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Design of Fuzzy PD+I Controller Based on PID Controller

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Abstract : *Since fuzzy controllers are nonlinear, it is more difficult to set the controller gains and to analyse the stability compared to conventional PID controllers. This paper proposes a fuzzy PD+I controller for tracking control which uses a linear fuzzy inference(product-sum-gravity) method based on a conventional linear PID controller. In this scheme the fuzzy PD+I controller works similar to the control performance as the linear PD plus I(PD+I) controller. Thus it is possible to analyse and design an fuzzy PD+I controller for given systems based on a linear fuzzy PD controller. The scaling factors tuning scheme, another topic of fuzzy controller design procedure, is also introduced in order to fine performance of the fuzzy PD+I controller. The scaling factors are adjusted by a real-coded genetic algorithm(RCGA) in off-line. The simulation results show the effectiveness of the proposed fuzzy PD+I controller for tracking control problems by comparing with the conventional PID controllers.*

Key words : *fuzzy PD+I controller, scaling factors, tracking control, product-sum-gravity method, RCGA*

1. Introduction

For tracking control problems one generally considers the error, the derivative and integral of the error to solve the problems. Namely, the PID control schemes are still used in industrial machinery mostly. Because firstly there are not so many parameters to tune comparing to other methods and the Ziegler-Nichols tuning method(Ziegler, 1942; Cohen and Coon, 1953) works reasonably well. Secondly the PID controller is familiar to field engineers who can easily manage the overshoot, rising time and settling time etc.

One of the intelligent control schemes, the fuzzy inference engine is widely used for control by using the Mamdani type (Mamdani, 1974). The fuzzy controllers which use fuzzy inference can be mostly diverted to the nonlinear and difficulty control problems which are complicated to get mathematical model.

During the past years, many scholars have been studying various types of fuzzy controllers and systematic design methods.

Malki et al.(1994) have studied bounded-input bounded-output (BIBO) stability issue of the nonlinear fuzzy PD control systems. Shao et al.(1999) presented fuzzy PD controllers with a one-to-two mapping inference structure. The presented controllers are supposed to keep the most preferred features with the conventional PID controllers, such as the individual control action calculation, reasoning inference without an input coupling effect. Morales-Mata and Tang(2006) addressed the design of a fuzzy PD control in the presence of hard nonlinearities for high precision servo mechanisms. This controller consists of a conventional fuzzy PD and a robust compensation component. Xu et al.(2006) presented a optimal fuzzy PID controller by utilizing the SQP nonlinear programming optimization algorithm to control the induction motor. Threesinghawong et al.(2008) proposed fuzzy PD control technique in order to achieve automatic control for a packed-bed reactor in the solid-state fermentation. Qingchun and Deyao(2009) proposed an incremental fuzzy PD+fuzzy ID controller which input variables are error, change of error and rate of change of error, analyzed its structure, and obtain its formulas in all regions.

In spite of these useful and effectiveness, the fuzzy controller has also a drawback such as difficulty of stability analysis due to the nonlinearities and complex parameters.

In this paper, therefore, an linear fuzzy inference scheme is used to eliminate an unnecessary nonlinearity. In this case the fuzzy PD controller is obtained firstly using the conventional PD control scheme and secondly improved the control performance by adding nonlinearities on purpose

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through adjusting membership functions. And lastly, to remove the stead-state error, the linear I controller is combined with fuzzy PD controller. Then this fuzzy PD+I controller is able to have the properties of the linearities and nonlinearities as occasion demands.

The scaling factor tuning scheme, another topic of fuzzy controller design procedure, is also introduced in order to fine performance of the fuzzy controller. In this paper, the authors present the scaling factor tuning method using the real-coded genetic algorithm(RCGA) in off-line.

The simulation results show the effectiveness of the proposed fuzzy controller for tracking control problems by comparing with the results of the conventional PI/PID controllers.

2. PID controller and fuzzy controller

2.1 PID controller

Typical PID controller uses the error, the derivative and integral of the error.

