Application of Arc sensor and Ultrasonic sensor Information Fusion in Welding

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Abstract: In this paper, a new method of joint control of seam tracking and welding quality was used. Arc sensor gets the welding deviation information and ultrasonic sensor gets the welding penetration information. Using the fusion algorithm of combination of optimal weight and recursive least square algorithm can improve the accuracy of seam tracking effectively. Putting the fused information and welding penetration information into fuzzy controller with three-input and two-output to realize inspecting the welding quality and improving accuracy of seam tracking at the same time.

Introduction

Multi-sensor information fusion provides a solution for the robot to work in a variety of complex, dynamic and uncertain or unknown environment. The control of welding quality has been an important research topic in automated welding since years ago. Using different sensors to obtain status information of welding during the welding process will get more accurate status information of welding process than one single sensor[1].

Arc sensor for seam tracking

Jiluan Pan deduced the dynamical physics-math model of arc sensor [2] under the premise of three assumptions. The model gives a quantitative mathematical description of dynamic input-output relationship of arc sensors. The configuration diagram of arc sensor system [3]is shown in figure 1, torch height H(s) for the input and current I(s) for the output.

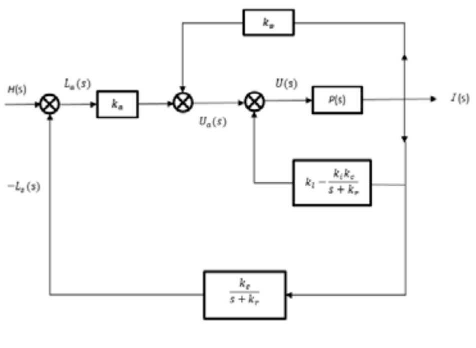

Fig.1Structure diagram of arc sensor system

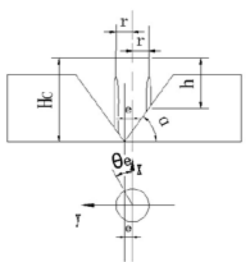

Fig.2 Schematic diagram of arc welding

Figure 2 is the schematic diagram of arc welding, we can assume that when the torch rotate at the far right, t=0. For the V-groove, in case of a deviation from the torch to the center of weld is $e(-r \le e \le r)$. The torch's height variation is

$$h(t) = H_C - |\cos wt + \sin\theta_e| r \cdot \tan\alpha \tag{1}$$

The welding current variation is :

$$I = I_0 + K_D \cdot r \cdot |\sin wt - \sin\theta_e| \cdot \tan\alpha \tag{2}$$

Where: $\theta_e = \arcsin(e/r)$; $-\pi/2 \le \theta \le \pi/2$; $\omega = 2\pi/T$; H_C、r、$\alpha$are constants.H_C is the static height of the torch; α is the gradient of V-groove; I_0 is the average current; K_D is the dynamic sensitivity of arc sensor and it is related to welding conditions and rotating speed.

There are several ways to choose the integral interval. Considering a strong disturbance of molten pool when the torch scanning to the rear of weld seam, the integral interval can be chosen as two π / 2 angle interval when the torch rotating to the leftmost position and rightmost position[3], that's $[\frac{\pi}{4},\frac{3\pi}{4}]and[\frac{5\pi}{4},\frac{7\pi}{4}]$. Relationship between integral differentials and lateral deviation is as formula (3) and (4).

On the left groove:

$$h = -(r \cdot \sin\theta - e)\tan\alpha \ \theta\epsilon[\frac{\pi}{4},\frac{3\pi}{4} \tag{3}$$

On the right groove:

$$h = (r \cdot \sin\theta - e)\tan\alpha \ \theta\epsilon[\frac{5\pi}{4},\frac{7\pi}{4}] \tag{4}$$

The height difference and current difference of a pair of point, belong to$\frac{\pi}{4} \le \theta \le \frac{3\pi}{4}$ and of which the angular coordinate is$\pm\theta$, are

$$\Delta h = 2e \cdot \tan\alpha \tag{5}$$

$$\Delta i = -2K_D \cdot e \cdot \tan\alpha \tag{6}$$

The integral differentials of left and right symmetric interval$[\frac{\pi}{4},\frac{3\pi}{4}]$、$[\frac{5\pi}{4},\frac{7\pi}{4}]$ is

$$\Delta S = \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} i d_\theta - \int_{\frac{5\pi}{4}}^{\frac{7\pi}{4}} i d_\theta = \Delta i \cdot \Delta\theta = -2K_D \cdot e \cdot \tan\alpha \cdot \frac{\pi}{2} \tag{7}$$

Therefore, when $|e| \le r$ the left and right symmetric current integral differentials and lateral deviation has a good linearity.

