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Design of Perfect Tracking Self-Tuning Fuzzy PID Controller with Reference Model

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ABSTRACT

Fuzzy Logic is a popular method to tune a PID controller. By using Fuzzy Logic, the PID is tuned automatically based on information of output error, which is better than other tuning rule methods. Fuzzy Logic Control will tune gains of PID controller by using a set of fuzzy rules designed specifically for that. However, specific transient requirements of the process output cannot be assigned to the controller. This research proposes a new method to overcome this problem by using a reference model. Step input from the reference model that contains the desired response information will be compared against the actual output. The reference model can be pre-selected by the user as desired. This study was simulated on a steam temperature process model while few sets of first-order model were used as reference. The results showed that the proposed Fuzzy PID controller with reference model provides better performance with perfect tracking during transient and steady-state.

Keywords: Component, PID controller, Reference model, Self-tuning fuzzy control, Steam temperature control

INTRODUCTION

The proportional integral derivative (PID) controller, a combination of Proportional (P), Integral (I), and Derivative (D) operations is commonly used in the process industry due to its simplicity and efficiency in a simple process control application. This combination is sufficient to produce satisfactory output, but somehow, a better alternative is always required as the process becomes more complex (Tang, Cui, Hua, Li, & Yang, 2012). For instance, PID controller has stability, reliability, and controllability as its combinations are based on mathematical models (Vindhya & Reddy, 2013).

The performance of PID control depends on the tuning of its parameters to obtain a

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perfect combination. It is hard to achieve desired responses despite many tuning rules discussed in the literature. Sometimes, a compromise between overshoot and the speed of response has to be made. In addition, PID controller is not suitable for complex processes and non-linear, as it is hard to modify the controller parameters and may need to be repeated on line tuning (Li, 1998; Korkmas, Aydogdu, & Dogan, 2012). Therefore, self-tuning fuzzy PID was introduced, and the Fuzzy Logic Controller (FLC) had been successfully applied to various control applications, including non-linear dynamic systems (Tajjudin, Hezri, Rahiman, Ishak, & Arshad, 2013; Vindhya & Reddy, 2013).

According to Precup and Hellendoorn, fuzzy logic is a better alternative to PID with rule-based tuning because it does not require a precise process model (Precup & Hellendoorn, 2011). Therefore, fuzzy PID is superior in handling the change in process dynamics (Das, Pan, Majumder, Das, & Gupta, 2011), and it accommodates real-time control applications. By combining the fuzzy method and PID controller, the problems faced by the latter can be solved (Yi, Wang, Zhao, Li, & Shi, 2013). Studies have shown that when the FLC is combined with PID controller, it will improve the transient response of the system such as shorter output response and a reduction of overshoot (Arulmozhiyal & Kandiban, 2012; Chen, Petráš, & Xue, 2009; Sinthipsomboon et al., 2011; Tsai, Chen, & Hwang, 2004). The FLC is an automatic tuning because the system can be adjusted to get the desired output. Therefore, the system depends only on feedback loop to make the output response becomes the desired output. This is a problem that must be faced by control engineers, and the difficulty lies in creating a membership function and fuzzy rules for the system (Hajiloo & Xie, 2013). However, the performance of fuzzy PID depends on the how much experience the human operator has. In designing a self-tuning fuzzy PID, fuzzy rules were set based on the error and rate of output error to determine the value of optimal PID that minimises the output error. Unfortunately, a desired transient performance of each application cannot be set beforehand.

This study proposed a solution to overcome this problem by introducing a reference model to the set point so that the output response will be aligned with the desired response. The fuzzy PID controller without reference model still has steady state error and overshoot (Habib, 2001). Therefore, by adding the reference model, it will get a better output response. This controller acts as a self-tuning device to improve the traditional PID controller (Adnan et al., 2011; Lou, Kuo, & Sheu, 1996). It is a step to evaluate the controller performance in terms of transient such as settling time, rise time and overshoot (Han, Kim, Kim, & Lee, 2003; Lou, Kuo, & Sheu, 1996). This paper presents simulation results of the proposed controller on a steam distillation process using four first-order reference models. The output will be compared with a fuzzy PID controller, where it is shown that the proposed method is more flexible and efficient for a perfect tracking control.