The transfer function of the PID controller is

$$u = K_p\left(e + \frac{1}{T_i}\int_0^t e\,d\tau + T_d\frac{de}{dt}\right) \tag{1}$$

where u, K_p, T_i and T_d represent control input, proportional gain, integral and derivative time respectively, and e describes the error between reference and plant output.

By using backward difference and trapezoidal integral with sampling time T_s, the discrete expression of Eq. (1) can be described as follows

$$u_n = K_p\left(e_n + \sum_{j=1}^{n}\frac{T_s(e_j + e_{j-1})}{2} + T_d\frac{e_n - e_{n-1}}{T_s}\right) \tag{2}$$

where n denotes the time instance.

2.2 Fuzzy controller

The general fuzzy controller consists of two dimensional control structure by taking error and derivative of it as an input as shown in Fig. 1.

The control scheme of the fuzzy controller can be categorized such as fuzzy PD(F-PD), fuzzy PI(F-PI), fuzzy PID(F-PID) controller(Abdelnour et al., 1991). In F-PD scheme, it is hard to remove steady state error comparatively, F-PI scheme could give a poor transient response for higher order system due to the self integral operation and the F-PID scheme is complicated to construct a fuzzy inference.

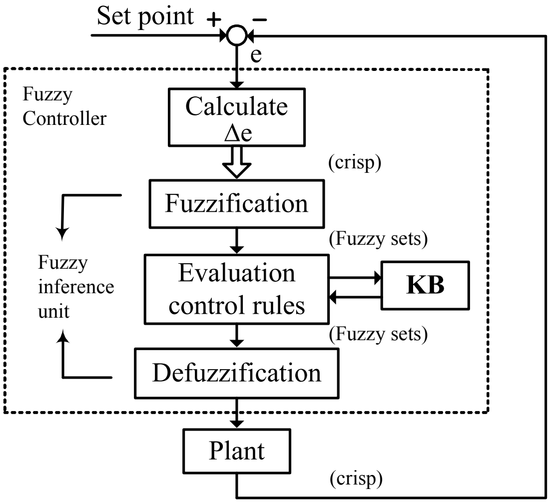

Fig. 1 Fuzzy control system architecture.

To avoid the problems above mentioned, the authors adopt the fuzzy PD+I controller which is composed of the F-PD controller and the linear I controller as shown in Fig. 2.

In this scheme fuzzy inference and the integration of the error are in parallel, the control input is summation of the output of fuzzy inference and the integration of the error.

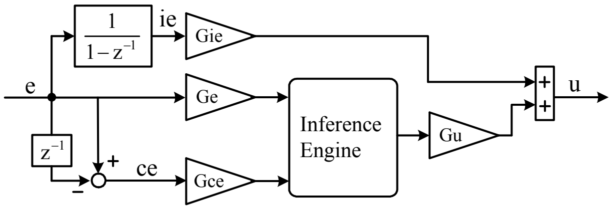

Fig. 2 Structure of fuzzy PD+I controller

3. Design of fuzzy PD+I controller

In fuzzy controller there exists nonlinearity due to the membership function of rule base, Min-Max operations of inference engine and defuzzification.

However it is possible to remove nonlinearity by mapping between input and output in rule base(Mizumoto, 1995; Qiao and Mizumoto, 1996). In this paper, an linear fuzzy PD controller is derived using the mapping method. Then we are able to handle the F-PD controller in Fig. 2 just like an linear PD controller and adjust nonlinear properties whenever necessary.

3.1 Selection of membership function

The membership function for the input linguistic variables are shown in Fig. 3. Two trapezoidal and one triangle membership functions are used for the error signal. Two trapezoidal membership functions are also used for the derivative of error signal. The overlap of the membership function is selected at 0.5 to avoid an uncertain nonlinearity.

