

Comparative Study of PID, Type-1 and Type-2 Fuzzy Control for Nonlinear Systems

Yao Chen^{1 a}, Jiahao Liu^{2 b} and Tao Zhao^{3 c}

¹. School of Electrical Engineering and Information Technology, Sichuan University, Chengdu 610065, China

². School of Electrical Engineering and Information Technology, Sichuan University, Chengdu 610065, China

³. School of Electrical Engineering and Information Technology, Sichuan University, Chengdu 610065, China

^a2017223035189@stu.scu.edu.cn; ^b2017223030076@stu.scu.edu.cn

^czhaotaozhaogang@126.com

Abstract. Traditional PID control is widely used in industry due to its advantages of stability. The traditional PID controller is very difficult to obtain satisfied control performance for complex nonlinear systems with uncertainties. Fuzzy control approach has better anti-interference ability than traditional PID control method, and thus it can be used to deal with many complex nonlinear systems. In this paper, a comparative study for the control performance and anti-interference ability of traditional PID, type-1 and type-2 fuzzy control approaches are considered. By numerical simulations, the performance of fuzzy control is better than that of traditional PID in some specific situations, and the anti-interference performance of type-2 fuzzy control is better than type-1 fuzzy control and traditional PID control for a certain nonlinear problem.

1. Introduction

The use of classical controllers such as PID controller can be a good choice for controlling some systems. However, the higher and the more accuracy requirement in system control make it difficult to adjust the parameters of the controller, which is quite sensitive to noise signals [1].

Fuzzy logic controllers are used successfully in many application areas, and these include control, classification, etc [2-6].

The traditional fuzzy controller refers to type-1 proposed by Zadeh in 1965[7], can take advantage of the human experience and knowledge to deal with many control problems. As a kind of nonlinear controller, type-1 fuzzy logic controller provides a kind of language information by experts and convert them to control method, the control strategy of the system that can get the accurate model of the complex and difficult system. Therefore, it is an effective mean to deal with uncertainty and inaccuracy. Type-1 fuzzy system (Type-1 FLS), however, it will also face many uncertainties, and the limitation of the type-1 fuzzy logic controller is that it uses the membership function by accurate representation of a type-1 fuzzy sets. Therefore, type-1 fuzzy logic controller does not directly deal with the uncertainty of fuzzy rules. As an extension of type-1 fuzzy logic control (T1-FLC) Zadeh proposed the type-2 fuzzy set (T2-FS) in 1975. The characteristic of T2-FS is the fuzzy representation of the membership value in the fuzzy set, that is, its membership is T2-FS [8-9].



This paper presents a comparative study for the control performance and anti-interference ability of traditional PID, type-1 and type-2 fuzzy control approaches. Numerical simulation is provided to show the advantages of type-2 fuzzy control in handling uncertainties. The paper is organized as follows. In section 2, some preliminaries are introduced. The PID, type-1 and type-2 fuzzy controller design is presented in section 3. The simulation comparisons of three kinds of control methods are provided in section 4. The last section draws the conclusion and puts forward the prospect.

2. Preliminaries

2.1 Controlled object analysis

In this paper, we use the nonlinear system shown in formula (1) to make a comparison among the control performance of PID, type-1 and type-2 fuzzy controllers, the control object adopted is the nonlinear model as shown in formula (1) [10].

$$Y(i) = 0.2 * y(i-3) * 0.07 * y(i-2) + 0.9 * y(i-1) + 0.05 * u(i-1) + 0.5 * u(i-2) \quad (1)$$

It can be seen from the formula (1) that the output of the nonlinear plant is related to the previous three outputs and the previous two control inputs. PID, as a classic and stable controller, has been widely applied in industry. Firstly, we explore whether the PID controller can meet the control requirements. Especially, some stochastic disturbances exist in the feedback channel, and thus the anti-interference ability of controller is required. Comparing with PID control method, fuzzy control method has stronger robustness. Secondly, type-1 and type-2 fuzzy controller is designed to enhance the ability to deal with nonlinear effects and uncertainties.

2.2 Performance criteria

To more clearly compare the control performance and anti-interference ability of PID, type-1 and type-2 fuzzy control approaches, three functions are used to evaluate the control results quantitatively. These evaluation functions have been widely used in literature [0].

1) Integral of Square Error (ISE)

$$ISE = \int_0^{\infty} [e(t)]^2 dt \quad (2)$$

2) Integral of the Absolute value of the Error (IAE)

$$IAE = \int_0^{\infty} |e(t)| dt \quad (3)$$

3) Integral of the Time multiplied by the Absolute value of the Error (ITAE)

$$ITAE = \int_0^{\infty} t |e(t)| dt \quad (4)$$

3. Controller design

In this section, PID, type-1 and type-2 fuzzy controllers are designed for the nonlinear system provided in formula (1) respectively.

