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A Practical Design Method of Fuzzy Controller Based on Control Surface

Yongli HUANG* and Seiji YASUNOBU**

It is difficult to design a fuzzy controller because there are many parameters should be adjusted. In this paper a new methodology is proposed for designing a fuzzy logic controller. Control surface is used to bridge the gap between the conventional PID controller and fuzzy controller. Based on a system model the conventional PID control parameters are tuning and its linear control surface is used as the knowledge basis for a fuzzy controller. This fuzzy controller is optimized by computer-aided design system according to the restriction condition of control response. The tuned control surface of the fuzzy control have non-linear properties which is corresponding to the controlled plant. The proposed method is applied to a non-linear control system design and simulation shows it is robust when the controlled system model has error and when it is in different initial conditions. Its effectiveness has been proved that it is a practical method for designing fuzzy controller.

Key Words: Fuzzy Logic Control, Non-linear Control, Control Design, Parameters Optimized, Robust Control

1. Introduction

With the development of computational intelligence and soft computing techniques, the fuzzy logic control(FLC) has received increasing attention in the control community. It has been shown that there are several different types of system which use FLC as essential system components [1]. The most popular type being studied by many researchers throughout the world is popularly called fuzzy linguistic control that is PID (proportional-integral-derivative) strategy. One of the distinct feature of this kind of fuzzy logic controller is that fuzzy logic provides a nonlinear relationship which make fuzzy logic promising for process control where conventional PID control technologies do a poor job. However, the fundamental problem in fuzzy control technology is that there lacks a design theory on fuzzy control and it is extremely difficult to establish a systematic design method for fuzzy controller.

Generally speaking, the design fuzzy control is composed of two steps, one is to set up the membership functions and rule-base the other is parameters tuning. Many efforts has been done on how to design a fuzzy controller. Based on a phase-plane analysis, Han-Xiong Li proposed a rule base establishing method in which a standard and robust rule bases are proposed for fuzzy two-term control, but it is remain a tedious work to adjust scaling factors [2),3)]. Hao Ying analyses the structure of fuzzy PI controller and proved theoretically that a fuzzy PI controller, the smallest possible with two inputs (error and rate change of error) and four rules is precisely equivalent to a conventional linear PI controller if a linear defuzzification algorithm is employed. But it do not supply more about when the system is not a smallest possible fuzzy system [4)]. In recent years there have been considerable developments in the tuning of parameters in fuzzy control system like training of fuzzy logic systems using artificial neural networks-the so-called back-propagation algorithm [9)]. Because the fuzzy logic system is nonlinear in its adjustable parameters, the back-propagation algorithm implements a nonlinear gradient optimization procedure and can be trapped at a local minimum and convergence [12)]. When sample data may be expensive to obtain, fuzzy logic system can be trained by nearest neighborhood, but it is time-consuming to take hundreds of learning epochs to train so many parameters [13)]. It is urgent that from both theoretical and practical points of view to explore a systematic design procedure following which a fuzzy controller with reasonably good performance can be quickly constructed.

It is said that a modern paradigm for a computer-aided control design should provide an environment that accepts the following challenges [11)]:

- Complexity of practical system;
- Required high quality and accuracy of design;
- Speed of design;
- Competition with available design tools; and
- Robustness, reliability and safety arising from the de-

* Doctor Program in Advanced Engineering System, University of Tsukuba, Tsukuba-shi, Ibaraki
** Institute of Engineering Mechanics and Systems, University of Tsukuba, Tsukuba-shi, Ibaraki

sign.

Challenging for these points, a new kind of methodologies for design and tuning the fuzzy controller is presented in this paper. Control surface is used to bridge the gap between the conventional linear controller and fuzzy controller. Firstly the conventional linear control parameters are tuned and then its linear control surface is used as the knowledge base of a fuzzy controller. A practical parameters tuning method of fuzzy control is also proposed which is carried out by computer. The tuned control surface of fuzzy control behaved non-linearity property which is corresponding to the controlled plant. The design principle is described in section 2 and a design example of a non-linear system presented in section 3.