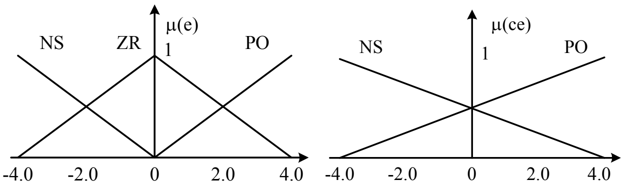

Fig. 3 Membership function for input variables

The membership functions for the output linguistic variables use six fuzzy singletons as shown in Fig. 4, where c_1 and c_2 are both set to 0.

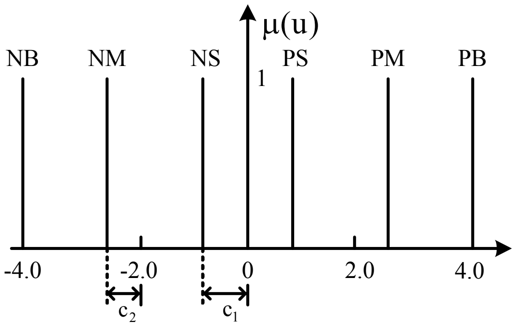

Fig. 4 Membership function for output variable

3.2 Selection of fuzzy rule bases

From the knowledge and experience, the six rules are selected as follows

(1) If (e is NE) and (Δe is NE) then (u is NB)
(2) If (e is NE) and (Δe is PO) then (u is NS)
(3) If (e is ZE) and (Δe is NE) then (u is NM)
(4) If (e is ZE) and (Δe is PO) then (u is PM)
(5) If (e is PO) and (Δe is NE) then (u is PS)
(6) If (e is PO) and (Δe is PO) then (u is PB)

where rules (2) and (5) relate to rising time, (3) and (4) to damping ratio which are engaged in c_1 and c_2.

3.3 Fuzzy inference and defuzzification

The simplified product-sum-gravity for fuzzy inference can be adopted to improve operation time and remove the nonlinearity during fuzzy inference(Mizumoto, 1995; Qiao and Mizumoto, 1996). Fig. 5 shows the schematic diagram of the simplified fuzzy reasoning.

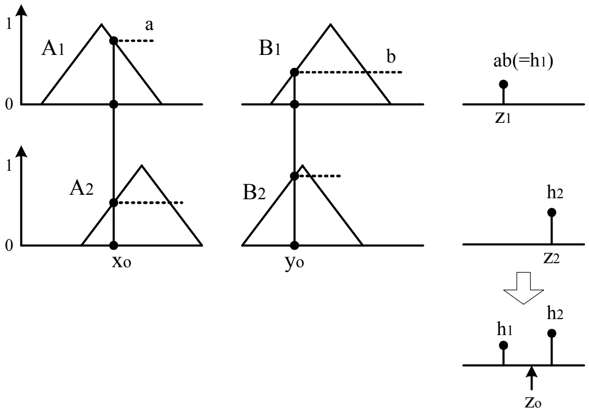

Fig. 5 Simplified fuzzy reasoning method

The i-th fitness becomes as follows

$$h_i = \mu_{A\,i}(x_o) \cdot \mu_{B\,i}(y_o) \tag{3}$$

From Eq. (3) the control input can be obtained

$$z_o = \frac{\sum_{j=1}^{n} \mu(h_i) \cdot z_i}{\sum_{j=1}^{n} \mu(h_i)} \tag{4}$$

where n denotes the number of the quantum level.

Fig. 6 shows the inference results of Min-Max gravity method and simplified reasoning method with the same membership functions shown in Fig. 3 and 4. It can be observed that the simplified reasoning method shows almost linear characteristic but not the Min-Max gravity method.

