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Rules-table rotating method to tune fuzzy control rules

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Abstract: The rule-table rotating method to modify the control rules was presented. A fuzzy controller was designed always based on the experience of expert or model of plant. But the experience and the fuzzy model is rough and unsatisfying. This method could adjust the original rules by rotating the rule table. The simulation result shows that it is an effective method to tune the fuzzy rules in fuzzy control system.

Key words: control rules; Fuzzy system; rules rotating

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调整模糊控制规则的规则表旋转法

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摘要：提出了用规则表旋转法修改控制规则的方法.模糊控制器通常是基于专家经验或对象模型而设计的.无论模糊模型或是经验都是粗糙和不能令人满意的.提出的方法可以通过旋转规则表来调整原始的规则.仿真结果说明,这个方法是一种在模糊控制系统中有效调整规则的方法.

关键词：控制规则；模糊系统；规则旋转

1 Introduction

Recently, the natural control laws combined with a regular fuzzy set are suggested[1]. The parallel structure adaptive fuzzy controller was proposed by Kim[2]. Stable adaptive fuzzy control of nonlinear systems was presented[3]. A globally stable adaptive indirect controller was researched for a class of continuous-time systems[4]. On the basis of sliding control and Lyapunov function, a stable fuzzy direct adaptive control was developed[5].

In actual fact, the effective and easy methods are needed to modify the fuzzy rules in industrial control process.

In order to avoid complex mathematical computation, the engineering method to modify the fuzzy control rules is presented to optimize the fuzzy rules. The simulation result also shows that it is an effective method to modify the fuzzy rules.

2 Principle of rules modifying

Consider the fuzzy controller with error e and error change Δe as inputs and control c as output. The fuzzy partition of e, Δe and c are given as follows:

$$\Delta e = \{N,Z,P\},\ e = \{N,Z,P\},\ c = \{N,Z,P\},$$

where N is negative linguistic value, Z is zero linguistic value, and P is positive linguistic value.

The left of Fig. 1 shows the fuzzy rules base which embodies 9 rules.

When we rotate the term one cell widdershins, we will get the same control rules as the right of Fig. 1. Likewise rotate one cell deasil, and we will get the right of Fig. 2.

The consequent terms N, Z, P have been arrayed into three columns in Fig. 1, and into three lines in Fig. 2. It shows that the table rotation is a powerful method to adjust the rules.

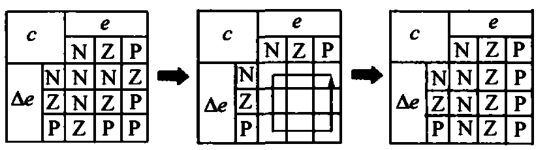

Fig. 1 Rotate one cell widdershins

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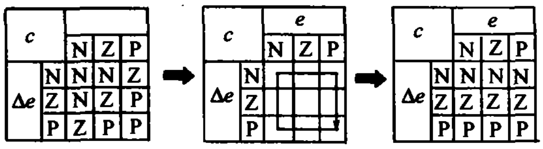

Fig. 2 Rotate one cell deasil

Consider the fuzzy control rules base which is expressed by IF-THEN sentence

$L_{i,j}$: IF $x = X_i$ and $y = Y_j$ THEN $z = U_{i,j}$.

And the membership functions of the consequent term are shown in Fig.3.

From Mandani inference, we obtain the control z when x_0, y_0 is input.

$$Z_{i,j} = X_i(x_0) \wedge Y_j(y_0) \wedge U_{i,j} \tag{1}$$

We define W as follows:

$$W_{i,j} = X_i(x_0) \wedge Y_j(y_0). \tag{2}$$

Then from neighbor rules we can get

$$Z_{i,j} = W_{i,j} \wedge U_{i,j}, \tag{3}$$

$$Z_{i,j+1} = W_{i,j+1} \wedge U_{i,j+1}, \tag{4}$$

$$Z_{i+1,j} = W_{i+1,j} \wedge U_{i+1,j}, \tag{5}$$

$$Z_{i+1,j+1} = W_{i+1,j+1} \wedge U_{i+1,j+1} \tag{6}$$

The actual output of the fuzzy controller is Z:

$$Z = Z_{i,j} \vee Z_{i,j+1} \vee Z_{i+1,j} \vee Z_{i+1,j+1} = (W_{i,j} \wedge U_{i,j}) \vee (W_{i,j+1} \wedge U_{i,j+1}) \vee (W_{i+1,j} \wedge U_{i+1,j}) \vee (W_{i+1,j+1} \wedge U_{i+1,j+1}). \tag{7}$$

Table rotation is a method which shift the consequent term to the neighbour rule in the right or left direction.

There exist a set of rules:

IF $x = X_i$ and $y = Y_{j-1}$ THEN $z = U_{i,j-1}$,

IF $x = X_i$ and $y = Y_j$ THEN $z = U_{i,j}$,

IF $x = X_i$ and $y = Y_{j+1}$ THEN $z = U_{i,j+1}$.