2. Fuzzy Control Design

Like the conventional control which has two-term (PD and PI) and three-term (PID) control, the fuzzy control also has two-term and three-term fuzzy control. Because three-term fuzzy controller requires a large number of rules in order to establish a complete control surface, two-term fuzzy controller is used to complete the control signals which are fuzzy PI control and fuzzy PD control. The difference between them is the shape of fuzzy rule. For PI control, the general rule is "*if e is A and is B then u is C*". For PD control, the general rule is "*if e is A and is B then* Δu *is C*". These two type fuzzy control are corresponding to conventional PI and PD control respectively [3]. In this paper the interesting is focused on fuzzy PD controller, because it yields quick response with less oscillation. The architecture of a fuzzy PD controller is the same as conventional PD controller that is to generate a control input based upon the error/output information resulting from feedback.

In view of the modular structure an FLC is composed of three basic parts:

1. Input signal fuzzification that transfer the values of input variables into fuzzy information;

2. A fuzzy engine that handles rule inference; and

3. Defuzzification that generates continuous signals for actuators such as control values.

The process of design the FLC can be divided to two stages: knowledge base design and FLC tuning. A knowledge base of a FLC is composed of two components, a data base and fuzzy control rule base. The later is the fuzzy inference rules. The data base include:

1. The actual range of universe of discourse for each decision variable. That is the scaling factor;

2. Number of fuzzy sets for each decision variable; and

3. Membership function which contains the fuzzification and defuzzification function.

From fig.1 we can see that to design a fuzzy controller there are many parameters should be adjusted, for a given plant it is difficult to construct a suitable knowledge base by human experience. In view of the control surface, the conventional PD controller which behaves a linear control surface can be thought as a special case of fuzzy PD controller and it is easy to be adjusted, because it only have two adjusted parameters. If a control surface of a fuzzy PD control is defined as the same surface of tuned conventional control, this fuzzy PD controller will have the same merit as this conventional PD control. That is this linear control surface can be used as the knowledge base of the fuzzy PD controller. The designing and tuning the fuzzy PD controller can be started from designing and tuning conventional PD controller. And the design process of the fuzzy PD controller can be divided to shape the control surface and its adjusted.

2.1 The control surface analysis

Fuzzy PD controllers are non-linear systems which implement a non-linear law between control inputs and control outputs [5]. The non-linear control law is characterized by a hyper surface in the product space of controller inputs and controller outputs. But if we choose the suitable parameters, the fuzzy control surface can be a linear surface as conventional PD controller. In order to find the relationship of the control surface between the con-

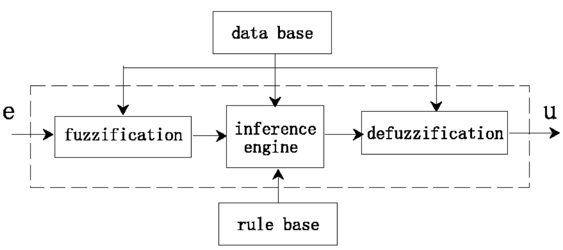


Fig. 1 The structure of fuzzy controller.

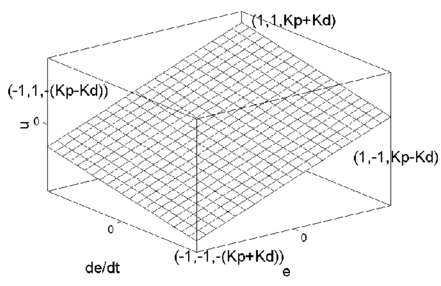


Fig. 2 The conventional PD control surface.

ventional PD controller and a fuzzy PD controller it is necessary to analyze the control surface property of the controller.

2.1.1 The conventional PD control surface

A conventional PD control algorithm is expressed as:

$$u = k_p\,e + k_d\,\dot{e} \tag{1}$$

After tuning the k_p and k_d to for a given plant by computer paradigm. A control surface with x, y and z (x example input e, y example input $\dot{e}$ and z example output u) expressed as:

$$k_p\,x + k_d\,y - z = 0 \tag{2}$$

Its control surface is a linear surface as fig.2.

