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A robot method based on self-adjusting factor fuzzy control algorithm for the seam tracking

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***Abstract*—This paper proposes a method for the seam tracking based on the self-adjusting factor fuzzy control algorithm. The method studies the self-adjusting factor with real-time variation of seam track deviation, and improves welding adaptability and dynamic performance. We combine the structured light vision sensor, image processing technology and robot to extract the seam track to the robot in real time. We use the self-adjusting factor fuzzy control algorithm to achieve smooth adaptive seam tracking. Finally, the simulation experiments show that the control method has good control precision and effectively improves the welding precision.**

***Index Terms*—seam track, fuzzy control, self-adjusting factor, dynamic compensation**

I. INTRODUCTION

Currently, the utility of robots in fulfilling various tasks in place of human beings in industrial production and daily life is gaining a significant importance [1]. Welding plays a very important role in the industrial manufacturing process [2]. Due to the complicated process of welding itself and the arduous working environment, the welding quality mainly depends on the welder's operation level and skill [3]. For mass production tasks, traditional welding is difficult to afford flexible production tasks. With the development of science and technology, welding automation and intelligence have been the main research direction in the field of welding. Automatic seam identification and tracking technology is the key to achieving welding automation, it is also difficult in the meanwhile.

There are currently few studies on welder experience and skills. Domestic research is mainly to identify electrical and acoustic signals and two-dimensional molten pool information during the welding process of skilled welders. Intelligent fusion algorithms such as fuzzy rough sets or neural networks are used for information fusion and processing to establish the correspondence between artificial experience and weld quality [4]-[5]. ERDEN M S studied the difference in welding behavior between skilled welders and novice welders by establishing a three-dimensional motion capture system [6]. By analyzing the welding process of skilled welders and novice welders, the standard of distinction between skilled welders and novice welders is proposed. Liu et al. established a human-machine interaction welding system based on skilled welder welding through motion tracking sensors and visual sensing technology [7], which improved the intelligence level of machine welding. But the welding process was inseparable from the real-time operation of skilled welders.

Many researchers have focused on more accurate weld inspection methods. Huang Shisheng et al. proposed a weld seam detection algorithm based on adaptive resonance theory neural network [8]. It determines the weld position according to the mode distribution and can correctly detect the weld position in a strong noise environment. Liu Suyi et al. proposed rapid element matching based on structural elements, corner detection method and fast Hough transform method to identify and extract the center of weld structure light [9], which has high real-time and fault tolerance. After the median filtering and adaptive threshold segmentation preprocessing, Huo Ping et al. uses the combination of slope analysis and least squares method to detect the weld image and obtain the feature information [10], which has strong anti-interference. LEE et al. used median filtering to filter out noise and then use Otsu method for binarization segmentation [11]. The improved Hough transform method for extracting weld features has achieved good results.

The neural network has the ability of uniform approximation and self-adaptation. It can play the role of nonlinear compensation, parameter identification, etc. It can also be used as a controller to directly control the robot system, and is widely used in robot systems and welding systems [12-14]. Narendra KS proposed an adaptive control strategy based on neural network to estimate unknown dynamic models [15], and adjusted the static and dynamic parameters of the system through backpropagation algorithm. Yang CG used dual-arm robot as the research platform Using neural network technology to estimate the uncertain nonlinear term in multi-mechanical arm coordinated control to improve the positional accuracy of coordinated control [16]. He W proposed a neural network-based adaptive impedance control strategy to compensate the robot through neural network [17]. Some of the uncertainties in the middle, under the control of the external interaction force to present a given ideal impedance relationship.

Fu Tao et al. proposed an improved neural network adaptive sliding mode control robot trajectory tracking method on the basis of the neural network sliding mode control method [18]. This method uses particle swarm optimization algorithm to optimize the radial basis function

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neural network structural parameters. The experiment results show that the control system designed by the proposed method has good robustness and control precision, and can reduce the chattering efficiently. Zheng Jun et al. proposed a real-time seam tracking technology based on particle filter for line structure light [19]. By extracting the weld feature template and using the correlation of the weld sequence image to observe the change of the weld position, the particle filter is used to realize the real-time tracking of the weld. The system can effectively eliminate the interference of arc and splash, and can track the weld with changing shape.

