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Research Article

Fuzzy Cognitive Map Based PID Controller Design

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Abstract

Linear proportional-integral-derivative (PID) controllers are the most widely used process controllers in industrial applications due to their simple structures and effective performances. However, performances of these controllers reduce as the nonlinear characteristics or the system orders of the industrial processes increases. Therefore, various nonlinear PID controller models are proposed in literature to improve the control performances of linear PID controllers. In this study, a new nonlinear PID controller design approach is proposed based on the fuzzy cognitive map (FCM) method. Two different FCM based PID controller models are introduced. The first controller model is in the conventional parallel PID structure with three inputs as the error, the derivative of the error, and the integral of the error. On the other hand, the second controller model is in the conventional fuzzy PID form with two inputs as the error and the derivative of the error. In the proposed method, each input signal is firstly fuzzified by using a membership function. Then, causal relationships between inputs and the output are determined by using weight parameters. Finally, the FCM inference is performed by using an activation function. Therefore, the proposed nonlinear PID controllers have four and six tuning parameters, respectively. Simulation studies are performed on a fourth order linear system in order to evaluate the performance of the proposed FCM based PID controller models. The performances of these controller models are compared with a conventional PID controller and a fuzzy PID controller. The comparison results show that the proposed FCM based PID controller models outperform the conventional PID and fuzzy PID controllers.

Keywords: Fuzzy cognitive map, PID, Control, Membership function

Bulanık Bilişsel Harita Tabanlı PID Kontrolör Tasarımı

Öz

Doğrusal oransal-integral-türev (PID) denetleyiciler sahip oldukları basit yapıları ve etkin performansları nedeniyle endüstriyel uygulamalarda en yaygın biçimde kullanılan denetleyicilerdir. Fakat, endüstriyel sistemlerin doğrusal olmayan karakteristikleri ya da sistem dereceleri arttıkça bu denetleyicilerin performansları düşmektedir. Bu nedenle, doğrusal PID denetleyicilerin performansını iyileştirmek için literatürde çeşitli doğrusal olmayan PID denetleyici modelleri önerilmiştir. Bu çalışmada bulanık bilişsel harita (BBH) tabanlı yeni bir doğrusal olmayan PID denetleyici tasarım yaklaşımı önerilmiştir. İki farklı BBH tabanlı PID denetleyici modeli sunulmuştur. İlk denetleyici modeli, hata, hatanın türevi ve hatanın integralinden oluşan üç girişli klasik paralel PID yapısında bir modeldir. İkinci model ise hata ve hatanın türevi olmak üzere iki girişten oluşan klasik bulanık PID yapısında bir kontrolör modelidir. Önerilen yöntemde, ilk olarak her bir giriş sinyali üyelik fonksiyonları kullanılarak bulanıklaştırılmaktadır. Daha sonra girişler ile çıkış arasındaki nedensel ilişkiler ağırlık parametreleri kullanılarak belirlenmektedir. Son olarak, bir aktivasyon fonksiyonu kullanılarak BBH çıkarımı gerçekleştirilmektedir. Bu nedenle, önerilen doğrusal olmayan PID modellerinde sırasıyla dört ve altı ayar parametresi bulunmaktadır. Önerilen BBH tabanlı PID denetleyici modellerinin performanslarını değerlendirmek için dördüncü dereceden doğrusal bir sistem üzerinde benzetim çalışmaları gerçekleştirilmiştir. Bu modellerin performanları, klasik PID denetleyici ve bulanık PID denetleyici performansları ile karşılaştırılmıştır. Karşılaştırma sonuçları, önerilen BBH tabanlı PID denetleyici modellerinin klasik PID ve bulanık PID denetleyicilerden daha üstün bir performans sağladığını göstermektedir.

