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Two Supplementary Methods for PI-Type Fuzzy Logic Controllers

Jihong Lee and Seog Chae

Dept. of Control Engineering, Kum-oh National Institute of Technology
188 Shinpyoung-dong, Kumi, Kyoungbuk 730-701, Korea

ABSTRACT

To improve limitations of fuzzy PI controller especially when applied to high order systems, we propose two types of fuzzy logic controllers that take out appropriate amounts of accumulated control input according to fuzzily described situations in addition to the incremental control input calculated by conventional fuzzy PI controllers. The structures of the proposed controller were motivated by the problems of fuzzy PI controllers that they generally give inevitable overshoot when one tries to reduce rise time of response especially when a system of order higher than one is under consideration. Since the undesirable characteristics of the fuzzy PI controller are caused by integrating operation of the controller, even though the integrator itself is introduced to overcome steady state error in response, we propose two fuzzy controllers that fuzzily clear out integrated quantities according to situation. The first controller determines the fuzzy resetting rate by situations described fuzzily by error and error rate, and the second one by error and control input. The two structures both give reduced rise time as well as small overshoot. To show the usefulness of the proposed controller, thet are applied to systems that are difficult to get satisfactory response by conventional fuzzy PI controllers.

1. Introduction

Recently, fuzzy logic control(FLC) has emerged as one of the most fruitful research areas in fuzzy set theory, and many practical applications to industrial process, as well as studies on the theory itself, have been reported in many works[1]. Surveying the areas of the applications of the fuzzy logic controllers, we may classify the areas into two groups: one is the case where controlled process has so many variables that conventional control methods are difficult to be applied[2], and the other one is the case where, even if the controlled system is simple, conventional linear control algorithms show limitations in the performances[3, 4, 5, 6, 7].

Irrelevalent to the application ares, mainly two types of structure of fuzzy logic controller have been studied so far: one is position-type fuzzy controller which generates control input(u) from error(e) and error rate($\dot{e}$), and the other is velocity-type fuzzy logic controller which generates incremental control input(Δu) from error and error rate(or rate of error rate $\ddot{e}$ may be included). The former is called PD FLC and the latter is called PI FLC according to the characteristics of information that they process. In the view point that the FLC is based on the knowledge of human experts, and generally FLC is applied to unknown or partially known systems, PI FLC is known to be more practical than PD FLC. Other comparisons also can be seen in the facts that human, generally, are not so sensitive to absolute values of data in their sensing and actuation, and besides sometimes it is not possible to remove out steady state error with PD type controllers for large class of systems. The PI controller(also PI FLC) is, however, known to give poor performance in transient response due to the internal integrating operation. To improve the transient response of PI FLC is not easy especially for a system of order more than one as in the case of crisp PI controllers[8]. This may be one of main reason why such many works handling PI FLC have adopted first order system for their simulations.

Actually, the rules of fuzzy logic controllers are designed with a phase plane in mind, in which the fuzzy controllers drive a system into the so called sliding mode[9]. The tracking boundaries in the phase plane are, however, are related not with the incremental control input but with control input itself which is accumulated by the following equation.

$$u(k+1) = u(k) + \Delta u(k) \qquad (1)$$

So, to select the maximum variation of the incremental control input(Δu) giving satisfactory rise time and maximum overshoot in step response is not so easy as in the case where the control input itself is to be determined.

One natural approach to overcome such difficult situation is to adopt rate of error rate($\ddot{e}$). If the quantity is adopted, the fuzzy controller may be called as PID FLC. It is not easy, however, to measure the instantaneous value of the quantity, and it is hardly believed that an expert senses acceleration terms of the error at every instance in his control action. Even in the method of approximating $\ddot{e}$ by $\dot{e}(k)$ and $\dot{e}(k-1)$, we can point out a problem that some information of previous sampling time should be memorized continuously. Moreover, direct use of the quantity results in a controller with large number of rules.

Noting that the difficulties in designing fuzzy PI controllers reside in the selection of the maximum absolute value of incremental control input(To make the response move faster a large one is necessary, but to make the system behave well damped a smaller one is better), we propose two methods fuzzily resetting the control input accumulated by the integrating operation according to situations. The basic operation is described by the following equation.

$$u(k+1) = (1 - (r(k))^p)u(k) + \Delta u(k) \qquad (2)$$

where k denotes sampling instance. Even though the details will be described in the following sections, note that if $r(k)$ is one there are no integrating actions in (2), and if $r(k)$ is zero it becomes identical with the conventional fuzzy PI controllers. Determining the resetting rate r by fuzzy methods has several advantages: i) Since the value of r is in the interval between zero and one, possible jerks occurring when the accumulated control input for a system with load is reset at once, and ii) the rules for determining the value of r is easily constructed by intuition or experience.