With the development of fuzzy control theory, many researchers began to focus their research on fuzzy control. The fuzzy control is based on the control rules containing fuzzy information, and the control system is better than the conventional control system in stability and robustness. Xie Guang et al. proposed a robot welding prospective control method based on fuzzy adaptive PID weld seam tracking [20], which effectively improved the welding precision of large-scale thin-walled structural parts. Xu Pengfei et al. designed a composite Fuzzy-PID controller for robot weld seam tracking [21]. According to the size of the weld deviation, PID control or fuzzy PID control is selectively used. The advantage of this controller is that the dynamic response is fast and the overshoot is small, but the deficiency is insufficient. Sun Hua proposed a welding seam tracking algorithm based on fuzzy neural network [22], which is satisfactory for tracking the curved weld trajectories of straight welds and smooth transitions.

In the actual welding environment, there are a lot of interferences such as arc, splash, dust, etc., which makes the actual welding process nonlinear and time-varying. Instant seam tracking becomes difficult, and classic control methods do not perform well seam tracking during welding. Therefore, this paper proposes a seam tracking method based on self-adjusting factor fuzzy control algorithm. Firstly, the weld image is obtained by the structured light vision sensor. The path is transmitted to the robot after processing. The self-adjusting factor fuzzy control algorithm is presented to perform the seam tracking immediately. It has good dynamic performance and improves the control precision and welding precision.

II. System Composition and Working Principle

A. System composition

The structure of the weld seam tracking system is shown in Figure 1. It is mainly divided into four parts: the structured light sensor module, the host computer module, the industrial robot module and the welding module. The structured light vision module consists of an industrial camera, a camera lens, a line laser generator, and a narrow band filter. Industrial robot module include six-axis industrial robot and corresponding control cabinet. The welding module consists of a welding torch, a wire feeder and a wire spool that are fixed at the end of the arm.

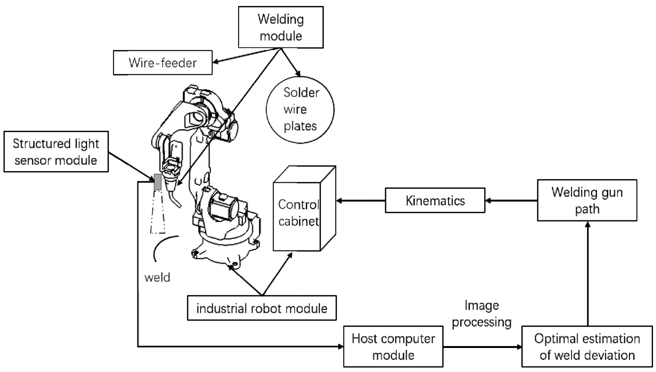

Fig. 1 Welding system composition.

B. Working Principle

The structured light stripes are projected onto the surface of the weld to form structured light stripes with weld features. Industrial cameras in structured light sensing modules collect weld image in real time through narrow-band filters. Image processing module is used to extract image coordinate information of weld feature points on structured light stripe. By determining the position coordinate of the weld center image, the self-adjustment factor fuzzy control model is used to obtain the deviation of the weld position. Through the system calibration, the distance deviation is fed back to the robot. The welding gun on the robot control arm is welded to realize the automatic tracking of the welding process. The working principle of the system is shown in Figure 2.

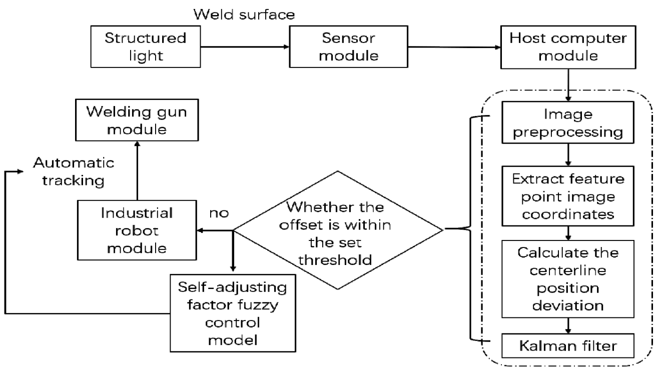

Fig. 2 System working principle.