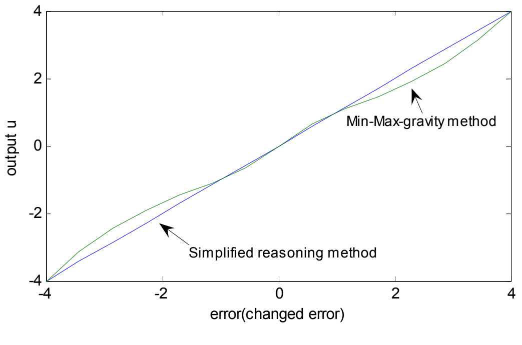

Fig. 6 "error versus u" plots of Min-Max-gravity and Simplified reasoning method

This means that firstly the numerical result of the simplified reasoning method could directly be compared with that of the linear PD controller. Secondly, the nonlinearity could be improved by performing the controller output saturation through the membership function saturation shown in Fig. 3, or by adjusting the distance between c_1 and c_2

shown in Fig. 4. Thirdly, the linear PD controller could be a kind of the F-PD controller. Fig. 9 shows the control surface of the F-PD controller. By comparing this result with that of Fig. 8, it can be observed that the two control surface seems nearly same except that the controller output of the PD controller becomes double of the F-PD controller. This is due to the output of the PD controller is derived from the sum of the e_n and Δe_n.

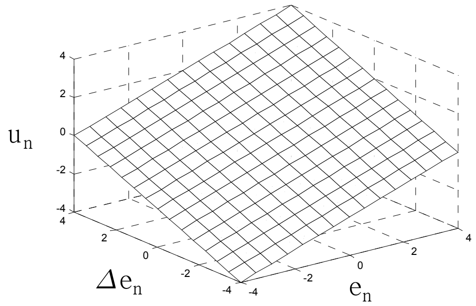

Fig. 7 Control surface of the linear fuzzy PD controller

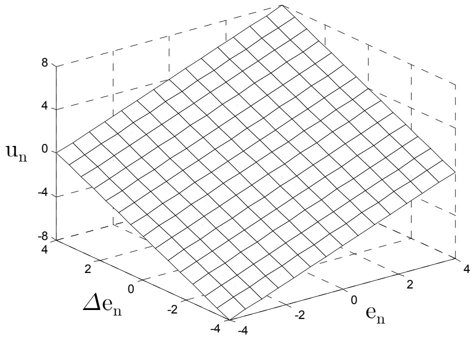

Fig. 8 Control surface of the linear PD controller

3.4 Scaling factor tuning

The role of the scaling factors in the fuzzy controller is very similar to that of the conventional PID parameters (Filev and Yager, 1994). The objective of the proposed algorithm is to select the scaling factors according to given systems in order to fine tune the fuzzy controller. Fig. 9 shows the scheme of scaling factor tuning using the RCGA.

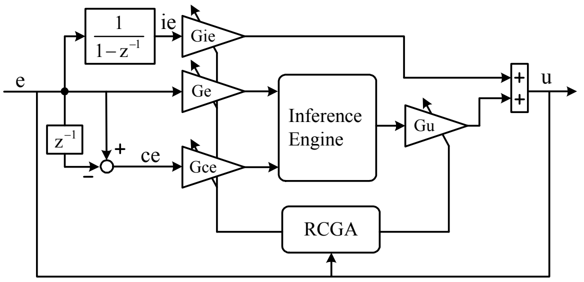

Fig. 9 The scaling factors tuning using the RCGA

For the scaling factor tuning, the RCGA is used to optimize the performance index in this paper as follows

$$J(\phi) = \int_0^{t_f} (te^2 + ru^2)dt \tag{5}$$

where t_f describes the final integral time and r is the weighting factor.

Then the RCGA(Jin, 2002) deals with the parameter optimization problem as

$$\phi = [Ge, Gce, Gu, Gie]^T \in R^4 \tag{6}$$

where Ge, Gce, Gu and Gie denote the scaling factor of the error, the change of error, the control input and the summation of error respectively.

The genetic operators used in this paper are gradient-like reproduction, modified simple crossover, dynamic mutation and the scale window Ws=1, elitism strategy are used(Jin, 2002).

4. Simulation results

For simulation we consider the second order plus time delay system G_1 and the third order plus large time delay system G_2.

$$G_1(s) = \frac{\exp(-2s)}{(10s+1)(s+1)} \tag{7}$$

$$G_2(s) = \frac{\exp(-5s)}{(s+1)^2(2s+1)} \tag{8}$$

The selected membership function is given in Fig. 10, and c_1=0.5, c_2=0.5 are used.