Anahtar Kelimeler: Bulanık bilişsel harita, PID, kontrol, üyelik fonksiyonu

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1. Introduction

PID controllers are widely used in industrial applications and provide an effective control performance for the systems having dominant linear characteristics [1-4]. However, performances of linear PID controllers reduce as the nonlinear characteristics and the order of dynamical systems increase. The control performance for such systems can be improved by using nonlinear PID control structures [5-8]. One way to design a nonlinear PID controller is to use soft computing methods such as the fuzzy logic approach [9,10]. Soft computing methods are frequently used in the modeling and control applications of high order and/or nonlinear systems. The fuzzy cognitive map (FCM) method, which is one of the soft computing methods, was first proposed by Kosko in 1986 [11]. Then it has gained popularity and is used in many fields such as economy, health, security, engineering, business, and management [12-17]. The fuzzy cognitive map method is effectively used in engineering applications since it provides a way to express complex systems by using existing knowledge and human experience.

In control applications, the FCM approach is generally used for the support or design of supervisory controllers [18-20]. It is very rare to use the FCM approach to design a main controller for process control applications [21-25]. In [21], the FCM method is used as the main controller for the temperature and humidity control of a room in winter and summer operation season. The performance of the FCM controller on this system was compared with a PID controller. The results show that the FCM controller is a better choice for this system. In [22], a dynamic fuzzy cognitive map method is used to control an industrial mixer. The performance of the FCM controller is compared with the performance of a fuzzy logic controller, and similar performance results are obtained. In [23], the main controller based on the FCM structure is designed for control of a heatex process. FCM based controllers are designed for the path tracking application of an unmanned air vehicle in [24]. In [25], three different FCM based controller models are proposed in the PI controller form, and their effective performances are shown by performing simulation studies on a nonlinear system.

In this study, a new nonlinear PID controller structure is proposed by using the FCM approach. Two different FCM based PID (FCM-PID) controller models, FCM-PID-Model-1 and FCM-PID-Model-2, are introduced and their performances are evaluated. The conventional parallel PID structure with three inputs (the error, the derivative of the error, and the integral of the error) and conventional fuzzy PID controller structure with two inputs (the error and the derivative of the error) are used for the proposed FCM-PID-Model-1 and FCM-PID-Model-2, respectively. In this way, control performances can easily be improved in control applications by replacing existing PID controllers with its proposed counterpart model. Additionally, conventional PID tuning methods can be applicable to a certain degree for the proposed controllers. In the proposed FCM-PID models, each input signal is fuzzified by using a membership function. Then, causal relationships are specified by using weight parameters. Finally, the FCM inference is performed by using an activation function. Thus, the proposed FCM-PID-Model-1 and FCM-PID-Model-2 have four and six tuning parameters in total, respectively. To show the effectiveness of the proposed FCM-PID controller models, simulation studies are done on a fourth order linear system. A conventional PID and a fuzzy PID controller are used for the performance comparison. The parameters of the controllers are tuned by using a genetic algorithm. The performance criteria in the comparisons are chosen as settling time, integral absolute error (IAE), integral square error (ISE), integral time absolute error (ITAE), and integral time square error (ITSE). The results show that the performances of the proposed controllers are better than the performances of the fuzzy PID controller and the conventional PID controller.

The organization of the study is as follows. In Section 2, the proposed controller models are given. In Section 3, simulation studies are presented. Finally, in Section 4, the results and future studies are provided.

2. Proposed FCM-PID Controller Models

The internal structure of the proposed FCM-PID controller models can be divided into three stages as shown in Figure 1. In the first stage, input signals are fuzzified by using membership functions. In the second stage, causal relationships between fuzzified inputs and the output are determined by using appropriate weight parameters. Finally, the crisp output value is obtained by using an activation function.