III. Self-Adjusting Factor Fuzzy Control Model

The fuzzy control structure of this paper uses two-dimensional form that are the weld trajectory deviation and deviation change as input variables as shown in Figure 3. The effect of the scale factor K_μ in this two-dimensional fuzzy controller is similar to that of proportional control. The larger the K_μ, the faster the response of the system and the higher the adjustment accuracy. The e, ec, and u are the system error, the error rate of change, and the control output of the fuzzy controller. The E and EC are the error and error rate of the system respectively, and U is the output of the fuzzy controller. The α is a self-tuning factor. The K_e, K_{ec}, and K_u are the error factors, the quantization factor of the error rate of change and the scale factor of the control amount. Adjusting these three values can change the control of the object by the fuzzy controller.

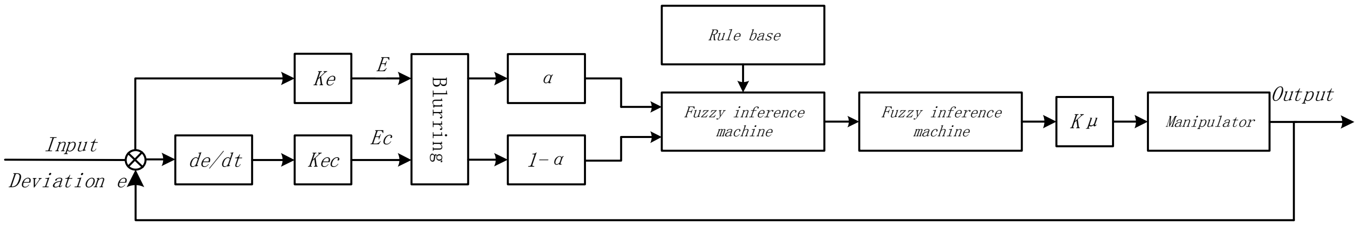

Fig. 3 Self-adjusting factor fuzzy control structure.

The image feature when defining the welding gun alignment weld is the reference feature, which is denoted as f_r. The image feature acquired in real time is the feedback feature, which is denoted as f_c and the difference between the two is the weld deviation. Then the input of the fuzzy controller is the weld deviation and the variation of the deviation, as shown in the following formula:

$$e(k) = f_r(k) - f_c(k) \tag{1}$$

$$ec(k) = e(k) - e(k-1) \tag{2}$$

The sensor detects the positional deviation $e(k)$ of the center of the weld and the exact value of the rate of change $ec(k)$, and blurs it to obtain E and EC. The domain defining E, EC, and U is {-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6}. The fuzzy sets of U and EC are {NB, NM, NS, O, PS, PM, PB}. The fuzzy set of E is {NB, NM, NS, NO, PO, PS, PM, PB}. The membership functions of E, EC, and U are trapezoidal. Then we establish a fuzzy control rule table as shown in Table 1.

TABLE I
Fuzzy control rule for output U

E \ EC	**NB**	**NM**	**NS**	**O**	***PS***	***PM***	***PB***
NB	PB	PB	PB	PB	PM	PS	O
NM	PB	PB	PB	PM	PM	O	PS
NS	PB	PM	PM	PS	O	NS	NM
NO	PB	PM	PS	PS	O	NM	NB
PO	PB	PM	PS	O	NS	NM	NB
PS	PM	PS	O	NS	NM	NM	NB
PM	PS	O	NM	NM	NB	NB	NB
PB	O	NS	NM	NM	NB	NB	NB

We use fuzzy conditional statements to describe, such as if E=NB or NM and EC=NB or NM then U=PB.

The fuzzy relation indicates that the first statement is:

$$R_1 = [(NB_E + NM_E)\times PB_U]\bullet[(NE_{EC} + NM_{EC})\times PB_U] \tag{3}$$

The total fuzzy relationship of the control rules is:

$$R = R_1 \vee R_2 \vee \cdots \vee R_m = \mathop{\vee}_{i=1}^{m} R_i \tag{4}$$

The E_I is used to represent the fuzzy subset of E. The EC_I is the fuzzy subset of EC. The U_I is the fuzzy subset of U. The output is obtained by max-min synthesis inference, as shown in the following equation.

$$u = \frac{\sum_{i=1}^{n} c_l u_i(e, ec, E, EC, U)}{\sum_{i=1}^{n} u_i(e, ec, E, EC, U)} \tag{6}$$

Where the c_l denotes the central coordinate of the first fuzzy set corresponding to the triangular membership function of the output variable. The $u_i(e, ec, E, EC, U)$ is the membership value corresponding to the i rule.

