Enhanced Methods of Fuzzy Logic Control

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Abstract

A simple fuzzy three-term controller is introduced in this paper. A small modification of the conventional FZ-PI control can greatly improve the performance without using acceleration error. A normal two dimensional rule base is used, keeping the control structure simple. The effectiveness of this control method is shown by computer simulation.

1. Introduction

Fuzzy logic control (FLC) has emerged as one of the most active and fruitful research areas in fuzzy set theory, and many practical applications to industrial processes as well as studies of the theory itself, have been reported [0,2].

Several types of structure of FLC have been studied so far: one is FZ-PD control which generates control input (u) from error (e) and change in error (Δe) and is a position type control, another is FZ-PI control which generates incremental control input (Δu) from error (e) and change in error (Δe) and is a velocity type control, and a third one is FZ-PID control which generates incremental control input (Δu) from error (e), change in error (Δe) and acceleration error ($\Delta^2 e$) [3]. FZ-PI type control is known to be more practical than PD type because it is difficult for the PD type to remove steady state error. The PI type control is, however, known to give poor performance in transient response for higher order process due to the internal integration operation. To improve the performance of FZ-PI control, a method with resetting capability has been proposed [4]. However, the method needs another rule-base for resetting capability, which makes the design task more complex. FZ-PID type control [3] needs three inputs, which will expand the rule-base greatly and make the design more difficult. Although some approximations on acceleration error ($\Delta^2 e$) can reduce the difficulties, the performance is not improved much over FZ-PI because of the small influence of acceleration error in general.

In this paper, a simple FZ-PID type method is proposed to greatly improve the performance of FLC with little change to the structure. The basic idea is to take the current fuzzy controller as a single unit, with little alternation inside the unit (rule-base, membership functions, etc), and shift most of the design and modification to the outside of the unit. Then, the performance can be improved by introducing derivative action.

0-7803-2461-7/95/$4.00

2. Fuzzy Logic Control

2.1 Conventional Fuzzy Control Algorithm

Basic structure

The structure of FZ-PI type and FZ-PD type control are shown in Figure 1. The fuzzy input parts are the same for both FZ-PI and FZ-PD control. The only difference lies in the fuzzy output processing. The FZ-PI control contains an integral action in the output.

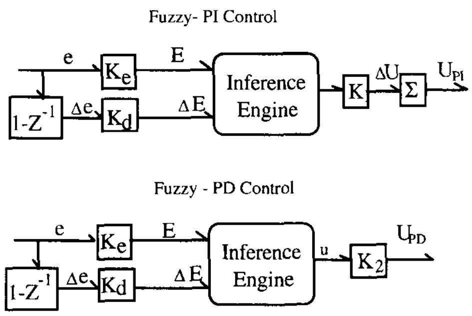

Figure 1 The structure of FZ-PI and FZ-PD control

The gains of FZ-PI can be expressed as:

$$K_p = K_1 F\{K_d\}$$
$$K_I = K_1 F\{K_e\} \qquad (1)$$

The gains of FZ-PD can be expressed as:

$$K_p = K_2 F\{K_e\}$$
$$K_D = K_2 F\{K_d\} \qquad (2)$$

F{ } represents the fuzzy operation.

Design procedure

The design process of fuzzy control is to design its knowledge base, which is composed of the rule-base and the data base [2,5]. The rule base includes all the inference rules and the data base contains the membership functions and gains.

The new methodology for designing a rule base appears in the recent paper [5]. The most common shapes of membership functions are triangle, trapezoid or Gaussian. As practical experience seems to show that the shape of the membership functions has little influence on the performance, most of the design and tuning of FLC can be shifted to the design and tuning of gains [5]. A different gain represents a different control resolution.

Performance analysis

FZ-PI control is more popular than FZ-PD control because integral action can remove the steady state error.

To achieve a faster response, the integral action should be large, i.e. the output gain K should be large. As the phase-lag of the first-order system is small, FZ-PI control can achieve good result with a large integral action. However, because of the additional phase-lag introduced by higher order systems, the large integral action may cause large overshoot and even instability. A small integral action (small output gain K) has to be used which slows down the response. This is why FZ-PI type control has a poor transient response performance with a higher order system.

2.2 Fuzzy-PI Control with Derivative Action

To solve the problem, the controller must have a predictive capability, which can increase/reduce the integral effects. By looking at the traditional PID control, it is easy to find that the derivative control has such predictive function.