3.1 PID controller design

The control law of PID control is as follows:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \quad (5)$$

where $e(t)$ is error, T_i is the integral coefficient, and T_d is the differential coefficient. The sampling time T is 0.1, and the sampling total number $N=150$. According to the responses of nonlinear system in (1), PID parameter is selected as $K_p=1$, $T_i=-1/6$, $T_d=1$.

3.2 Type-1 fuzzy controller design

Firstly, the tracking error $e(t)$ and the error variation $\Delta e(t)$ are selected as the inputs of type-1 fuzzy controller and then act on the plant. Secondly, for each of the inputs of the type-1 fuzzy logic system, $e(t)$ and $\Delta e(t)$, three type-1 fuzzy Gaussian MFs were defined as: negative, zero, positive. The universe of discourse of these membership functions is in the range $[-10, 10]$; their centers are -10, 0 and 10 respectively, and their standard deviations is 4.2466 as is illustrated in Figure.1[10].

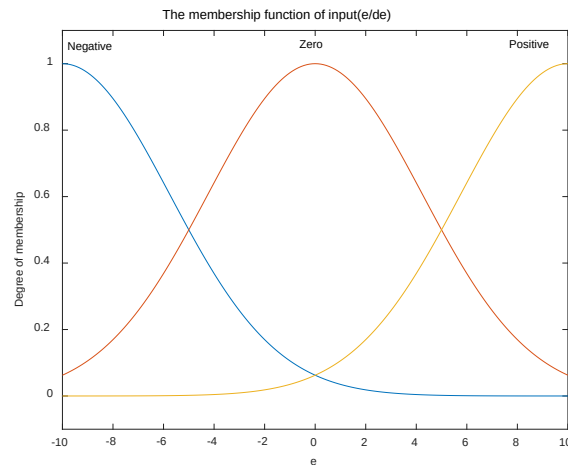


Figure 1. The membership function diagram of inputs

For the output of the type-1 fuzzy logic system, we have five type-1 fuzzy Gaussian MFs: NG, N, Z, P and PG. They are in the interval $[-10, 10]$, their centers are -10, -5, 0, 5 and 10 respectively; and their standard deviation is 2.1233 as can be seen in Figure.2[10].

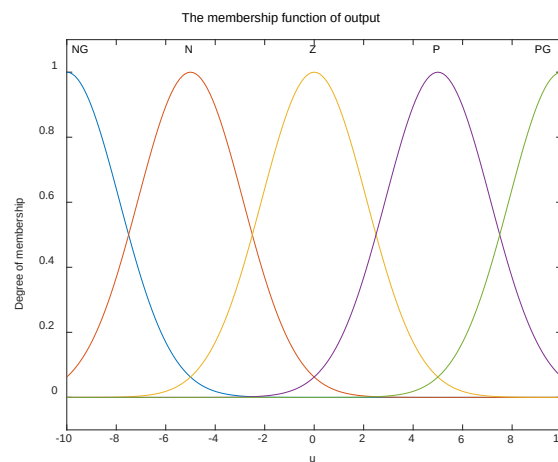


Figure 2. The membership function diagram of output

Table 1. Rules table of type-1 fuzzy logic system

$\Delta e(t)$ $e(t)$	N	Z	P
N	NG	N	Z
Z	NG	Z	P
P	Z	P	PG

The rules of type-1 fuzzy controller is shown in Table.1 and centroid defuzzification are used to obtain a crisp output.

3.3 Type-2 fuzzy controller design

Firstly, the type-1 fuzzy logic system principle diagram is presented by Figure.3