2.1.2 Fuzzy PD control surface

As stated before, fuzzy PD control surface is a non-linear surface. But if suitable parameters are chosen which include two inputs partitioned into uniformly distributed fuzzy regions, a linear-like fuzzy control surface can be generated by linearly defined control rules with simplified inference method[10),15),16)]. Such a controller is named Linear-like Fuzzy Logic Controller. A linear-like fuzzy PD control is defined as following:

1. The actual range of universe of discourse for each of two decision variable is $[-L_1,L_1]$,$[-L_2,L_2]$ respectively;

2. For each decision variable the fuzzy sets is 2n+1 that is (mf_{-n}, $mf_{-(n-1)}$, ... , mf_{-1}, mf_0, mf_1, ... , $mf_{(n-1)}$, mf_n);

3. The membership function of fuzzification is as fig.3 ($L = L_1$ or L_2), the apex of each triangular membership function is ($-L$, $\frac{-(n-1)}{n}\,L$,...$\frac{-1}{n}\,L$, 0, $\frac{1}{n}\,L$,...$\frac{(n-1)}{n}\,L$, L); and

4. The simplified inference method is used and the $(2n+1)^2$ fuzzy rules are defined as following:

1.) if e is mf_{-n} and $\dot{e}$ is mf_{-n} then u is $-R$;

2.) if e is $mf_{-(n-1)}$ and $\dot{e}$ is mf_{-n} then u is $-R+\frac{R-S}{2n}$;

...... ;

2n.) if e is $mf_{(n-1)}$ and $\dot{e}$ is mf_{-n} then u is $-R+(2n-1)\frac{R-S}{2n}$;

2n+1.) if e is mf_n and $\dot{e}$ is mf_{-n} then u is $-S$;

2n+2.) if e is mf_{-n} and $\dot{e}$ is $mf_{(n-1)}$ then u is $-R+\frac{R+S}{2n}$;

...... ;

2(2n+1).) if e is mf_n and $\dot{e}$ is $mf_{(n-1)}$ then u is $S+\frac{R+S}{2n}$;

...... ;

...... ;

$(2n+1)^2$.) if e is mf_n and $\dot{e}$ is mf_n thun u is R.

The surface equation is:

$$\frac{R-S}{2L_1}\,x + \frac{R+S}{2L_2}\,y - z = 0 \tag{3}$$

if

$$R = L_1\,k_p + L_2\,k_d \tag{4}$$

$$S = L_2\,k_d - L_1\,k_p \tag{5}$$

The control surface of fuzzy PD controller shown as fig.4. If L1 and L2 are large enough, a fuzzy PD controller can be easily acquired which has the same control surface as the tuned conventional PD controller. This linearity surface is used as the knowledge base of fuzzy PD controller.

2.2 The tuning of fuzzy PD controller

The non-linearity of the control surface should correspond to the plant characteristics in order to ensure a desirable controller response. Two sources of non-linearity can be distinguished in a fuzzy controller. Firstly, there is the non-linear relation described by the fuzzy rules. Secondly, additional non-linearity is introduced by the inference mechanism depending on the particular choice of membership functions, aggregation, implication and the defuzzification operators. If the simplified inference method is used, the non-linearity property tuning of fuzzy PD controller is focused on tuning the antecedent membership function and consequent value.

Tuning the parameters of fuzzy controller is a non-linear optimistic problem. It is said the Sequential Quadratic Programming(SQP) methods represent state-of-the-art in non-linear programming methods. A non-linearly constrained problem can often be solved in fewer iterations

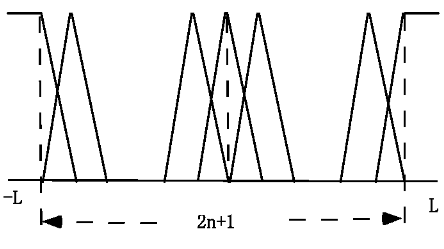


Fig. 3 The fuzzification membership function of Linear- like Fuzzy Logic Controller.