In this paper two methods for determining the resetting rate will be presented. In the first method the reset rate r is determined from a rule defined on $(e, \dot{e})$ space, and in the second one from a rule defined on (e, u) space, where e is error between reference command and output, $\dot{e}$ is time derivative of e, and u is control input.

The structures and application examples of two controllers will be shown in the Section 2 and 3, respectively. In the Section 4, a brief concluding remarks will be offered.

2. Fuzzy PI Controller with Resetting Capability based on error and error rate

In this section, we describe a fuzzy PI controller which fuzzily resets the control input accumulated by integrating action according to situations described fuzzily by error and rate of error.

A. The model

The basic structure of the controller proposed here is identical to conventional fuzzy PI controller except the resetting operation, which is shown in Fig. 1.

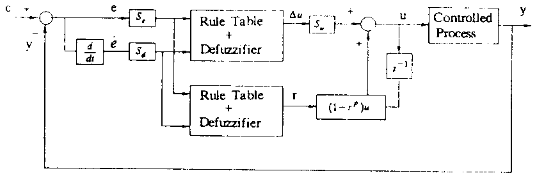

Fig. 1. Structure of fuzzy logic controller of Section 2.

The basic principle of the operation of the controller is described as follows:

1) Normal Δu is calculated by the following rules and equations.

$$R_i : \textit{if } e \textit{ is } A_i \textit{ and } \dot{e} \textit{ is } B_i, \textit{ then } \Delta u \textit{ is } C_i. \tag{3}$$

$$\alpha_i = \mu_{A_i}(e) \wedge \mu_{B_i}(\dot{e}) \tag{4}$$

$$\mu_{C_i'} = \alpha_i \wedge \mu_{C_i} \tag{5}$$

$$\Delta u_i = cog(C_i') \tag{6}$$

$$\Delta u = \frac{\sum_{i=1}^{N} \alpha_i \Delta u_i}{\sum_{i=1}^{N} \alpha_i} \tag{7}$$

2) The resetting rate r is calculated by the principles which is described linguistically as

If the response approaches set value with abnormal rate then reset the accumulated control input in fuzzy manner according to the measured error and error rate.

(8)

The rules for calculating the resetting rate are described as

$$R_j : \textit{If } e \textit{ is } A_j \textit{ and } \dot{e} \textit{ is } B_j, \textit{ then } r \textit{ is } R_j. \tag{9}$$

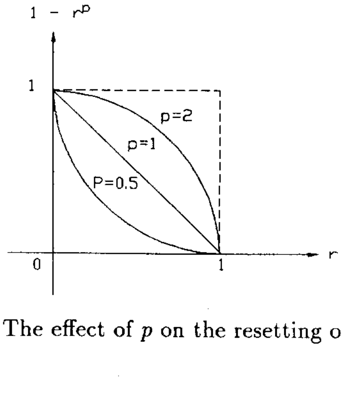

Fig. 2. The effect of p on the resetting operation.

and for inference and defuzzification the same methods with the ones for Δu (4)-(7) are adopted.

3) Finally the control input for the kth control instance is calculated by the following equation.

$$u(k+1) = (1 - (r(k))^p)u(k) + \Delta u(k) \tag{10}$$

The constant p determines the nonlinearity of the effect of r in resetting operation, which is depicted in the Fig. 2.

B. Illustrative Example

At first we apply conventional fuzzy PI controller to the following plant with the rules for calculating incremental control input of Fig. 3.

$$G_1(s) = \frac{1}{s(s+1)} \tag{11}$$

$\dot{e}$ \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

Fig. 3. Fuzzy control rules for calculating Δu.

With several values of the scaling factors, we got the results shown in Fig. 4 and 5. The scaling factors used here are:

- **(a)** $(S_e, S_d, S_u) = (1, 0.7, 0.5)$
- **(b)** $(S_e, S_d, S_u) = (1, 2.0, 0.5)$
- **(c)** $(S_e, S_d, S_u) = (1, 3.0, 0.5)$
- **(d)** $(S_e, S_d, S_u) = (0.8, 2.5, 0.5)$

and the membership functions for error, error rate, and incremental control input are shown in the Fig. 6-(a), (b) and (c).

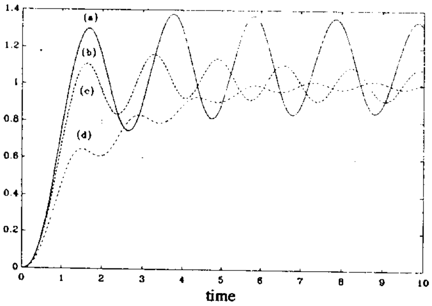

Fig. 4. Responses of (11) by conventional fuzzy PI controllers.