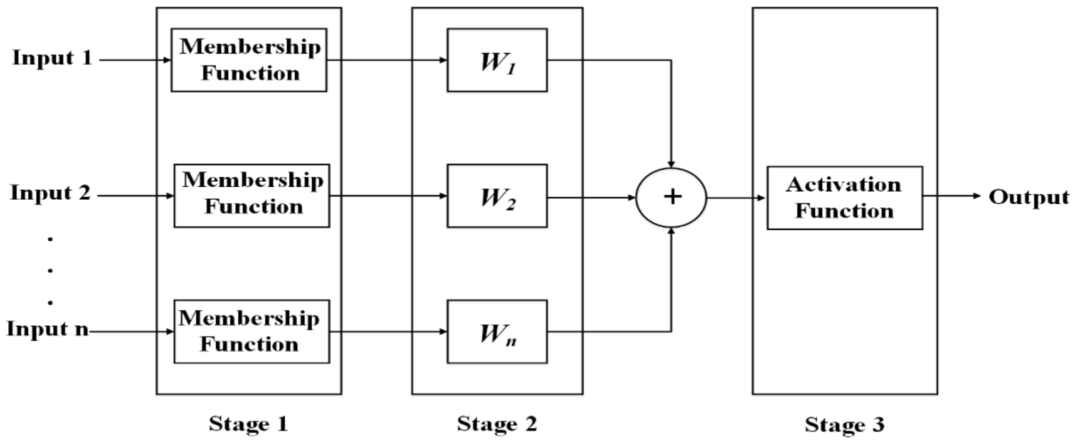

Figure 1. Internal structure of the proposed FCM-PID controller models

2.1. FCM-PID Model-1

The proposed Model-1 is constructed in the conventional parallel PID form as shown in Figure 2. Here, the controller inputs are the error, the derivative of the error, and the integral of the error.

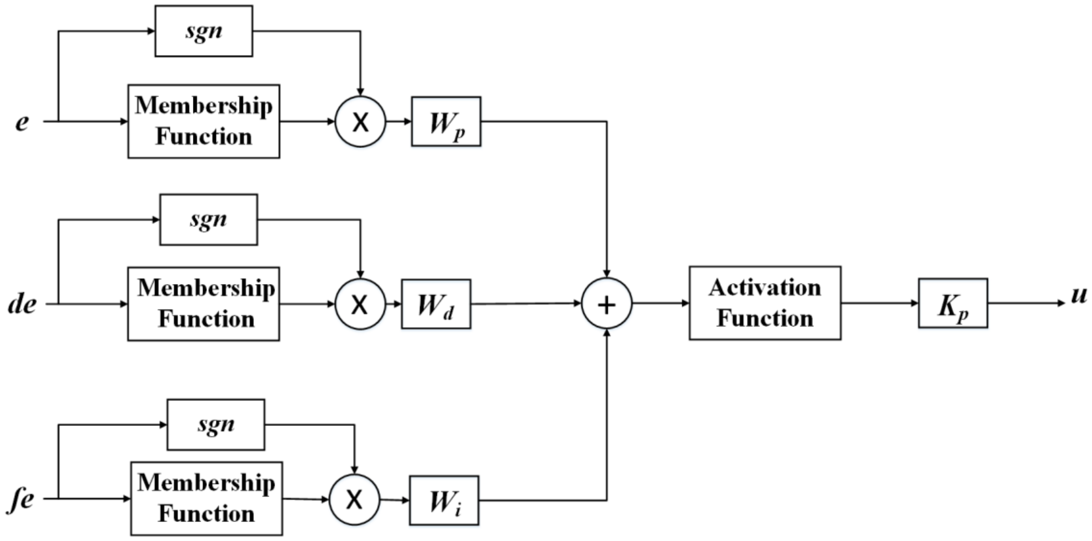

Figure 2. Structure of FCM-PID controller Model-1

There are four tuning parameters in this model. These parameters are three causal relationship weights, W_p, W_d, W_i, and one output gain, K_p. Depending on this controller structure, the control signal is defined as follows.

$$u = f\left(\text{sgn}(e)\mu(e)W_p + \text{sgn}(de)\mu(de)W_d + \text{sgn}\left(\int e\right)\mu\left(\int e\right)W_i\right)K \tag{1}$$

Here, $\mu(.)$ and $f(.)$ denote the input membership function and the activation function, respectively. Since the membership degrees are defined in [0 1], the sign function, *sgn(.)*, is used to obtain negative values of the control signal.

2.2. FCM-PID Model-2

The conventional fuzzy PID form with two inputs is used for the controller structure of the proposed Model-2 as shown in Figure 3. The inputs of this model are the error and the derivative of the error. The final output of this controller is obtained as the summation of the inference result and its integral.