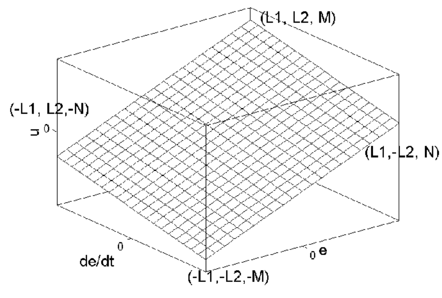


Fig. 4 Linear-like fuzzy control surface.

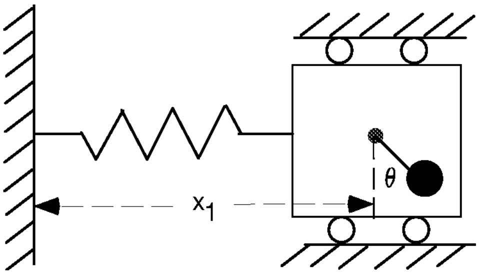


Fig. 5 TORA system configuration.

using SQP than an unconstrained problem. One of the reasons for this is that, due to the limits on the feasible area, the optimizer can make well informed decisions regarding directions of search and step length [14].

On the basis of fuzzy rules and scaling factors which behave a line surface, using SQP the parameters of fuzzy controller is tuned by computer using MATLAB tool at the same time [6), 7)].

3. A Design Example

As a design example, we consider the problem of controlling translational oscillations with a rotational actuator(TORA) [8]. The problem is of interest as a case study in nonlinear controller design because the model exhibits nonlinear interaction between the translational and rotational motions. The structure of the TORA system depicted in Fig.5.

It consists of a platform that can oscillate without damping in the horizontal plane. On the platform a rotating eccentric mass is actuated by a DC motor. Its motion applies a force to the platform which can be used to damp the translational oscillations. Assuming that the motor torque is the control variable, our task is to design a control system to asymptotically stabilize the system at the equilibrium as soon as possible from its different initial conditions.

Let x_1 be the normalized displacement of the platform from the equilibrium position, $x_2 = \dot{x_1}$, $x_3 = \theta$ be the angle of the rotor, and $x_4 = \dot{x_3}$. The dynamics of the system are described by

$$\dot{X} = f(x) + g(x)\,u + q(x)\,d \tag{6}$$

where u is the torque applied to the eccentric mass and d is a disturbance. The vectors f, g, q are given by:

$$F() = \begin{bmatrix} x_2 \\ \frac{-x_1+\varepsilon\, x_4^2 \sin x_3}{1-\varepsilon^2\, \cos^2 x_3} \\ \frac{\varepsilon\, \cos x_3 (x_1 - \varepsilon\, x_4^2 \sin x_3)}{1-\varepsilon^2\, \cos^2 x_3} \end{bmatrix} \tag{7}$$

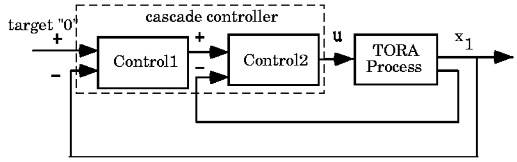


Fig. 6 The cascade TORA control system.

$$G(x) = \begin{bmatrix} 0 \\ \frac{-\varepsilon\, \cos x_3}{1-\varepsilon^2\, \cos^2 x_3} \\ \frac{1}{1-\varepsilon^2\, \cos^2 x_3} \end{bmatrix} \tag{8}$$

$$Q(x) = \begin{bmatrix} 0 \\ \frac{1}{1-\varepsilon^2\, \cos^2 x_3} \\ \frac{-\varepsilon\, \cos x_3}{1-\varepsilon^2\, \cos^2 x_3} \end{bmatrix} \tag{9}$$

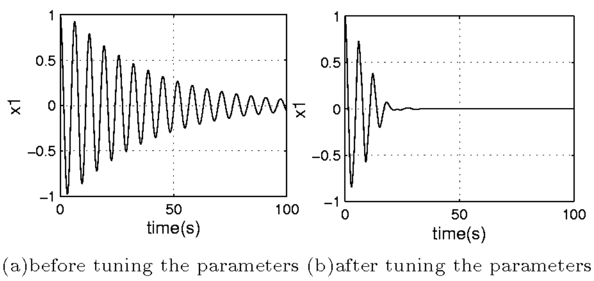
where ε is a constant parameter which depends on the rotor, platform and eccentricity(usually $\varepsilon = 0.1$).