A. Combination of FZ-PI control and traditional derivative control (FZ-PI+D)

A general algorithm of this FZ-PI+D control is shown in Figure 2. Practically, the derivative action can be implemented by the traditional method which can avoid the 'derivative kick' and reduce the high frequency noise [6].

Fuzzy - PI + D Control

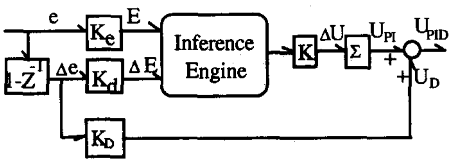

Figure 2. The algorithm of combined FZ-PI and conventional-D control

B. Fuzzy three-term control (FZ-PID)

Because of the limited computer resolution, the $\Delta^2 e$ input in the pure velocity type FZ-PID [3] has little influence on the performance. To avoid having to use the $\Delta^2 e$ input, a hybrid velocity/position type PID algorithm is presented as in (3).

$$U_k^{PID} = U_k^{PI} + U_k^{PD} \quad (3)$$

where U_k^{PI} is the velocity type PI control and U_D^{PD} is the position type PD control.

$$\begin{aligned} U_k^{PI} &= U_{k-1}^{PI} + \Delta U_k^{PI} \\ \Delta U_k^{PI} &= K_I e_k + K_P \Delta e_k \end{aligned} \quad (4)$$

$$U_k^{PD} = K_P e_k + K_D \Delta e_k \quad (5)$$

If the e_k and Δe are fuzzy variables, (1) becomes FZ-PID control. This FZ-PID control can be implemented by combining FZ-PI and FZ-PD in Figure 1. To reduce the complexity of the rule-base design and gain tuning, a common rule-base for both FZ-PI and FZ-PD parts is used in this paper. The structure of this new FZ-PID control is shown in Figure 3. The rule-base design is the same as for FZ-PI/PD control.

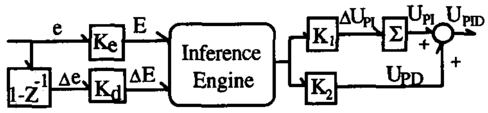

Figure 3. The general structure of Fuzzy - PID Control

The gains of the fuzzy three-term control can be expressed as shown in (6).

$$\begin{aligned} K_P &= K_1 F\{K_d\} + K_2 F\{K_e\} \\ K_I &= K_1 F\{K_e\} \\ K_D &= K_2 F\{K_d\} \end{aligned} \quad (6)$$

F{ } represents the fuzzy operation.

2.3 Tuning Strategy

A two-step heuristic method used in this paper is presented as follows.

For tuning FZ-PI+D control:

i) Tune the FZ-PI control first without using D-control.
ii) Keep input gains K_e and K_d unchanged after adding D-control. A good result can still be obtained by just tuning D-control and re-tuning the output gain K in FZ-PI.

For tuning FZ-PID control:

i) Tune the FZ-PI control first without using FZ-PD control.

ii) Keep input gains K_e and K_d unchanged after adding FZ-PD control. Adjust the output gains K_1 and K_2 in FZ-PI and FZ-PD to obtain a good result.

3. Simulation

The simulation is made by DCS - a simulation language developed by the control laboratory, Electrical Engineering Department, University of Auckland. The numerical integration method used is 4^{th} order Runge-Kutta method. The integration interval T is chosen as 0.01 second.

The quantitative criteria for measuring the performance is chosen as IAE (Integral of Absolute Error) and ITAE (Integral of Time Absolute Error).

$$IAE = \int |e| dt \qquad (7)$$

$$ITAE = \int t|e| dt \qquad (8)$$

IAE accounts mainly for error at the beginning of the response and to a lesser degree for the steady state duration. ITAE is a better criterion which keeps account of errors at the beginning but also emphasises the steady state.

3.1 Model and its knowledge base

A second order model with time delay is chosen for the simulation.

$$\frac{2.2}{1+0.5s+s^2} e^{-\tau s} \qquad (9)$$

Two fuzzy inputs and one fuzzy output are used for the FLC. The rule base used in this paper is given in Table 1 with each input/output variable having a seven term definition (nl,nm,ns,ze,ps,pm,pl). A triangular shape is chosen for membership functions in this paper.