After rotating, there are

IF $x = X_i$ and $y = Y_{j-1}$ THEN $z = U_{i,j-2}$,

IF $x = X_i$ and $y = Y_j$ THEN $z = U_{i,j-1}$,

IF $x = X_i$ and $y = Y_{j+1}$ THEN $z = U_{i,j}$,

or

IF $x = X_i$ and $y = Y_{j-1}$ THEN $z = U_{i,j}$,

IF $x = X_i$ and $y = Y_j$ THEN $z = U_{i,j+1}$,

IF $x = X_i$ and $y = Y_{j+1}$ THEN $z = U_{i,j+2}$.

Definition 1 After fuzzy set $A1, A2$ are defuzzied, there are $D(A1) = a1, D(A2) = a2$.

If $a1 < a2$ such that fuzzy set $A1$ is less than $A2$, we write

$$A1 < A2.$$

Theorem 1 There exists a fuzzy rule table which is similar to the left of Fig.1. If the consequent term is rotated, then the output action of fuzzy controller will change to increase or decrease, in rotating direction.

Proof when x_0, y_0 is the input signal, if using the original rule table, we have the output result

$$Z = (W_{i,j} \wedge U_{i,j}) \vee (W_{i,j+1} \wedge U_{i,j+1}) \vee (W_{i+1,j} \wedge U_{i+1,j}) \vee (W_{i+1,j+1} \wedge U_{i+1,j+1}). \tag{8}$$

After rotating one step, we have the new output signal

$$Z' = (W_{i,j} \wedge U_{i,j-1}) \vee (W_{i,j+1} \wedge U_{i,j}) \vee (W_{i+1,j} \wedge U_{i+1,j-1}) \vee (W_{i+1,j+1} \wedge U_{i+1,j}). \tag{9}$$

or

$$Z^* = (W_{i,j} \wedge U_{i,j+1}) \vee (W_{i,j+1} \wedge U_{i,j+2}) \vee (W_{i+1,j} \wedge U_{i+1,j+1}) \vee (W_{i+1,j+1} \wedge U_{i+1,j+2}). \tag{10}$$

From Fig.3 and Definition 1, there are

$$U_{i,j-1} < U_{i,j} < U_{i,j+1} < U_{i,j+2}, \tag{11}$$

$$U_{i+1,j-1} < U_{i+1,j} < U_{i+1,j+1} < U_{i+1,j+2}. \tag{12}$$

Compare(8) with (9), (10), we obtain

$$Z' < Z < Z^*.$$

Thus the proof is completed.

Distinctly, rotating the rule table can adjust the size of control signal. If the correct direction and the times of rotation are properly decided, it will quickly reach the optimum situation.

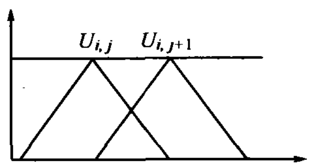

Fig. 3 Membership function of consequent

3 Rotation algorithm

Rule-table rotating method is a parallel one whose consequent part fuzzy control values are changed at the same time. The consequent parts in the rule-table move counterclockwise or clockwise according to the output error of system.

In order to detect the level of the system errors, the objective function $J(e)$ is provided.

$$J(e) = \frac{1}{2}\sum_{i=1}^{n}(S - S_i)^2. \tag{13}$$

Where S_i is the actual output of system, S is the expected output of system, n is the sample number.

The steps of the rotation algorithm are offered as follows:

Step 1 The system works using the original rules and the value J_0 of the object function $J(e)$ is obtained.

Step 2 The rule-table is rotated at one position clockwise and the new rules are got, the system is controlled under the new rules and the value J_1 of the objective function is reaped.

Step 3 If $J_1 < J_0$, the rule-table is rotated at one position clockwise again; and the system works and productes J_2. If $J_2 < J_1$, the procedure of rotating clockwise has to go on $\cdots$. It must stop when $J_{i+1} \geqslant J_i$ and turn to Step 5.

Step 4 If $J_1 > J_0$, the rule-table must be rotated at two positions widdershins; the system runs using the updated rules and gets J_2. If $J_2 < J_1$, the rotating procedure has to go on $\cdots$. It should stop when $J_{i+1} \geqslant J_i$ and turn to Step 5.

Step 5 If $J_{i+1} > J_i$, the rule-table related to J_i is the optimal result, If $J_{i+1} = J_i$, the rule-table corresponded to J_{i+1} is the optimal one.

4 Simulation results

A) Result of first order system.

We consider the transfer function of plant as follows:

$$G(s) = e^{-10s}/(90s + 1). \tag{14}$$

The values of $e, \Delta e$ all are parting into five fuzzy sets. The original rule-table is shown in Fig.4.