The first step to design the fuzzy controller is to choose the controlled parameters. According to the property of the TORA control system, x_1 and x_3 should be as two of the control parameters. Because one fuzzy PD controller with two input only accept one control parameter, a cascade control system composed by two controllers is proposed shown as fig.6.

The cascade TORA control system design process are stated as following:

(1) Turning the parameters of conventional PD controller.

At first, the cascade control system is composed two conventional PD controllers. There are only four parameters should be tuned k_{p1},k_{d1},k_{p2} and k_{d2}. Based on the linearity TORA system, the parameters of the conventional PD controller are k_{p1}=0.5, k_{d1}=0.5, k_{p2}=-0.5 and k_{d2}=-0.5, when TORA in its initial variable $x_1(0)$=1.0 tune the four parameters using SQP by computer(Intel Pentium 200MHZ) because it is also a constrained minimization optimistic problem. After 55 seconds, we get following results: k_{p1}=1.45, k_{d1}=-1.32, k_{p2}=-0.88 and k_{d2}=-0.79. The simulation of control result before tuning and



(a)before tuning the parameters (b)after tuning the parameters

Fig. 7 The result of conventional PD controller before and after tuning the parameters ε=0.1,$x_1(0)$=1.0.

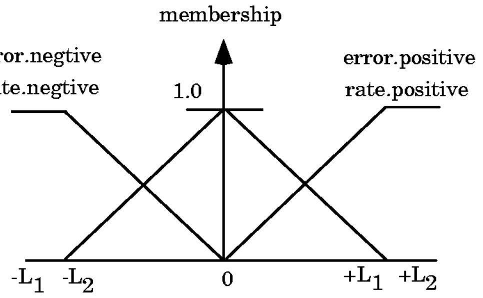


Fig. 8 The membership function of a linearity fuzzy PD controller with 3*3 partitions.

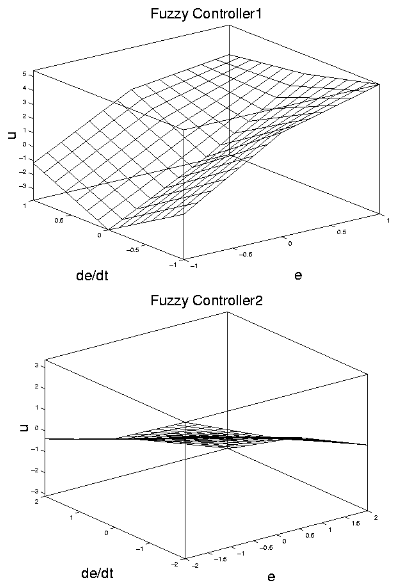
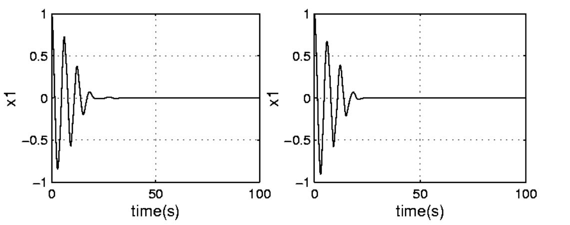


Fig. 9 The tuned control surface of two fuzzy PD controllers.



(a)before tuning the parameters (b)after tuning the parameters

Fig. 10 The control result of fuzzy PD controller ε=0.1, $x_1(0)$=1.0.

after tuning are shown as fig.7.

(2) Fuzzy PD controller design.

Change two of the controllers by two fuzzy PD controllers. Each controller is with 3*3 partitions. Based on equation (4) and (5), for FLC1 let L_1=L_2=2, and for FLC2 letL_1=L_2=1.3, the membership function is fig.8.