The controller changes the control rule by adjusting the correction factor, and then controls it with the optimized control rule. The performance of the fuzzy controller is fundamentally improved by adjusting the fuzzy rules.

When the error is large, the main task of the control system is to eliminate the error. At this time, the weighting of the error in the control rule should be larger. Conversely, when the error is small, the system is near steady state. The main task of the control system is to stabilize the system as soon as possible. This requires the rate of change of error to play a greater role in the control rules. These requirements are difficult to satisfy by a fixed weighting factor α. Therefore we consider online adjustment of α to achieve self-adjustment of fuzzy control rules.

The control rule resolution is:

$$U = \alpha E + (1-\alpha)E_c \qquad 0 < \alpha < 1 \tag{7}$$

When the weld deviation and deviation change rate are relatively large, the membership function is extended to both ends to improve the adjustment speed of the controller. When the weld deviation and deviation change rate are small, the membership function shrinks to the middle to improve the sensitivity of the controller.

$$c_{ei2} = \beta |e_{kT}| c_{ei}, (i = 1, 2, \cdots\cdots, 7) \tag{8}$$

$$c_{eci2} = \chi |ec_{kT}| c_{eci}, (i = 1, 2, \cdots\cdots, 7) \tag{9}$$

$$c_{ui2} = \delta |u_{kT}| c_{ui}, (i = 1, 2, \cdots\cdots, 7) \tag{10}$$

The c_{ei}, c_{eci} and c_{ui} represent the pre-adjustment membership function center. The β, γ, δ represent the adjustment coefficients, respectively. The c_{ei2}, c_{eci2}, c_{ui2} respectively represent the center of the membership function after adjustment. The e_{KT} represents the mean of the deviation. The ec_{KT} represents the mean value of the deviation change. The u_{KT} represents the output mean.

During the seam tracking process, due to the influence of environmental interference such as welding arc and splash, the weld image processing cannot guarantee that each control cycle is correct. If the control output is directly sent to the robot joint motor, it is bound to cause large fluctuations in control due to image processing errors. In order to improve the smoothness of the weld seam tracking, this paper judges and limits the output control amount as follows:

$$u_o(k)=\begin{cases} u(k), & |u(k)|<u_{t1}, \quad |\Delta u(k)|<u_{t2} \\ u(k-1)+\varepsilon\Delta u(k), & |u(k)|<u_{t1}, \quad |\Delta u(k)|>u_{t2} \\ u_{t1}, & |u(k)|>u_{t1} \end{cases} \tag{11}$$

Where $u(k)$, $u_o(k)$ are the control output before and after clipping. The u_{t1} is the limit of the single control amount. The u_{t2} is the threshold of the difference between the control quantities of the adjacent two times. $\Delta u(k)=u(k)-u(k-1)$. The ε is the clipping coefficient.

The self-tuning factor α is generated by fuzzy inference, so it is equivalent to adding a fuzzy controller for adjusting the weighting factor α based on the original basic fuzzy controller. The design is as follows: the output deviation E and the output deviation change rate EC of the original basic fuzzy controller are taken as the input of the fuzzy controller. The argument of the output α is taken as {0, 1}, and the fuzzy subset is {VS (very small), S (small), M (medium), B (large), VB (very large)}, the membership function is trapezoidal. The control rules obtained according to the design principle are shown in Table 2.

We also use fuzzy conditional statements to describe, such as if E=NB and EC=NB or NM then U_α=B.

The fuzzy control rules are completed by 7x7=49 fuzzy conditional statements.

