations (such as Fig. 9D), so it cannot detect the deviation and inclination simultaneously.

**Welding Gun Deviations and Inclinations Detection Method**

**The Construct of Character Plane**

Taking the welding of a V-groove as an example, a Cartesian frame as shown in Fig. 10 is constructed. The frame \([X \ Y \ Z\ O]\) is linked to the welding gun, and the coordinate origin is the center of the arc rotation, the Z axis is parallel with the axis of the welding gun, and the X axis is parallel with the direction of welding.

Because the welding velocity is far less than the arc rotation velocity, the height of welding gun \(H(t)\) can be computed as Equation 24 in one rotation cycle, and \(X(t)\) and \(Y(t)\) can be written as

\[
\begin{align*}
    x(t) &= r \cos (\omega t + \pi / 2) \\
    y(t) &= r \sin (\omega t + \pi / 2)
\end{align*}
\]

Based on Equations 24 and 25, the graph of heights in one rotation cycle is plotted in three dimensions in Fig. 11.

From Fig. 11, it can be seen that the heights of the welding gun show different three-dimensional characteristics in space with the change of deviations and inclinations. If we use the least-squares method to fit the heights into a plane, the plane will reflect the deviation and inclination of the welding gun. For the sake of clarity, the graph of Fig. 11B and Fig. 11C is projected into the X-Z and the Y-Z surfaces, and shown as Fig. 12.

The lines \(aa\) and \(aa'\) in Fig. 12 are the intersection lines of the fitting plane with the X-Z plane, and the lines \(bb\) and \(bb'\) are the intersection lines of the fitting plane with the Y-Z plane. It can be seen that the slopes of lines \(aa\) and \(aa'\) are only related to the deviations, and the slopes of lines \(bb\) and \(bb'\) are only related to the inclinations. By

\[
\begin{align*}
    x(t) &= r \cos (\omega t + \pi / 2) \\
    y(t) &= r \sin (\omega t + \pi / 2)
\end{align*}
\]

Based on Equations 24 and 25, the graph of heights in one rotation cycle is plotted in three dimensions in Fig. 11.

<table>
<thead>
<tr>
<th>Actual values (deg)</th>
<th>Detection values (radian)</th>
<th>Variances (radian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>–45</td>
<td>–0.9079</td>
<td>0.1027</td>
</tr>
<tr>
<td>–34</td>
<td>–0.6215</td>
<td>0.1219</td>
</tr>
<tr>
<td>–22</td>
<td>–0.4416</td>
<td>0.1217</td>
</tr>
<tr>
<td>–11</td>
<td>–0.3136</td>
<td>0.1637</td>
</tr>
<tr>
<td>0</td>
<td>0.0136</td>
<td>0.1860</td>
</tr>
<tr>
<td>11</td>
<td>0.0930</td>
<td>0.1243</td>
</tr>
<tr>
<td>22</td>
<td>0.3601</td>
<td>0.1085</td>
</tr>
<tr>
<td>34</td>
<td>0.4701</td>
<td>0.1122</td>
</tr>
<tr>
<td>45</td>
<td>0.6046</td>
<td>0.1105</td>
</tr>
</tbody>
</table>

Table 4 — Experimental Results of Welding Gun Deviation Detection

<table>
<thead>
<tr>
<th>Actual values (mm)</th>
<th>Detection values</th>
<th>Variances</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 mm</td>
<td>0.7733</td>
<td>0.0843</td>
</tr>
<tr>
<td>0 mm</td>
<td>0.0515</td>
<td>0.1670</td>
</tr>
<tr>
<td>–3 mm</td>
<td>–0.7812</td>
<td>0.0723</td>
</tr>
</tbody>
</table>
Vector and matrix marks are introduced in order to facilitate discussion. Equation (26) is changed to

$$Z = Ax + By + C$$

In order to facilitate discussion, Equation 26 is changed to

$$Z = \beta_0 + \beta_1 x_1 + \beta_2 x_2$$

Vector and matrix marks are introduced

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & 1 & x_{21} & x_{22} & \cdots & \cdots & 1 & x_{n1} & x_{n2} \end{bmatrix}$$

For fitting the welding gun heights into one plane, $\beta$ must meet the following conditions.

$$\sum_{i=1}^{n} \left( H_i - \sum_{j=0}^{2} \frac{x_j \beta_j}{2} \right)^2 = \min \sum_{i=1}^{n} \left( H_i - \sum_{j=0}^{2} \frac{x_j \beta_j}{2} \right)^2$$