The left picture of fig.10 shows that when the parameters of fuzzy PD controller are chosen according to the method of section 2, it has the same function as PD con-

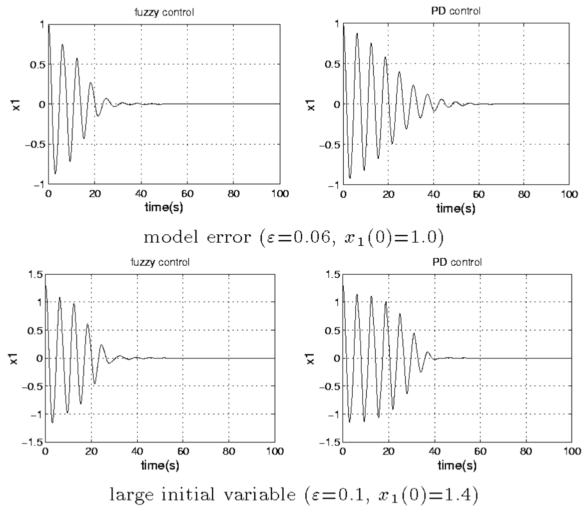


Fig. 11 Compare the control result of two type control systems.

troller. Then tuning the parameters of two fuzzy controllers with the antecedent membership function and consequent value in the same situation, there are 20 parameters tuned. After 2 minutes and 40 seconds two control surface behave nonlinearity shown in fig.9 and its control result is in fig.10. The right picture of fig.10 shows its control result after tuning.

(3) Compare the control result of conventional and fuzzy PD control system.

From fig7 and fig.10, both the conventional PD control and fuzzy PD control get the steady result after 20 seconds. It seems there is no difference between the two type controllers. To compare the property of these two type controllers, two situation are considered which are when there is a model error (ε=0.6)and x_1 has large initial condition($x_1(0)$=1.4) the simulation results of conventional and fuzzy PD control system are shown in fig.11. When there is a model error, the TORA get its desired equilibrium after 30 seconds by fuzzy control and after 50 seconds by conventional linear control. When x_1 has large initial condition, the TORA get its desired equilibrium after 30 seconds by fuzzy control and after 40 seconds by conventional linear control. These results show that the cascade fuzzy control system behaves more robust property than the cascade conventional control system especially when there is a model error and in the different initial condition.

4. Conclusion

In this paper a new type of practical methodology for design fuzzy controller are proposed which avoids a painstaking parameters design for a knowledge base. Due to the fact that the problem of fuzzy control system design is equivalent to a multi-dimensional, multi-modal, multi-objective optimum problem, the proposed method provides a practical and effective way and it is easy for practising engineers to use. Although it can not ensure that the designed fuzzy controller is the best one for the controlled plant, it is better than a conventional linear controller. According to the control surface analysis, the conventional linear controller can be thought as a special fuzzy controller which explain the reason why the fuzzy control has a better control characteristics than a conventional linear controller. The methodology meet the challenges required for a computer-aided control design.

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Yongli Huang (Member)

Born on January 11.1996. Received the B.E.degree and M.E.degree in Automatic Engineering from TaiYuan University of Technology, China in 1987 and 1990, respectively. She was a Lecture at TaiYuan University of Technology from 1990 to 1996. From Oct.1996 to Mar.1998, she was a visiting scholar at the University of Tsukuba. Presently a Ph.D student at the University of Tsukuba. Current research area is Fuzzy Control Applications to nonlinear system. Member of SOFT.

Seiji Yasunobu (Member)

Born on March 28.1951. Received the B.E.degree and M.E.degree in Instrumental Engineering from Koube University in 1973 and 1975, respectively. Worked in Hitachi Corporation from 1975 to 1992. Now he is professor of Department of Mechanical Engineering and System in the University of Tsukuba. He received the Japan Science and Technology Award in 1992. His research interests include intelligent control, fuzzy and GA computing technique. Doctor of Engineering. Member of SOFT, IEE, and IEEE.

問い合わせ先

〒 305-8573 茨城県つくば市天王台 1-1-1
筑波大学機能工学系安信研究室
黄　永利
TEL (0298)53-6186
FAX (0298)53-5207
E-mail: huang@esys.tsukuba.ac.jp