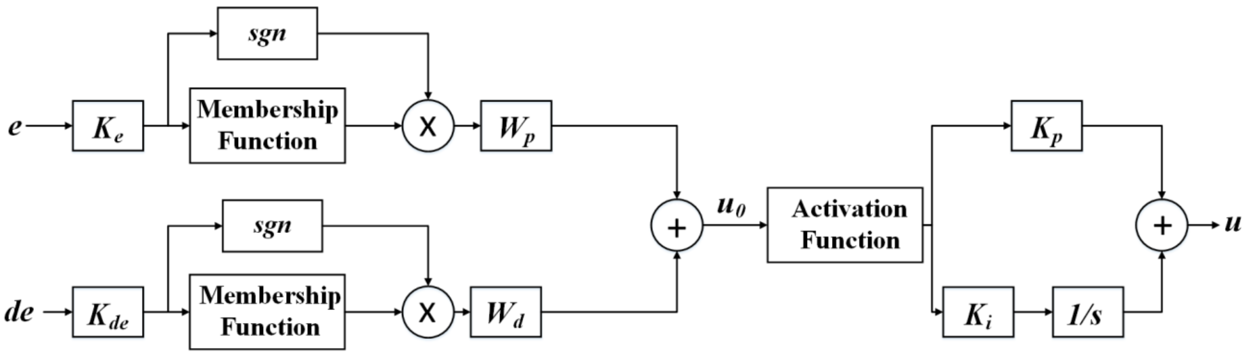

Figure 3. Structure of FCM-PID controller Model-2

This model has six tuning parameters which are two input gains K_e and K_{de}, two output gains K_p and K_i, and two causal relationship weights W_p and W_d. The mathematical expression of the control signal is given as follows

$$u = K_p f(u_0) + K_i \int f(u_0) \tag{2}$$

where

$$u_0 = \text{sgn}(K_e e)\mu(K_e e)W_p + \text{sgn}(K_{de} de)\mu(K_{de} de)W_d \tag{3}$$

3. Simulation Studies

In this section, simulation studies are done on a fourth order linear system to evaluate performances of the proposed FCM-PID controller models. The transfer function of the system is given as follows

$$G(s) = \frac{1}{(s+1)^4} \tag{4}$$

In the simulation, the sampling time is chosen as 0.1 seconds. The reference input is the unit step function. For both controllers, an inverted Gaussian membership function is used for each input as shown in Figure 4, and the activation function is chosen as $f(x) = x$.

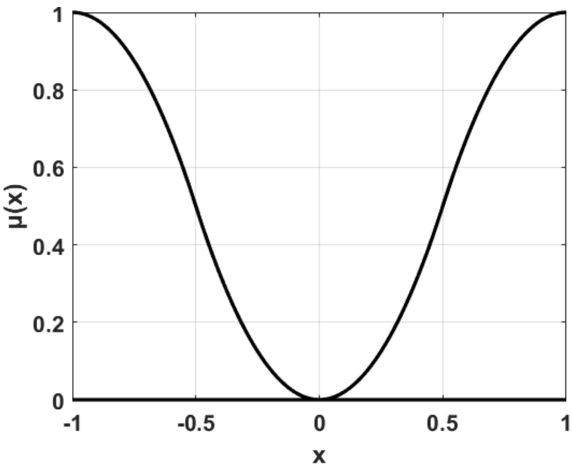

Figure 4. Membership function used in the proposed FCM-PID controller models

The genetic algorithm is used for the determination of the parameter values of FCM-PID controller models [26]. The number of generation and the population are chosen as 50 and 100, respectively. ITAE is used as the performance criterion with additional overshoot constraint. The optimized parameter values are given in Table 1.

Table 1. Tuned Parameter Values of FCM-PID Controller Models

Parameters	**Controllers**	
	FCM-PID Model 1	***FCM-PID Model 2***
K_e	-	3.8798
K_{de}	-	2.2829
K_i	-	1.6031
K_p	4	2.8442
W_p	0.29	0.7010
W_d	0.6025	0.9104
W_i	0.25	-

To show the effectiveness of the proposed FCM-PID controller models, the performances of the proposed controllers are compared with the performances of a conventional PID controller and a fuzzy PID controller with two inputs as shown in Figure 5 and Figure 6, respectively.