MATERIALS AND METHOD

The plant that is used in this study was obtained from an empirical model of steam temperature for a steam distillation process. Only linear region is considered in the study. The details are described in (Tajjudin et al., 2013) for further information. The steam temperature is described by a second-order model as given below:

$$G(s) = \frac{0.000366}{(s + 0.011)\,(s + 0.0074)} \quad ; 70^{o}C < T < 100^{o}C \qquad (1)$$

Fuzzy PID Controller

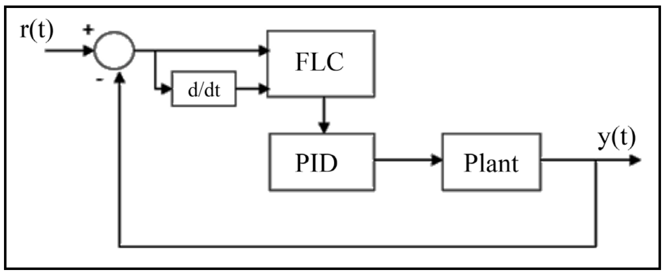

Figure 1. Fuzzy PID controller

Figure 1 shows the structure of Fuzzy PID controller. The FLC obtained input signals from output error, and rate of the error relative to the set point is normally a constant value. Using these inputs, FLC will identify an optimal value of gain for the PID by analysing the relationship of input-output set in the fuzzy rules. Prior to designing the rules, input and output variables were divided accordingly by membership functions that were then assigned literally with Linguistic Variable (LV). In this study, the LV is listed in Table 1.

Table 1
Linguistic variable

Linguistic Variable	Definition
NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

Membership function (MF) of error is shown in Figure 2 with a defined full range of ±60ºC to represent the steam temperature. The MF divided the range equally using triangular function and was assigned to the rate of error but the range was selected as ±20ºC that was found suitable during the study. The MF is shown in Figure 3. Figure 4 shows the MF of the output that will determine the value of PID gain. In this case, the same design of MF was used for each P, I and D. So, the range is normalised between -1 and 1, and it will be multiplied with a constant to get the actual gain of P, I and D, accordingly.

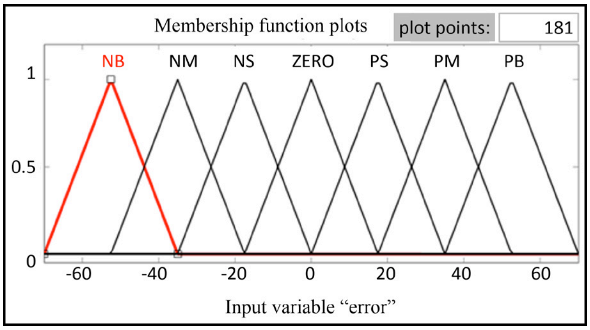

Figure 2. Membership function of error

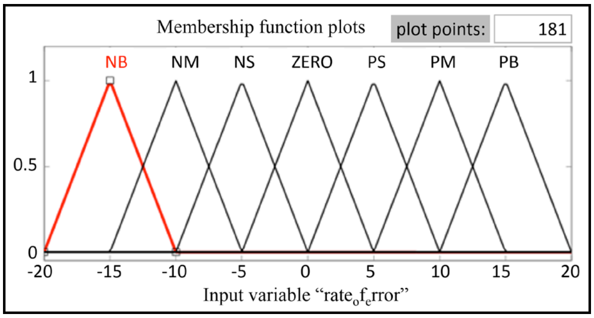

Figure 3. Membership function of rate of error

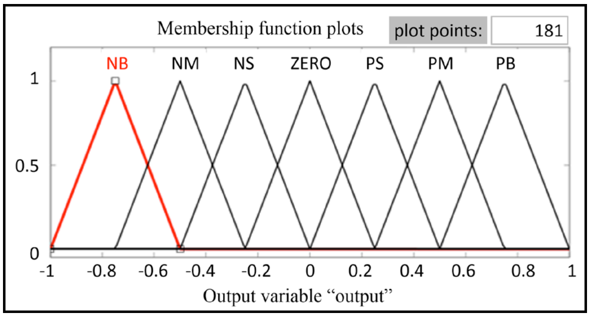

Figure 4. Membership function of output

Fuzzy Rules mapped the relationship between input and output using *if – then* rules for all the membership functions defined earlier. These rules operate based on by human logic and decision-making capability (Table 2). The interconnected membership function between input and output will hence produce 49 fuzzy rules.