When performing blurring, the center of gravity method can also be used as a deblurring strategy.

$$\alpha=\frac{\sum_{i=1}^{n}c_l\alpha_i(e,ec,E,EC,U_\alpha)}{\sum_{i=1}^{n}\alpha_i(e,ec,E,EC,U_\alpha)} \tag{12}$$

The c_l denotes the central coordinate of the first fuzzy set corresponding to the triangular membership function of the output variable. The $\alpha_i(e, ec, E, EC, U_\alpha)$ is the membership value corresponding to the i rule.

TABLE I
fuzzy rule of α

E \ EC	**NB**	**NM**	**NS**	**O**	***PS***	***PM***	***PB***
NB	B	B	VB	VB	VB	B	B
NM	M	B	B	B	B	B	M
NS	S	M	M	B	M	M	S
O	VS	S	M	M	M	S	VS
PS	S	M	M	B	M	M	S
PM	M	B	B	B	B	B	M
PB	B	B	VB	VB	VB	B	B

IV. EXPERIMENTAL SIMULATION AND ANALYSIS

The membership curves of E, EC, U and α obtained according to the design principles are shown in Fig 4, Fig.5 and Fig 6.

The falling half trapezoidal distribution is:

$$\mu(x)=\begin{cases} 1 & x\le a \\ \frac{b-x}{b-a} & a<x<b \\ 0 & x>b \end{cases} \tag{13}$$

The trapezoidal distribution in the middle is:

$$\mu(x)=\begin{cases} 0 & 0\le x\le a \\ \frac{x-a}{b-a} & a<x<b \\ 1 & c\ge x\ge b \\ \frac{d-x}{d-c} & c<x<d \\ 0 & x\ge d \end{cases} \tag{14}$$

The rising semi-trapezoidal distribution is:

$$\mu(x)=\begin{cases} 0 & x\le a \\ \frac{x-a}{b-a} & a<x<b \\ 1 & x\ge b \end{cases} \tag{15}$$

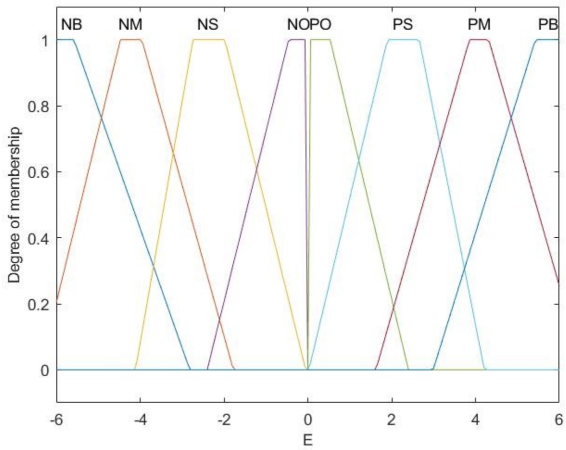

Fig. 4 Membership curve of E.

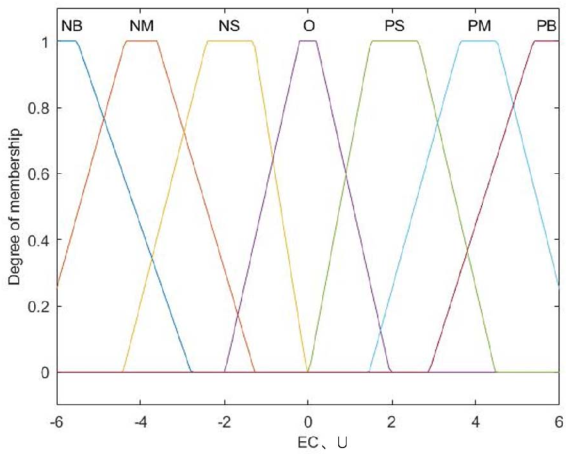

Fig. 5 Membership curve of EC、U.

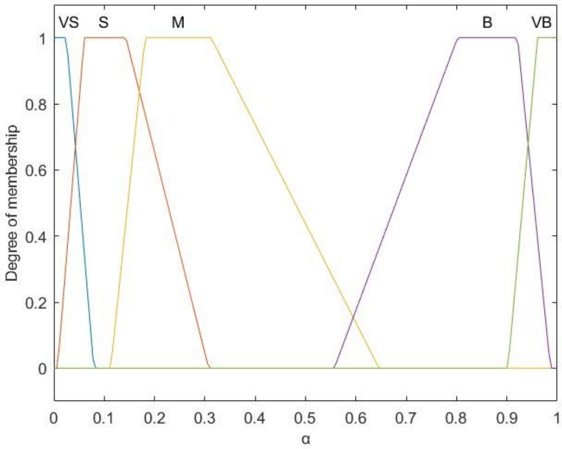

Fig. 6 Membership curve of α.