(29)

Using the differential method to solve Equation 29, we have

$$\sum_{i=1}^{n} \left( H_i - \sum_{j=0}^{2} \frac{x_j \beta_j}{2} \right) x_k = 0 \quad (k = 0, 1, 2)$$

(30)

Changing Equation 30 to

$$\sum_{i=1}^{n} H_i x_k = \sum_{j=0}^{2} \sum_{i=1}^{n} x_j x_k \beta_j$$

(31)

Expressed by matrix, the above equation can be written as

$$X'X\beta = (X'X)\beta$$

(32)

By analyzing, we know that the matrix $X'X$ is a positive matrix, therefore it has an inverse matrix $(X'X)^{-1}$. So $\beta$ can be computed as

$$\beta = (X'X)^{-1}X'H$$

(33)

Experimental Study

To verify the performance of the proposed method in detection deviation and inclination of the welding gun, numerous experiments were performed. In the experiments, the inclination of the gun was set at $-45$ deg, $-34$ deg, $-22$ deg, $-11$ deg, $0$ deg, $11$ deg, $22$ deg, $34$ deg, and $45$ deg, respectively. The negatives denote backward inclination, and the positives denote forward inclination. The deviations of the gun were set at $-3$ mm, $0$ mm, and $3$ mm, respectively. The experimental results are shown in Tables 3 and 4.

For achieving welding gun inclination detection, the data of Table 3 were fit into a second-order polynomial, and plotted, as shown in Fig. 13.

From Fig. 13, it is seen that the detection values correspond to the actual values, and their relationship is shown as

$$y = 2.7576 + 61.0594x + 9.2245x^2$$

(34)

where $y$ is the actual value of inclination, and $x$ is the detection value.

Similarly, the relationship of deviations can be fitted into a one-order polynomial and is shown as

$$y = -0.0560 + 3.8532x$$

(35)

From Equations 34, 35, and Tables 3 and 4, we can get the average variance of inclination and deviation as $\pm 7.85$ deg and $\pm 0.42$ mm, respectively.

To further verify the proposed algorithm, an experimental method was designed, as shown in Fig. 14. Keeping the welding speed unchanged, the deviation of the gun changes from ($e>0$) to ($e = 0$) and ($e<0$). Because the shape of the welded fillet joint is in an arc, the inclination of the gun changes from forward incline to backward incline. Thus, the detection results representing the deviation and inclination will be a time-variable function. The detection results are shown in Fig. 15.

From Fig. 15, we can see that the detection results of deviation and inclination are in accord with the actual ones, which verifies that the proposed method can correctly detect the deviation and inclination of the welding gun simultaneously.

Curved Fillet Joint Tracking by Mobile Robot

Design of Mobile Welding Robot

Figure 16 shows the mobile welding robot. The robotic welding system consists of a main controller, a robot body, driving actuator parts, and a rotational arc sensor. An industrial computer is used as the main controller. The welding current is measured by a Hall-effect current sensor and is acquired by a plug-in DAQ board (Ad-
ventech PCI-1713). The control value is sent to driving actuator parts by a plug-in data output card (Adventech PCI-1723). The robot body consists of a differential driving vehicle and a cross-slider manipulator. The right and left wheels are driving wheels and the front and back wheels are omnidirectional. The mass center of the mobile robot is in the middle of the axis of the driving wheels, and the cross-slider is over the axis of the driving wheels and can move horizontally and vertically. In order to avoid skidding, four magnets are attached in four corners under the body. The driving part is composed of four Maxon RE35 DC servo motors, and they drive two wheels and the cross-slider, respectively. The rotational arc sensor is attached to the cross-slider to detect the deviation and inclination, and it is used as a welding gun as well.

The Design of the Controller for Tracking Curved Fillet Welds

For the curved fillet joint tracking, as shown in Fig. 17, $v_c$ and $\omega_c$ are the robot’s current center linear velocity and angular velocity, respectively. Suppose $v_t$ is the linear velocity of the welding gun’s front-end point, and $v_r$ is the reference linear velocity. We then know that the angular error is $\alpha$. The inclination of the welding gun detected by the rotational arc sensor is $\theta$, and apparently $\theta$ is equal to $\alpha$. So the control process is described as follows: when tracking the curved fillet joints, the deviations are used to control horizontal slider extension, and the inclination is used to control the wheels moving and turning along the joints.