Table 2
The proposed fuzzy rule

Rate of Error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PB
PS	NS	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fuzzy PID with Reference Model

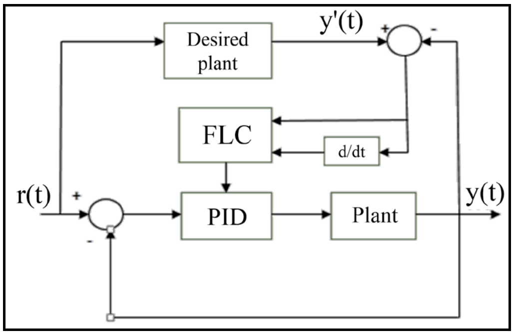

Figure 5. Fuzzy PID with reference model

Figure 5 shows the structure of the proposed Fuzzy PID with reference model. The new feature introduced in this paper is the desired plant that acts as a reference model to define the desired output to the system. By referring to Figure 5, the constant set point input is supplied to the desired plant before it is compared with the actual output. In the new structure, FLC will obtain the error between desired plant and actual output to synthesise the optimal PID gain. Hence, hypothetically, the output can be shaped during its transient as desired. In this paper, first-order transfer function has been evaluated as a reference model to the steam distillation plant control.

The first-order transfer function is given by:

$$G(s) = a / (s + a) \tag{2}$$

Where a is constant. The value of a is related to the time constant, τ as described by the following equation:

$$\tau = 1 / a \tag{3}$$

Thus, by adjusting *a*, the time constant of a response is adjusted which is related to the speed during transient. In this paper, only four models were evaluated based on different values of *a* as shown in Table 3. Obviously, a larger value of a produces a smaller time constant for a faster response.

Table 3
First-order reference model

τ	a
200	0.005
100	0.01
50	0.02
20	0.05

RESULTS AND DISCUSSION

In this section, simulation results of the proposed controller will be presented and compared with a standard fuzzy PID controller. All membership functions and fuzzy rules governing the FLC were maintained for both controllers. Comparison will be done based on transient performance criteria such as settling time and overshoot.

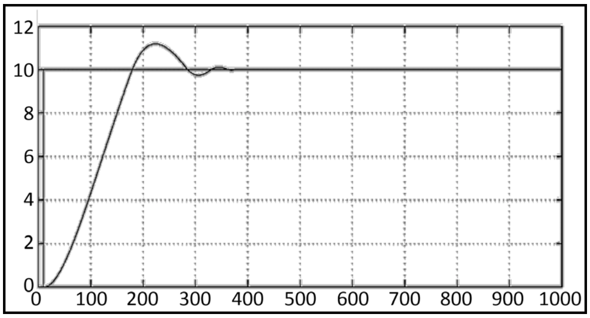

Figure 6. Output response from Fuzzy PID controller

Figure 6 shows the output response of a fuzzy PID. The magnitude of set point was set to 10ºC which corresponds to 70ºC to 80ºC. The steam temperature overshot over 10% from its set point.

Figure 7 shows the output of a fuzzy PID with reference model when a = 0.005 which corresponds with 200 seconds of time constant. It can be observed that the output response is very slow but it followed the response of the model perfectly towards the set point.

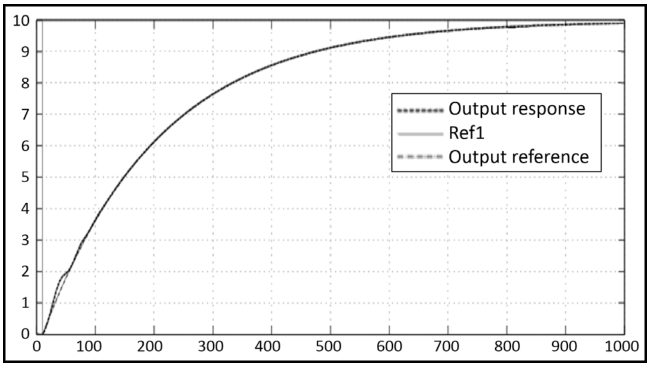

Figure 7. Output response for $a = 0.005$

In Figure 8, the speed of the response was improved when a was set to 0.01. Again, the output response could track the output of a model perfectly towards set point.