Ultrasonic sensor for penetration depth measuring

Figure 3 is the path diagram of RGLS wave [4]. The laser pulse generates a Rayleigh wave on the bottom surface of the weld sample. The generated Rayleigh wave travels to the weld seam where it travels up the seam and strikes the bottom of the weld bead. A LS Mode converted wave is then generated at the bottom of the weld bead and travels to the sensor.

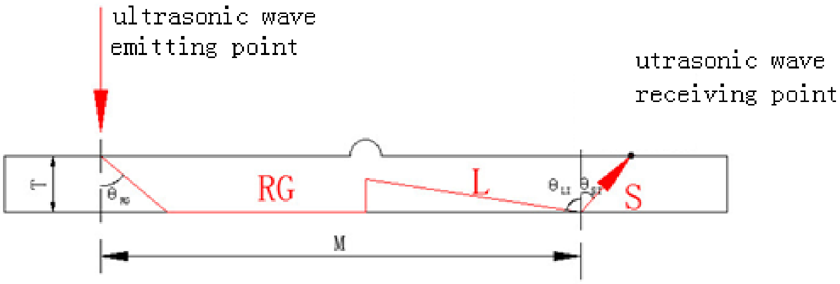

Fig.3 Path of the RGLS wave

Experimental setup to measure weld penetration depth with RGLS TOF method are shown in Figure 4. Laser pulses from a Laser is redirected to the surface of the sample using a 45° mirror. The LURL EMAT is placed on the other side of the weld bead against an adjustable locating stop.

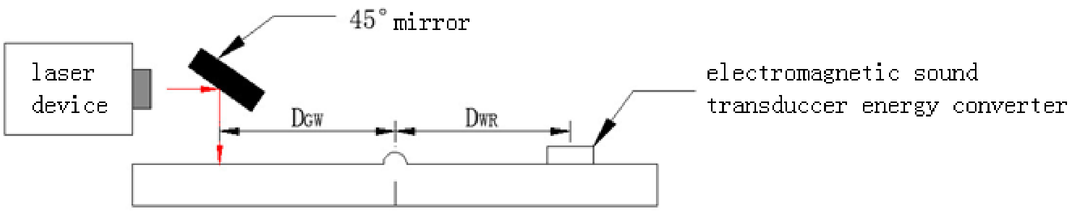

Fig.4 Experimental setup to measure weld penetration depth with RGLS TOF method

Propagation time of RGLS wave from the ultrasonic generated point to the receiving sensor is:

$$TOF_{RGLS} = t_{RG} + \frac{(D_{GW}+T-d_p-D_{RG})}{C_R} + \frac{T-d_p}{C_L\cos(\theta_{LI})} + \frac{T}{C_S\cos(\theta_{SI})} \quad (8)$$

Where: t_{RG} :Time between laser pulse and bottom surface Rayleigh wave generation ; D_{RG}:Horizontal distance between laser pulse and bottom surface Rayleigh wave generation point; D_{GW}:Distance between laser ultrasound generation point and weld bead; D_{WR}: Distance between weld bead and ultrasound reception point; T : Thickness of weld samples; d_p:Weld penetration depth; θ_{RG}:Rayleigh wave generation angle; C_R、C_L、C_S:Rayleigh, longitudinal, and shear wave speed; θ_{LI}、θ_{SI}:Angles for LS mode conversion of the wave path; D_{WR}、D_{GW}、C_R、C_L、$C_S$and T are constants; t_{RG}、D_{RG} can be obtained through the following three formula (9)、(10)、(11).

$$D_{RG} = T\cdot\tan(\theta_{RG}) \quad (9)$$

$$t_{RG} = \frac{T}{C_S\cos(\theta_{RG})} \quad (10)$$

$$\theta_{RG} = \frac{\arcsin(C_R/C_L)+\arcsin(C_R/C_S)}{2} \quad (11)$$

The relationship of θ_{LI}、$\theta_{SI}$are as formula (12).

$$\frac{\sin(\theta_{SI})}{C_S} = \frac{\sin(\theta_{LI})}{C_L} \quad (12)$$

$$D_{WR} = T \cdot \tan(\theta_{SI}) + (T - d_p) \cdot \tan(\theta_{LI}) \tag{13}$$

Weld penetration d_p can be calculated using formulas (8)~(13).