As shown in Fig. 4 and 5, it is not so easy to get satisfactory response with conventional fuzzy PI controller alone for the plant of (11).

For this plant the controller proposed in this section is applied with the membership functions for the resetting rate r of Fig. 6-d, each scaling factor as $(S_e, S_d, S_u) = (1, 0.7, 5)$, and the fuzzy rules for determining the resetting rate as Fig. 7. In the rules the meaning of linguistic variables is as follows.

NR : No Reset
VS : Very Small Reset
SR : Small Reset
MR : Medium Reset
BR : Big Reset
VB : Very Big Reset
CR : Complete Reset

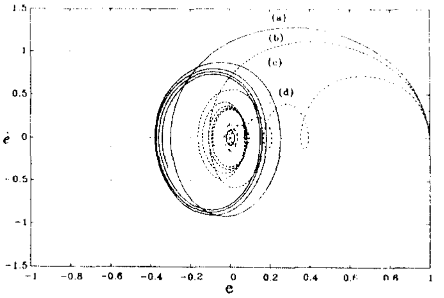

Fig. 5. Redrawn results of Fig. 4 on $(e, \dot{e})$ space.

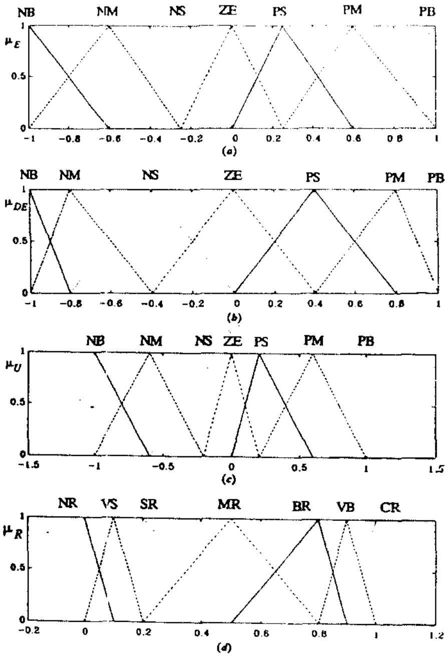

Fig. 6. Used fuzzy sets for (a)error, (b)error rate, (c)incremental control input, and (d)resetting rate.

$\dot{e}$ \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NR	SR	BR	CR	BR	SR	NR
NM	NR	NR	MR	VB	MR	NR	NR
NS	NR	NR	VS	BR	VS	NR	NR
ZE	NR	NR	NR	NR	NR	NR	NR
PS	NR	NR	VS	BR	VS	NR	NR
PM	NR	NR	SR	VB	SR	NR	NR
PB	NR	VS	MR	CR	MR	VS	NR

Fig. 7. Fuzzy rules determining resetting rate for the controller of Section 2.

Note that the resulted number of rules is 49+49=98, while direct use of $\ddot{e}$ gives the rules of 7×7×7=343. The result is shown in the Fig. 8.

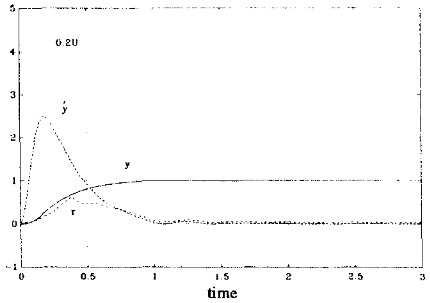

Fig. 8. Responses of (11) by the proposed controller of Section 2.

As shown in the Fig. 8, the resetting rate has so small values for the range of relatively large errors that it does not affect accumulating necessary control input, while it has appropriate values for the range of relatively small error to remove the excessively accumulated control input.

3. Fuzzy PI Controller with Resetting Capability based on error and control input

In this section, we describe a fuzzy PI controller which fuzzily resets the control input accumulated in integrating action according to a situation described fuzzily by error and control input. Our motivation of introducing control input u instead of $\ddot{e}$ stems from the following observations: i) an expert may know the control input exerted by himself fuzzily at every sampling time, and ii) acceleration of a system is related to the force exerted on the system.

The structure of the proposed FLC is shown in Fig. 9, and the basic idea is summarized as

If response approaches given set value with large control input,
then take out the accumulated control input appropriately.

(12)

The responses of the (11) with conventional fuzzy PI controllers are redrawn in (e, u) space, which is shown in Fig. 10. With the fuzzy rules determining reset rate as shown in Fig. 11, scaling factors $(S_e, S_d, S_{\Delta u}, S_U) = (1.0, 0.52, 300, 1/18)$ and the same situations with the Section 2, we apply the proposed controller to the system 11. The result is shown in Fig. 12. The same analysis on the results of the Section 2 can be made on the result.