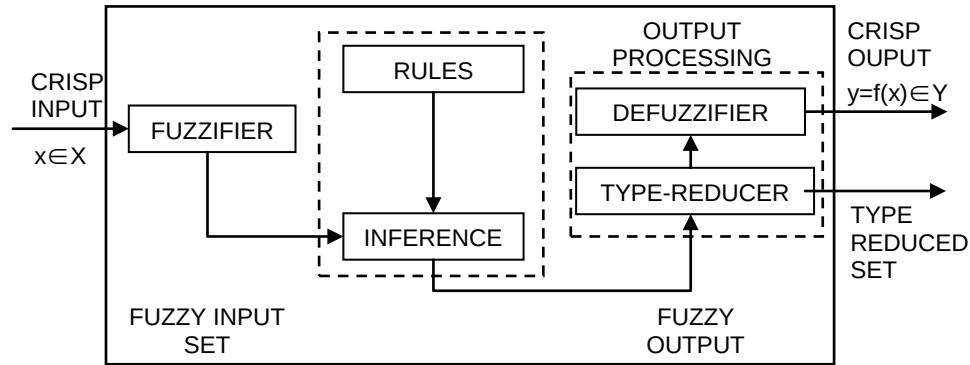


Figure 3. Type-2 fuzzy logic system

Secondly, the type-2 fuzzy controller also selects the error $e(t)$ and the error variation as input, and the membership function of type-2 fuzzy controller is shown in Figure.4; The type-2 fuzzy controller can deal with uncertainties directly because its' membership function is also fuzzy. In other words, a type-1 fuzzy set is a special case of a type-2 fuzzy set; the type-2 fuzzy system's secondary membership function is a subset with only one element [10].

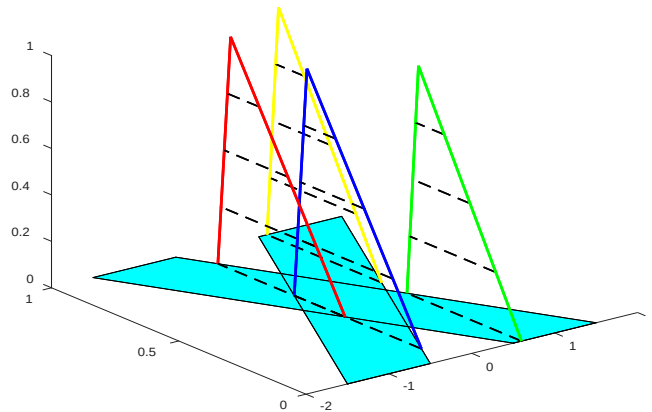


Figure 4. The membership function diagram of type-2 fuzzy controller

Thirdly, the rule base has the following four rules:

$$R^1: IF x_1 \text{ is } \tilde{X}_{11} \text{ and } x_2 \text{ is } \tilde{X}_{21}, THEN y \text{ is } Y^1.$$

$$R^2: IF x_1 \text{ is } \tilde{X}_{11} \text{ and } x_2 \text{ is } \tilde{X}_{22}, THEN y \text{ is } Y^2.$$

$$R^3: IF x_1 \text{ is } \tilde{X}_{12} \text{ and } x_2 \text{ is } \tilde{X}_{21}, THEN y \text{ is } Y^3.$$

$$R^4: IF x_1 \text{ is } \tilde{X}_{12} \text{ and } x_2 \text{ is } \tilde{X}_{22}, THEN y \text{ is } Y^4.$$

Where x_i and y are the input and output of the type-2 FLS, respectively; $\tilde{X}_i$ and Y^i are the type-2 antecedent and the consequent sets, respectively. And COS type-reduction + average of end-points defuzzification are used to obtain a crisp output.

4. Simulation

4.1 Simulation of an Ideal System

The simulation results of the tradition PID, type-1 and type-2 fuzzy controllers are shown in Figure.5.

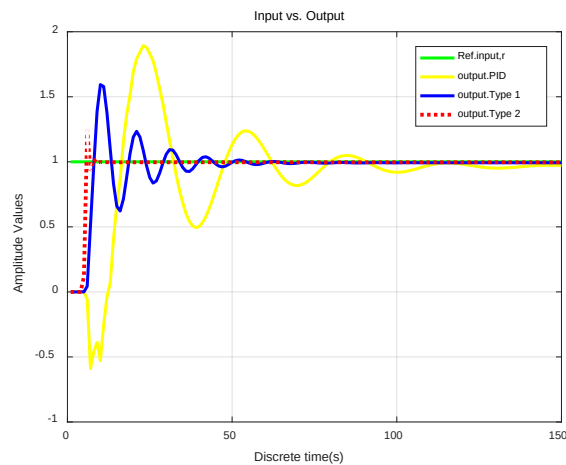


Figure 5.Simulation results of the tradition PID controller, type-1 and type-2 FLC

Table 2. Comparison of performance criteria for the traditional PID controller, type-1 and type-2 FLC

Performance Criteria	PID	Type-1 FLC	Type-2 FLC
ISE	24.97	4.79	1.87
IAE	33.90	9.70	2.72
ITAE	109.50	20.10	5.05

As shown in Figure.5 and Table.2, The highest point of the traditional PID response curve is 1.73, which means the overshoot is 73%. The adjust speed is slow and the final tracking input signal has a static error. Obviously, the performance of PID controller is not ideal, we consider to use the fuzzy logic controller to get a better control performance.