Design of seam tracking control system based on Arc sensor and ultrasonic sensor

Figure 5 shows the structure of control system which based on the seam tracking of arc sensor and ultrasonic sensor. The control system is composed of arc sensor, ultrasonic sensor, a part of computer information processing, fuzzy controller and the system of robot joint. Compared with the traditional and single welding seam tracking system, the system mentioned in this article has better predicted precision of welding seam tracking and the welding quality can also be controlled in real time.

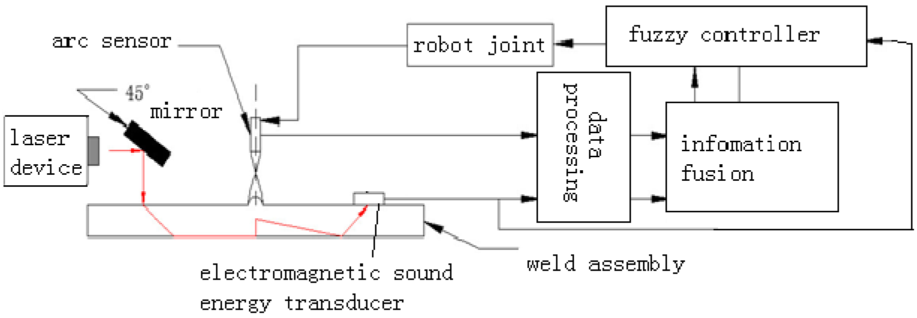

Fig.5 Structure diagram of seam tracking control system based on arc sensor and ultrasonic sensor

As shown in Figure 6, ultrasonic sensor and arc sensor are fixed position with welding torch relatively. Due to the needed process of weld pool from formation to stability, while the RGLS method of depth of fusion is also a process from getting data to the steady state, which will last about 9-13s[4].Ultrasonic receiver(LURL EMAT) must have a delay distance of M=(9~13)· V_s to the welding torch, V_s is the welding speed of welding torch. Distance between source and receiver point of laser ultrasonic remains the same set and set as N, e is the welding deviation and assumes that the left deviation is positive.

$$D_{GW} = N + e \tag{14}$$

$$D_{WR} = N - e \tag{15}$$

The formula (14) and (15) are substituted into the formula (8) and (13), which can be obtained the relation between weld penetration d_p and weld deviatione. With the unchanged situation of welding average current I_m, welding torch speed V_s and other welding factors, the change of measured value of welding penetration d_p can reflect the change of welding deviatione.

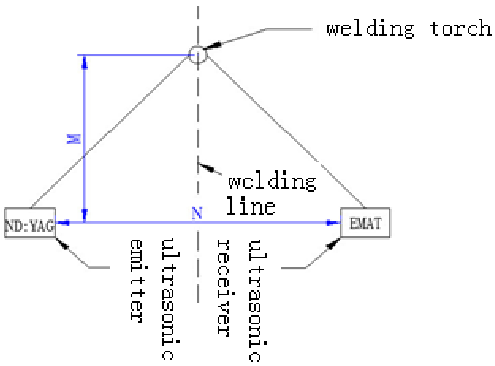

Fig.6 The relative position of ultrasonic sensor and welding torch

Information Fusion Algorithms.

Information Fusion Algorithms can be divided into the methods of probabilistic fusion theory (random set theory) and non-probabilistic fusion theory (artificial intelligence methods). The methods of probabilistic theory include classical probability reasoning, classical Bayesian reasoning, Bayesian convex set theory, information theory (Shannon theory) etc. The methods of non-probabilistic theory include D-S evidence reasoning, fuzzy logic, artificial neural network, wavelet transform, rough set theory etc[5].