According to the transfer function model of the established tracking compensation system and the designed weld deviation compensation fuzzy controller model, the corresponding fuzzy adaptive PID adjustment control block diagram is established in simulation in the Matlab, as shown in figure 7. In order to verify the effectiveness of the proposed algorithm, the fuzzy adaptive PID control algorithm is compared with the traditional PID control algorithm. We set the sampling time t=0.01s.

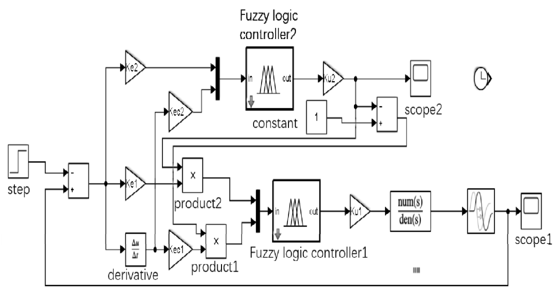

Fig. 7 System simulation block diagram in Simulink.

The K_{e1}, K_{ec1} and K_{u1} are the deviation of the basic fuzzy controller, the quantization factor of the deviation rate of change, and the scale factor of the output. We can change the control effect of this controller by adjusting these 3 parameters. The K_{e2}, K_{ec2} and K_{u2} are the deviation of the fuzzy controller of α, the quantization factor of the deviation rate of change, and the scale factor of the output.

A. Simulation of step input

The comparison of the effects of two algorithms on the step signal is shown in Figure 8. It can be seen from the adjustment of the step deviation signal that the self-tuning factor fuzzy control method has reached the stable following state earlier, and the overshoot is also small. The traditional PID control method has not reached the stable following state after 2000ms. The overshoot is large and there is a certain oscillation phenomenon. Therefore, the self-adjusting factor fuzzy control method is superior to the traditional PID control method in overshoot, rise time and settling time.

Fig. 8 The effect of two algorithms on the step signal.

B. Simulation of anti-disturbance capability

When the system returns to steady state, a 20% step signal is applied at t=1700ms for a duration of one sampling period. As shown in Fig. 9, after adding the interference signal, the fuzzy adaptive PID control method reaches the stable following state at t=3000ms. There is no oscillation after the stabilization. The traditional PID control method has not yet reached the stable following state. The response speed is slow and oscillating.

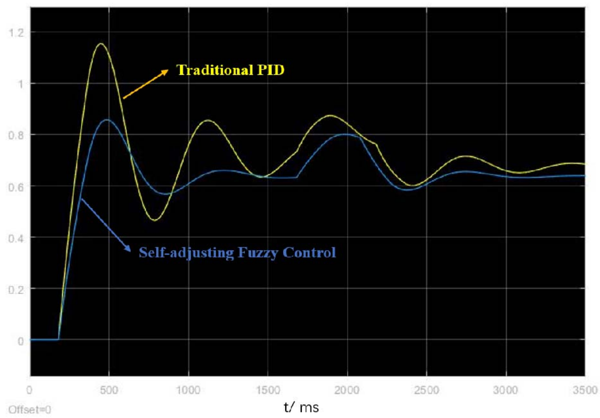

Fig. 9 The effect of two algorithms on the step signal.

V. CONCLUSION

In order to realize welding automation, flexibility and intelligence, we use the visual image processing method to extract the weld trajectory coordinates and the visual information to feedback the actual weld trajectory deviation in real time. A fuzzy control method based on self-adjusting factor is proposed to improve the accuracy of robot welding operation. Through the real-time variation of the self-adjustment factor α, the accurate tracking compensation for the deviation form with small deviation, gentle change and large deviation and sharp change is realized. The simulation results show that the proposed parameters of the self-adjusting factor fuzzy control algorithm are superior to the traditional PID control algorithm.

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