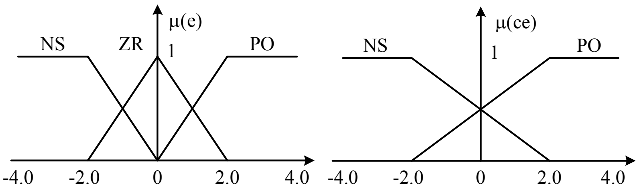

Fig. 10 Input membership functions for simulation

Fig. 11 shows the control surface of the fuzzy PD controller designed. It is observed that the characteristics of the designed PD controller is nearly similar to that of the linear PD controller shown in Fig. 8 except that the edge surface which represents the saturation area of the controller output.

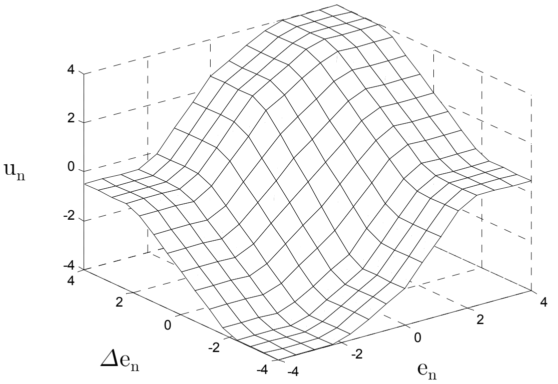

Fig. 11 Control surface of fuzzy PD controller

The scaling factors of the fuzzy PD+I controller obtained by RCGA are shown in Table 2. The RCGA parameters were used in our simulation as follows.

(1) Population size: N= 20
(2) Reproduction coefficient: h= 1.8
(3) Crossover rate: Pc=0.9
(4) Mutation rate and parameter : Pm=0.2
(5) Scaling window size: Ws=1
(6) Search ranges : $0 \le \Phi \le 5$

Table 2 Scaling factors for fuzzy PD+I controller

	Ge	Gce	Gu	Gie
system1	1.9353	3.0201	1.7337	0.2283
system2	0.7356	1.4179	0.8510	0.1074

Fig. 12 and 13 show the control results for the system of Eq. (7) and Eq. (8) with Ziegler-Nichols tuned PID controller, Cohen-Coon tuned PID controller, and proposed fuzzy PD+I controller respectively.

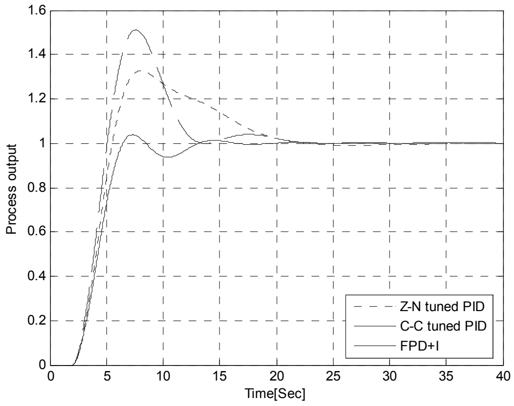

Fig. 12 Step responses of Z-N/C-C tuned PID, and fuzzy PD+I controller for system 1.

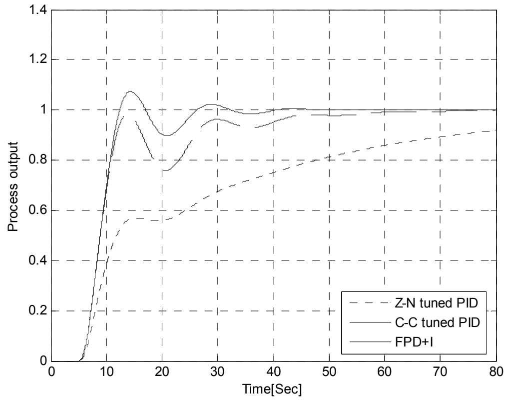

Fig. 13 Step responses of Z-N/C-C tuned PID, and fuzzy PD+I controller for system 2.