This paper adopts combination of optimal weight and recursive least square fusion algorithm to process welding seam deviation information obtained from arc sensor and ultrasonic sensor. This method first weights real-time measurement values of each sensor to fuse values obtained from multiple sensors into one value, and then using the recursive least square fusion algorithm to process the sequence of the fused value so as to further decrease the number of estimation errors. By setting n sensors to test the same target parameters from the different position, the measuring equation of the nth sensor can be identified as follow:

$$Z_i = X + V_i \tag{16}$$

In which, X is the true value of the estimated parameters, Z_i is the measurement value, V_i is the measurement noise which can satisfy $\mathrm{E}[V_i] = 0$, $\mathrm{D}[V_i] = \sigma_i^2$, $\mathrm{E}[V_i V_j] = 0$, $(\mathrm{i} \neq \mathrm{j})$ in the meantime.

a. Optimal weights. First，establish expression of the weighted estimate X .

$$\hat{X} = \sum_{i=1}^{n} \alpha_i Z_i \tag{17}$$

α_i is the weighting coefficient of i-th sensor's measurement data

$$\mathrm{E}[\hat{X}] = \mathrm{E}[\sum_{i=1}^{n} \alpha_i Z_i] = \mathrm{E}[\sum_{i=1}^{n} \alpha_i (X + V_i)] = \mathrm{E}[\sum_{i=1}^{n} \alpha_i X] + \mathrm{E}[\sum_{i=1}^{n} \alpha_i V_i] = \mathrm{X} \sum_{i=1}^{n} \alpha_i = X \tag{18}$$

to ensure the no deviation estimate satisfy E=e，namely

$$\sum_{i=1}^{n} \alpha_i = 1 \tag{19}$$

Second，establish expression of weighted estimation mean square error $\mathrm{E}[(X - \hat{X})^2]$

$$\mathrm{E}\left[(X - \hat{X})^2\right] = \mathrm{E}[(X - \sum_{i=1}^{n}(X + V_i))^2] = \mathrm{E}[(\sum_{i=1}^{n} \alpha_i V_i)^2] = \sum_{i=1}^{n} \alpha_i^2 \sigma_i^2 = \min \tag{20}$$

We can get a weighting factor from formula (20) .

$$\alpha_i = \frac{\sigma_i^{-2}}{\sum_{i=1}^{n} \sigma_i^{-2}} \tag{21}$$

the formula (21) shows that sensor with small noise variance has big weights，whose measured data have the high proportion in the weighted values，which is reverse compared with the sensor with big noise variance.

b. Recursive least square method. Weighted estimates can filter some parts of noise interference to some extent，but with no obvious decrease，whose reason is that the weighted measured noise is still can be reduced in some space. However，recursive least-squares method，can further reduce the noise disturbance to the target parameter. Here is the recursive least-squares method of recursive equation as formula (22) and (23).

$$P_{K+1} = P_K - \frac{P_K^2}{1+P_K} \tag{22}$$

$$\hat{Y}_{K+1} = \hat{Y}_K + P_{K+1}(\hat{X}_{K+1} - \hat{Y}_K) \tag{23}$$

where, $\hat{Y}_K$ and $\hat{Y}_{K+1}$ are estimates of system in the K andK+1 moment, $\hat{X}_{K+1}$ is weighted estimates of n sensors' measurements in theK+1 moment， P_K and P_{K+1} are the intermediate quantity， $\hat{Y}_1$ and P_1 are the initial values of system.

Acquired weld deviation information from arc sensor e_1 and information from ultrasonic sensor e_2, fusing above-mentioned steps we can get estimated value e. The fused estimated value of weld deviation e can be processed into two steps. First step，put it into fuzzy controller directly. Second step，put it into fuzzy controller after the differential. Fuzzy controller uses the model with three inputs and two outputs. Input information includes e、d_p and de/dt; Output information includes output deviation control information e_k and weld speed control information v_k.Specific measurement noise variance of arc sensor and ultrasonic sensor is unknown，which can be estimated its variance by using the adaptive method，according to measurement value sequence. The advantages of combined computing method of the optimal weighting algorithm and recursive least square method have been discussed in paper[6]，which not only has high accuracy and robustness，but also has reduced calculation and good real-time performance as for computational complexity.

Conclusion

Integration of ultrasonic sensor and arc sensor in seam tracking system ensures the online testing of welding quality and raises the seam tracking accuracy effectively. Using the combination of optimal weight and recursive least square algorithm can reduce the influence of noise and improve seam tracking accuracy.

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