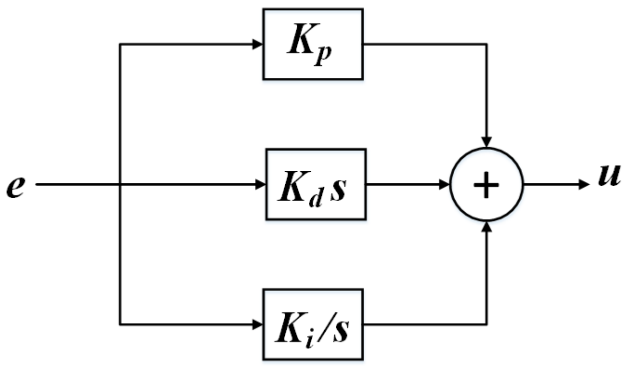

Figure 5. Conventional PID Controller Structure

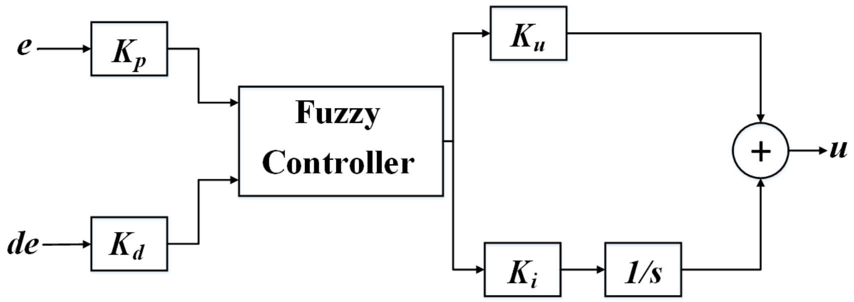

Figure 6. Structure of Fuzzy PID Controller with Two Inputs

In fuzzy PID controller design, Takagi-Sugeno type controller structure with a 3x3 symmetrical rule base is preferred. Three triangular membership functions are used for each input universe of discourse as shown in Figure 7. Three singleton fuzzy sets are used for the output universe of discourse as Negative, Zero, and Positive. The corresponding singleton values are chosen as -1, 0, and 1, respectively. The centroid method is used for the defuzzification.

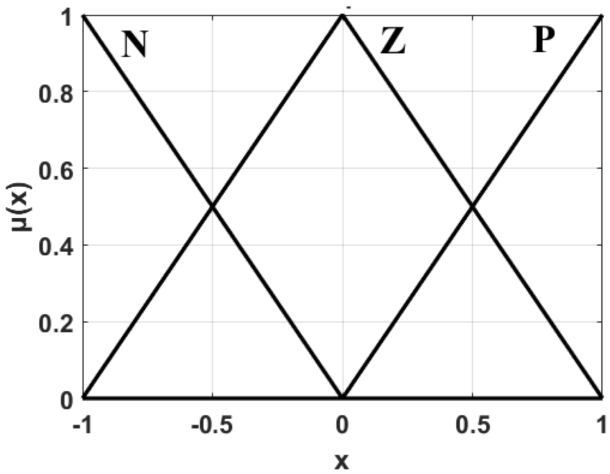

Figure 7. Input Membership Function of The Fuzzy PID Controller

The parameter values of the fuzzy PID and the conventional PID controller are determined by using the genetic algorithm with the same structure. The determined parameter values are given in Table 2.

Table 2. Tuned Parameter Values of Conventional PID and Fuzzy Controllers

Parameters	**Controllers**	
	PID	***Fuzzy PID***
K_p	1.16365	1.25
K_d	1.01834	1.69
K_i	0.30227	0.41
K_u	-	0.68

After the optimization process, the obtained system responses and corresponding control signals are given in Figure 8 and Figure 9, respectively. The performance comparison results are given in Table 3 which shows values of the settling time, IAE, ISE, ITAE, and ITSE of system responses.