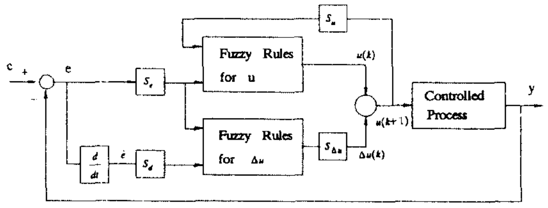

Fig. 9. Structure of fuzzy logic controller of Section 3.

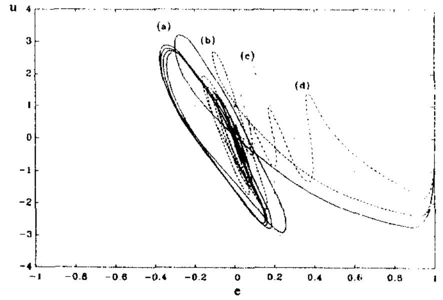

Fig. 10. Redrawn responses of Fig. 4 on (e, u) space.

u \ e	NB	NM	NS	ZE	PS	PM	PB
NB	NR	VB	CR	CR	CR	CR	CR
NM	NR	NR	BR	CR	CR	CR	CR
NS	NR	NR	SR	SR	NR	CR	CR
ZE	NR	NR	NR	NR	NR	NR	NR
PS	CR	CR	NR	SR	SR	NR	NR
PM	CR	CR	CR	CR	BR	VS	NR
PB	CR	CR	CR	CR	CR	VB	NR

Fig. 11. Fuzzy rules determining resetting rate for the controller of Section 3.

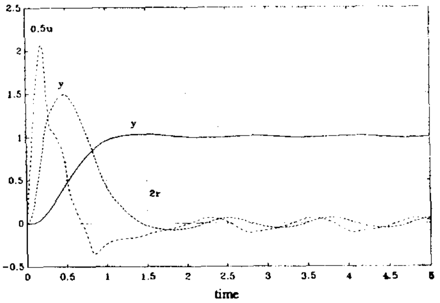

Fig. 12. Response of (11) by fuzzy controller proposed in Section 3.

4. Concluding Remarks

The limitations of conventional fuzzy PI controller especially when applied to systems of order higher than one was investigated, and two fuzzy PI controllers that take out appropriate amounts of accumulated control input incorporated with the incremental control input calculated by the conventional fuzzy PI controllers were proposed. The structures of the proposed controller structure were motivated by the characteristics of fuzzy PI controller caused by the internal integrating operation: it generally gives inevitable overshoot when one tries to reduce rise time in response especially when a system of order higher than one is under consideration, even though the integrator itself is introduced to overcome steady state error in response.

The first controller determines the resetting rate according to situations which are fuzzily described by error and error rate, and the second one by error and control input. The two structures both gave reduced rise time as well as small overshoot compared to the results obtained by applying conventional PI FLCs.

Even though the proposed controllers were proven to improve the performance of the conventional fuzzy PI controllers, further researches on designing the newly added items, i.e., rule table for the resetting rate and the linguistic variables for the reset rate, and on the relation between the newly added items and existing items will be necessary.

References

[1] C. C. Lee, "Fuzzy Logic in Control Systems: Fuzzy Logic Controller-Part I,II," *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 20, no. 2, pp. 404-435, 1990.

[2] M. Sugeno edited, *Industrial Applications of Fuzzy control*, North-Holland, 1985. vol. 15, no. 1, pp. 175-189, 1985.

[3] K. Tanaka and M. Sano, "A New Tuning Method of Fuzzy Controllers," *Proc. IFSA '91*, pp. 207-210, 1991.

[4] M. Maeda, T. Sato, and S. Murakami, "Design of the Self-Tuning Fuzzy Controller," *Proc. Int'l Conf. Fuzzy Logic and Neural Networks*, pp. 393-396, 1990

[5] S. Yamada, H. Fujikawa, A. Fuji, and J. Yamakawa, "A Tuning Method for a Fuzzy Controller," *Proc. Int'l Conf. Fuzzy Logic and Neural Networks*, pp. 397-400, 1990.

[6] M. Yoshida, Y. Tshutsumi, and T. Ishida, "Gain Tuning Method for Design of Fuzzy Control Systems," *Proc. Int'l Conf. Fuzzy Logic and Neural Networks*, pp. 405-408, 1990.

[7] S. Hayashi, "Auto-Tuning Fuzzy PI Controller," *Proc. IFSA '91*, pp. 41-44, 1991

[8] B. C. Kuo, *Automatic Control Systems*, pp.469-479, Prentice-Hall International Ed., sixth edition, 1991.

[9] R. Palm, "Sliding Mode Fuzzy Control," pp. 519-526, Proc. Fuzzy IEEE, 1992.