U		Δe				
		NB	NS	O	PS	PB
	NB	NB	NB	NS	NS	O
	NS	NB	NB	NS	O	PS
e	O	NS	NS	O	PS	PS
	PS	NS	O	PS	PB	PB
	PB	O	PS	PB	PB	PB

Fig. 4 Original rule-table

After the quantization, we have a control table, and the control table can be expressed by the formula as follows:

$$u = \langle \alpha e + (1 - \alpha) c \rangle$$

where e is the error, c is the change of error, u is the control. $\langle \cdot \rangle$ is the operating of integer algorithm, α is called the control factor, $\alpha \in [0,1]$.

We optimize the rules using two methods — tuning control factor and rule-table rotating. The optimal rule-table is shown in Fig.5 using rule-table rotating method and the relative control surface is illustrated in Fig.6

U		Δe				
		NB	NS	O	PS	PB
	NB	NB	NB	NB	NS	NS
	NS	NS	NS	NB	NS	O
e	O	NS	O	O	O	PS
	PS	O	PS	PB	PS	PS
	PB	PS	PS	PB	PB	PB

Fig. 5 Rule table after rotating

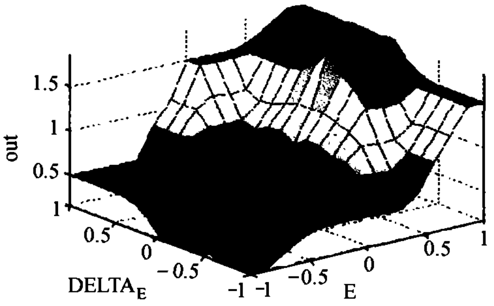

Fig. 6 Related control surface for rule-table rotating

The output responsive curves are given in Fig.7 respectively. It shows that the rule-table rotating is a better method than the tuning control factor to optimize the rules.

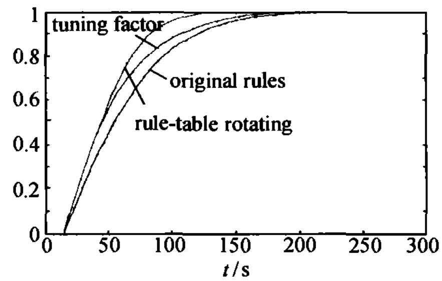

Fig. 7 Output responsive curves

B) Result of second order system.

The transfer function of second order system is

$$G(s) = e^{-s}/[(0.2s + 1)(s + 1.48)]. \tag{15}$$

The original rule-table of fuzzy system is shown in Fig.8. The control surface is shown is Fig.9.

U		Δe				
		NB	NS	O	PS	PB
	NB	NS	NS	NB	NB	NB
	NS	O	NS	NS	O	NB
e	O	PS	NS	O	PS	NS
	PS	PB	O	PS	PS	O
	PB	PB	PB	PB	PB	PS

Fig. 8 Original rules of second order system

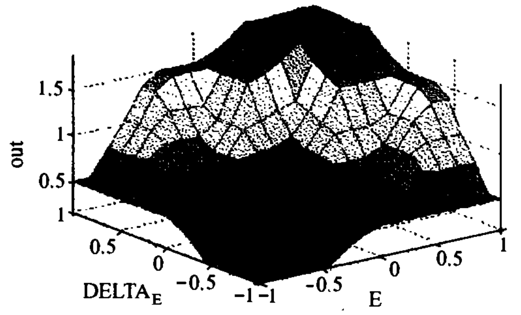

Fig. 9 Related control surface for second order system

After using the rule-table rotating method to optimize the rules, we have the optimal rule table and control surface shown in Figs. 10, 11, respectively. The results of output responsive curves are plotted in Fig. 12. It is obvious that the rule-table rotating method is capable of optimizing the performance of second order system.

U		Δe				
		NB	NS	O	PS	PB
e	NB	O	NS	NS	NB	NB
	NS	PS	PS	O	NS	NB
	O	PS	PS	O	NB	NS
	PS	PB	PS	O	NS	NS
	PB	PB	PB	PS	PS	O

Fig. 10 Optimal rule table

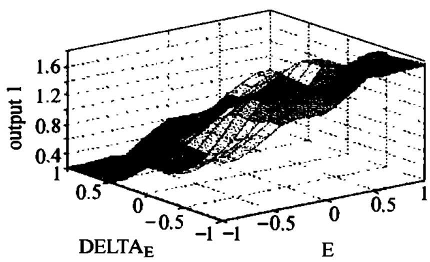

Fig. 11 Related control surface

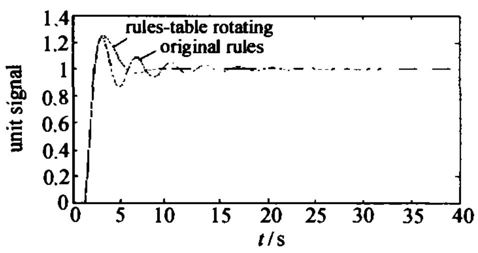

Fig. 12 Output responsive curves

5 Conclusions

In this paper, we present the new method to modify the rules of the fuzzy control system. The algorithm of optimization is also given. The simulation results of two systems, first order and second order system, are obtained through the rule-table rotating method. It proves that it is a highly effective method to tune the fuzzy controller.

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