Table 1 Rule base

Δe/e	NL	NM	NS	ZR	PS	PM	PL
PL	zr	ps	pm	pl	pl	pl	pl
PM	ns	zr	ps	pm	pl	pl	pl
PS	nm	ns	zr	ps	pm	pl	pl
ZR	nl	nm	ns	ZR	ps	pm	pl
NS	nl	nl	nm	ns	zr	ps	pm
NM	nl	nl	nl	nm	ns	zr	ps
NL	nl	nl	nl	nl	nm	ns	zr

3.2 Simulation results

The performances of FZ-PI, FZ-PI+D, FZ-PID and PID control are compared. The power limitation is considered. The PID control is implemented by anti-windup technique.

The aim of the simulation is to compare the performance robustness of all these controllers. The procedure of the simulation is: 1) Tune all controllers to their approximate optimum performance for step input under no dead time condition. 2) Operate all controllers with step inputs in long dead time conditions without changing their parameters. 3) Operate all controllers with velocity input under no dead time condition without changing their parameters.

A. Step response when dead time is zero (τ =0)

The quantitative comparison (for 30 seconds) is shown in Table 2. As shown in Figure 4 and Table 2, PID control can achieve the best result in this ideal situation, following by FZ-PID control.

Table 2 The performance index for step input with zero dead time

control type	IAE	ITAE
FZ-PI	3.83	11.25
FZ-PI+D	2.3	3.70
FZ-PID	1.65	2.34
PID	0.89	0.82

B. Step response when dead time exists (τ =0.2sec.)

As shown in Figure 5 and Table 3, FZ-PID achieves the best performance with FZ-PI+D next.

Table 3 The performance index for step input for dead time situation

control type	IAE	ITAE
FZ-PI	4.23	18.07
FZ-PI+D	2.39	4.58
FZ-PID	1.23	1.44
PID	178	5.27

C. Performance for velocity input with zero dead time (τ =0)

The reference input r is chosen as

$$r=0.5+t/15 \qquad (10)$$

As shown in Figure 6 and Table 4, FZ-PID achieves a much better result than the others.

Table 4 The performance index for ramp input

control type	IAE	ITAE
FZ-PI	2.79	14.19
FZ-PI+D	130	4.73
FZ-PID	0.71	1.64
PID	104	5.73

4. Conclusions

The fuzzy control with derivative action can achieve much better results than the conventional FZ-PI control. The derivative action can be implemented by the traditional control methods or simply by combining the conventional FZ-PI and FZ-PD control. The combined FZ-PI and FZ-PD can be considered as another type of FZ-PID control which uses only a normal two dimensional rule base. Thus the control structure is simple.

Acknowledgment

Authors are grateful to the OMRON electronics for their technical support on fuzzy hardware and software.

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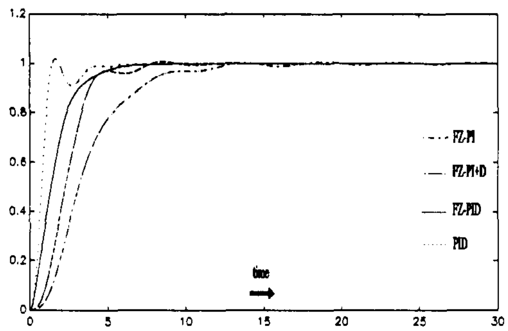

Figure 4 Performance comparison for step input under no deadtime situation

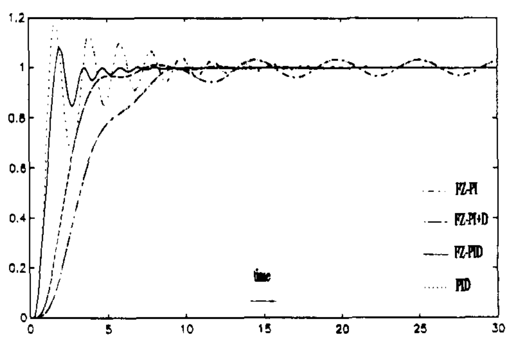

Figure 5 Performance comparison for step input with dead time

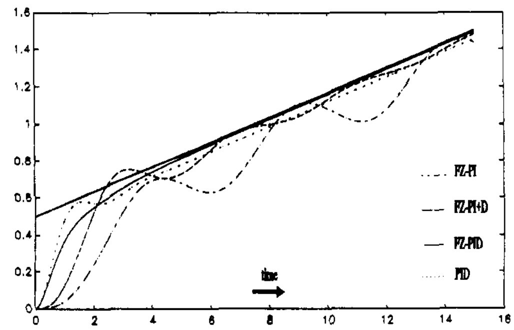

Figure 6 Performance comparison for ramp input under no dead time