The control performance indexes are given in Table 3. From the simulation results, it is observed that the control result of the proposed fuzzy PD+I controller is better than the conventional PID controllers.

Table 3 performance index for the systems

controllers systems		PID		Fuzzy PD+I
		Z-N	C-C	
system1	IAE	6.71	6.24	4.59
	ITAE	39.58	29.53	13.58
system2	IAE	26.60	12.35	9.98
	ITAE	644.7	137.8	64.58

5. Conclusion

In this paper, the fuzzy PD+I controller which uses the linear fuzzy inference method(product-sum-gravity) was proposed based on a conventional linear PID controller. In this scheme the fuzzy PD+I controller works similar to the control performance as the linear PD plus I(PD+I) controller.

The scaling factors tuning method was also introduced in order to good performance of fuzzy PD+I controller. The RCGA is used to optimize the scaling factors in terms of minimizing the performance index. The simulation results show the effectiveness of the proposed fuzzy PD+I controller for tracking control problems by comparing with the conventional PID controllers.

References

[1] Abdelnour, G. M., Chang, C. H., Huang, F. H., and Cheung, J. Y.(1991), "Design of a Fuzzy Controller Using Input and Output Mapping Factors", IEEE Trans.

Systems, Man. and Cybernetics, Vol. 21, Issue 5, pp. 952-960.

[2] Cohen, G. H. and Coon, G. A.(1953), "Theoretical considerations of retarded control", Trans. ASME, Vol. 75, pp. 827-834.

[3] Filev, D. and Yager, R.(1994), "On the Analysis of Fuvy Logic Controllers", Fuzzy Sets and Systems, Vol. 68, pp. 39-66.

[4] Jin, G.(2002), Genetic Algorithms and It's Application, KyoWooSa.

[5] Malki, H. A., Li, H., and Chen, G., "New design and stability analysis of fuzzy proportional-derivative control systems", IEEE Trans. Fuzzy Syst., vol. 2, pp. 245-254, 1994.

[6] Mamdani, E. H.(1974), "Applications of fuzzy algorithms for simple dynamic plant", Proc. IEE, vol. 121, no. 12, pp. 1585-1588.

[7] Mizumoto, M.(1995), "Realization of PID controls by fuzzy control methods", Fuzzy Sets and Systems, Vol.70, pp. 171-182.

[8] Morales-Mata, I. and Yu, T.(2006), "An Effective Fuzzy PD Control for High Precision Servo Mechanisms", WCICA 2006., Volume 1, pp. 134-138.

[9] Qiao, W. Z. and Mizumoto, M.(1996), "PID type fuzzy controller and parameters adaptive method", Fuzzy Sets and Systems, Vol. 78, pp. 23-35.

[10] Qingchun, L. and Deyao, S.(2009), "A New Incremental Fuzzy PD+Fuzzy ID Fuzzy Controller", 2009 WASE International Conference, Volume 1, pp. 615-619.

[11] Shao, H. F., Hu, B. G., and Zhu, Z. L.(1999), "A case study of one-to-two mapping fuzzy PD controllers on inverted pendulum", Fuzzy Systems Conference Proceedings, Volume 1, pp. 424-429.

[12] Threesinghawong, N., Sanposh, P., Chinthaned, N., and Srinophakun, P.(2008), "Temperature control of Koji process by using fuzzy PD controller", Proceedings of ECTI-CON 2008, Volume 2, pp. 669-672.

[13] Xu, J., Xin, F., and Mirafzal, B.(2006), "Application of Optimal Fuzzy PID Controller Design: PI Control for Nonlinear Induction Motor", WCICA 2006, Volume 1, pp. 3953-3957.

[14] Ziegler, J. G. and Nichols, N. B.(1942), "Optimum setting for PID controllers", Trans. ASME, Vol. 64, pp. 759-768.

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