The fuzzy controller used to control the welding gun was described in Hu (Ref. 13), Wang (Ref. 14), and Liang (Ref. 15). In this project, a fuzzy controller was developed to deal with the disturbance of the welding processing and the dynamic uncertainties of mobile robots. The control scheme is shown in Fig. 18.

The Design of Multisegment Controller

For controlling the horizontal slider, a multisegment controller was proposed and the key idea is shown in Fig. 19. The controller is composed of a proportion controller and a fuzzy controller. When the deviation is large, the proportion controller will be used to quickly reduce the deviation, otherwise the fuzzy controller will be used to avoid overshoot and achieve smooth tracking. In view of that, a fuzzy controller cannot eliminate static errors. An integral operation was introduced, and its principle is described as follows: the deviation change rate is used as a switch threshold, and when it is small, the deviations will be integrated and then put into the fuzzy controller, otherwise the deviations will not be integrated.

The two inputs of the fuzzy controller are the welding gun deviations $e$ and its
change rates \( e_c \), and the output is the control value \( u \) of the horizon slider. In order to keep the number of fuzzy rules at a reasonable level, we defined the fuzzy sets of inputs and outputs as the same as \{PB (Positive Big), PM (Positive Middle), PS (Positive Small), ZE (Zero), NS (Negative Small), NM (Negative Middle), NB (Negative Big)\}. The membership functions of inputs and output are shown in Fig. 20.

For fuzzy control, the mathematical model of adjusting the modifying gene can be written as

\[
\alpha = 2 \left( \frac{1}{1 + \exp\left(-e_c\right)} \right)^{0.5} \quad (37)
\]

(36)

where \( e \) and \( e_c \) are the fuzzy values of \( e \) and \( e_c \), respectively, and \( \alpha \) is the modify gene.

From Equation 36 we can see that \( \alpha \) reflects the different weights of \( e \) and \( e_c \), so the parameters of the fuzzy controller can be changed by adjusting \( \alpha \). Usually \( e \) should be eliminated when it is big, so \( \alpha \) should be augmented. On the contrast, \( \alpha \) should be reduced. In view of the real-time application of welding joint tracking, a function is used to modify \( \alpha \) and it is written as

\[
u = \left( \alpha e + \left( 1 - \alpha \right) e_c \right) \quad (36)
\]
Curved Fillet Joint Tracking Experiments

The welding parameters used in experiments were Miller DeltaWeld 450 welding machine, 85% Ar + 15% CO2 shielding gas, 17 l/min gas flow rate, 24 cm/min welding speed, 25 V, 11 m/min wire feed speed, 6-mm diameter of arc rotation, 20-Hz frequency of arc rotation, 0.4-s sample time, and 20-mm average CTWD.

The shape of the weld joint is shown in Fig. 21, where s is the start point, e is the end point, and the robot is right of the joint.

Figure 22 shows the deviations $\gamma_e$ detected by the rotational arc sensor. From the figure, we can see that the deviations are $-2.50 \sim +2.50$ mm. Figure 23 shows the welding gun inclination $\theta_e$, and it reflects the orientation change of the mobile robot in tracking a curved joint. The actual tracking result is shown in Fig. 24. It is important to note that the deviations shown in Fig. 22 are detected by the rotational arc sensor, but not the actual tracking errors. For getting the actual tracking errors, the welded joint is cut into six sections of equal length. Figure 25 is a sectional view of the welding joint, in which $L_1$ is the length of the weld toe horizontally, $L_2$ is the length of the weld toe vertically, OC is the angle bisector of AOB, M is the midpoint of AB, MD is parallel to OC, and $e$ is the tracking error, which is negative when MD is under OC, otherwise it is positive. The measurement of $e$ is shown in Table 5. From Table 5 we can see that the maximal tracking error is $-0.495$ mm, so the joint tracking quality meets the production requirement.

Conclusion

A dynamic model of a rotational arc sensor was established, and the parameters of the model were identified by experiments. The transfer function from CTWD to the welding current shows that the sensing system is linear. By constructing the fitting plane in three dimensions, the deviations and inclination of the welding gun were projected to two orthogonal planes, so they are decoupled and can be calculated simultaneously. Compared with other approaches, the developed method can work in real time and shows a high degree of detection accuracy. For the curved welding joint tracking, a fuzzy controller was developed to control the wheels and horizontal slider of the welding robot based on the measurements of deviation and inclination. The experimental results demonstrated the feasibility and advantages of the fuzzy controller on the curved fillet joint tracking.

References