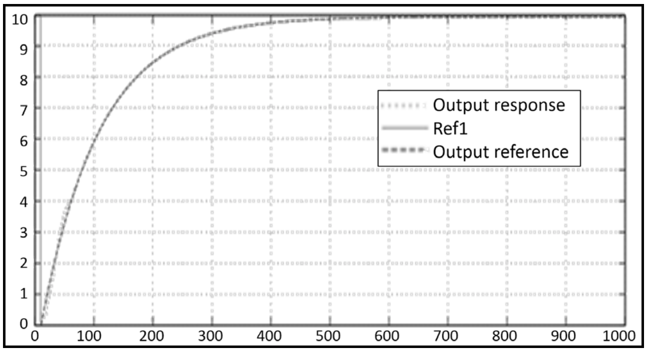

Figure 8. Output response for $a = 0.01$

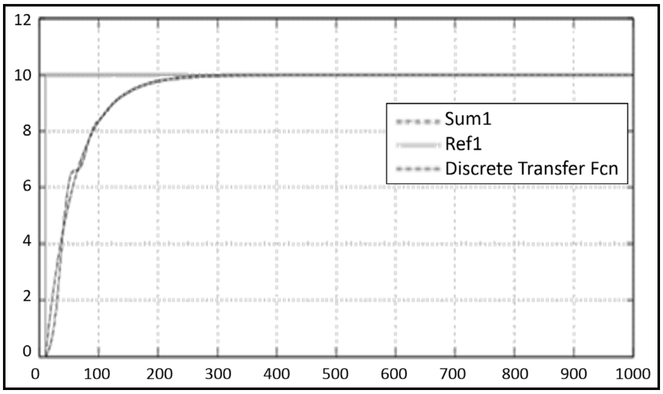

Figure 9. Output response for $a = 0.02$

Figure 9 shows a response of a fuzzy PID when *a* was set to 0.01. The output response was fast and approached set point within 200 seconds without overshoot.

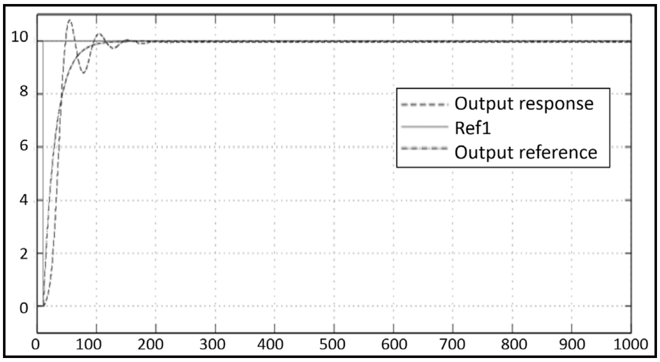

Figure 10. Output response for *a*=0.05

Figure 10 also shows the output response when *a* = 0.05. The output was trying to track the model output, but the desired transient is too fast, causing high control output command. As a result, the output overshot by 9% but returned to the set point within 150 seconds.

Table 4 is a summary of data for ease of comparison. In general, it can be observed that the proposed fuzzy PID with model reference had significantly improved the output response during its transience. Furthermore, the proposed method provides control flexibility in adjusting the desired transient performance by providing a valid model reference at the set point. From the results, the validity of the proposed method had been proven but somehow, the desired speed was limited to 20 seconds of time constant which is equivalent to 1/0.05. Beyond this value, the output response will have significant overshoot which is undesirable in this kind of process.

Table 4
Output response of the controller

Type of controller	Transient	
	Ts (s)	*OS%*
Fuzzy PID	400	10
Fuzzy PID with Reference Model		
0.005	800	0
0.01	400	0
0.02	200	0
0.05	150	9

CONCLUSION

This paper proposed a new structure of fuzzy PID with model reference, which showed better flexibility to the existing fuzzy PID control because desired transient performances can be assigned easily using a standard first-order transfer function. The results from simulation on a steam distillation process had shown significant improvement over the same fuzzy PID controller where the proposed system could track the desired model output perfectly until $a = 0.05$. The performance might be improved if a second-order model is used as a reference model instead.

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