Firstly, we can see the performance of type-1 and type-2 FLC are faster and more accurate than traditional PID controller, especially the type-2 fuzzy controller is much better. The type-2 fuzzy controller's response speed is quick and the overshoot is small. Therefore, we can conclude that the fuzzy controller has better control performance.

4.2 Simulation result of a System with Uncertainty

To observe anti-interference ability of the fuzzy controllers, the feedback channels of the three controllers were added to the random disturbance of $0.05 \cdot \text{random}(1)$, and then the simulation results are shown in Figure.6

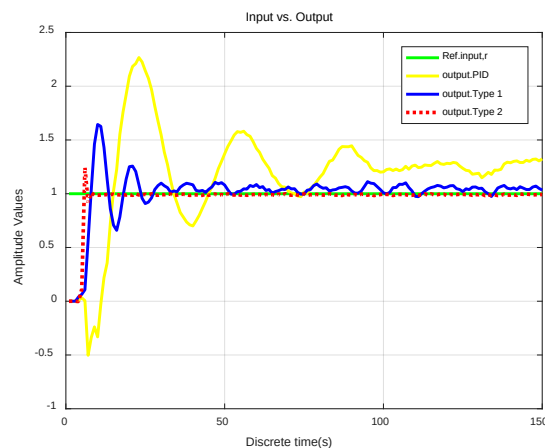


Figure 6.Simulation results of the traditional PID controller, type-1 and type-2 FLS with uncertainties

Table3. Comparison of performance criteria for PID controller, type-1 and type-2 FLC with uncertainties

Performance Criteria	PID	Type-1 FLC	Type-2 FLC
ISE	34.20	4.86	1.87
IAE	53.97	13.73	3.60
ITAE	306.99	61.37	11.73

As can be seen from Figure.6 and Table.3, the anti-interference ability ranges from high to low: type-2 fuzzy controller, type-1 fuzzy controller and the traditional PID controller. The type-2 fuzzy controller has strong anti-interference ability, which also demonstrates that type-2 fuzzy controller does have a strong ability to deal with uncertainties.

5. Conclusions and prospects

The simulation results indicate that the fuzzy control's response speed is quick, overshoot is small, the ability of resistance is better. The type-2 fuzzy control shows good control performance and anti-interference ability. However, the traditional PID controller also has some advantages that fuzzy controller does not have. Therefore, it is a wise choice to combine fuzzy control with PID control to achieve better control performance and anti-interference ability in a subsequent study.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (61703291) and the Applied Basic Research Program of Science and Technology Department of Sichuan Province, China (2016JY0085).

References

- [1] Castillo, O., Melin, P.: Soft Computing for Control of Non-Linear Dynamical Systems. Springer, Heidelberg (2001)
- [2] Al-Jaafreh, M.O., Al-Jumaily, A.A.: Training type-2 fuzzy system by particle swarm optimization. In: IEEE Congress on Evolutionary Computation, CEC 2007, Singapore, pp. 3442–3446 (2007)
- [3] Cai, A., Quek, C., Maskell, D.L.: Type-2 GA-TSK fuzzy neural network. In: Proceedings of IEEE Congress on Evolutionary Computation, CEC 2007, pp. 1578–1585 (2007)
- [4] Hidalgo, D., Melin, P., Mendoza, O.: Evolutionary optimization of type-2 fuzzy systems based on the level of uncertainty. In: Proceedings of the IEEE World Congress on Computational Intelligence, WCCI 2010, Barcelona (July 2010)
- [5] Juang, C.-F., Hsu, C.-H.: Reinforcement ant optimized fuzzy controller for mobile robot wall-following control. IEEE Transactions on Industrial Electronics 56, 3931–3940 (2009)
- [6] Castro, J.R., Castillo, O., Melin, P., Martinez, L.G., Escobar, S., Camacho, I.: Building fuzzy inference systems with the interval type-2 fuzzy logic toolbox. Advances in Soft Computing, vol. 41, pp. 53–62 (2007)
- [7] L. A. Zadeh, “Fuzzy sets,” Inf. Control, vol. 8, no. 3, pp. 338–353, 1965
- [8] Mendel J M. Type-2 Fuzzy Sets and Systems: an overview[J]IEEE Computational Intelligence Magazine, 2007, 2(1):30-43
- [9] Mendel J M. Uncertain Rule-Based Fuzzy Systems: Introduction and New Directions, 2nd Edition[M]. Springer Publishing Company, Incorporated, 2017.
- [10] Janusz Kacprzyk. Type-2 Fuzzy Logic in Intelligent Control Applications. Studies in Fuzziness and Soft Computing, Volume 272