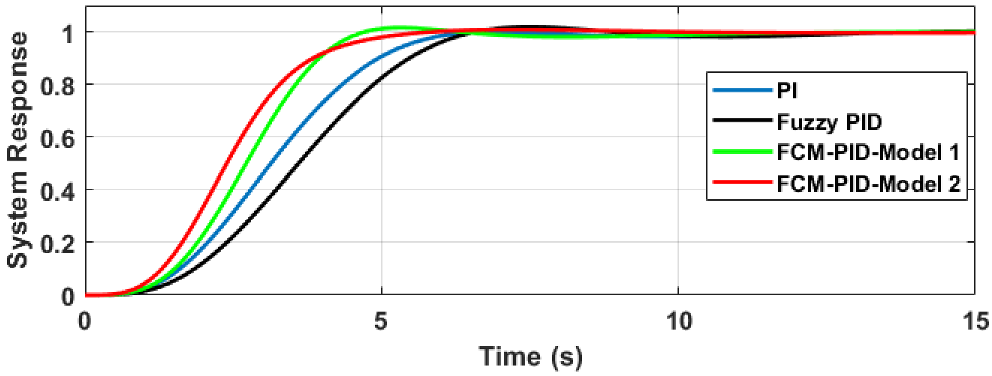

Figure 8. System responses

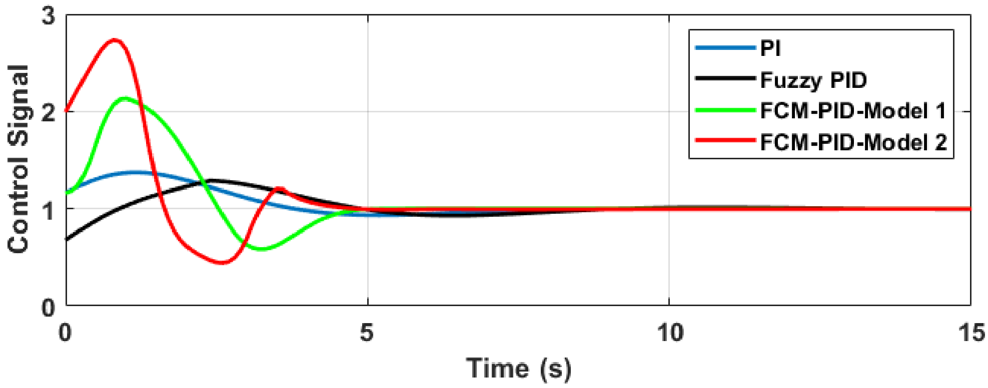

Figure 9. Control signals

Table 3. Performance Comparison Results

Table Head	**Controllers**			
	PID	***Fuzzy PID***	***FCM-PID Model 1***	***FCM-PID Model 2***
Settling Time [s]	5.9	6.3	**4.5**	5.1
IAE	3.2942	3.7131	2.8120	**2.5370**
ISE	2.4958	2.8595	2.2022	**1.9404**
ITAE	6.8070	8.3417	4.8917	**3.9965**
ITSE	3.5937	4.6841	2.7112	**2.1383**

As it is seen from Figure 8 and Table 3, higher control performances are obtained by using the proposed FCM-PID controller models than the performances of the conventional PID controller and the fuzzy PID controller with 3x3 rule base. FCM-PID-Model-1 provides the lowest settling time value. On the other hand, FCM-PID-Model-2 has the best control performance in terms of the other performance criteria. Classical PID and Fuzzy PID controllers have lower control performances with the settling time values of 5.9 and 6.3 seconds, respectively. It is important to note that the performances of the proposed FCM-PID controller models can be improved further by using different types of membership functions and activation functions.

4. Conclusion

In this study, fuzzy cognitive map based PID controller design is introduced. Two different FCM based PID controller models are proposed and their performances are evaluated by performing simulation studies. The simulation results show that the proposed FCM-PID controller models exhibit better control performance than the conventional PID and fuzzy PID controllers. Therefore, the proposed FCM based PID controller models can effectively be used in practical control applications.

Existing PID controllers can easily be replaced with FCM based PID controller counterparts to improve the control performances. Additionally, conventional PID tuning methods can be applicable to a certain degree for the proposed controllers since they preserve the basic PID form. Moreover, the proposed FCM based PID controller models provide additional design degrees of freedom due to their membership functions and activation functions. By using different types of functions, nonlinear characteristics and also performances of FCM based PID controller models can be increased especially in control applications of complex systems. Similarly, parameters of these functions can be used for fine tuning of controllers.In future studies, the proposed fuzzy cognitive map based PID controller models will be applied to practical control problems.

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