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Design of Sliding Mode Fuzzy-Model-Based Controller Using Genetic Algorithms

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Abstract

This paper addresses the design of sliding mode fuzzy-model-based controller using genetic algorithms. In general, the construction of fuzzy logic controllers has difficulties for the lack of systematic design procedure. To release this difficulties, the sliding mode fuzzy-model-based controllers was presented by authors. In the proposed method, the fuzzy model, which represents the local dynamic behavior of the given nonlinear system, is utilized to construct the controller. The overall controller consists of the local compensators which compensate the local dynamic linear model and the feed-forward controller which is designed via sliding mode control theory. Although, the stability and the performance is guaranteed by the proposed method, some design parameters have to be chosen by the designer manually. This problem can be solved by using genetic algorithms. The proposed method tunes the parameters of the controller, by which the reasonable accuracy and the control effort is achieved. The validity and the efficiency of the proposed method are verified through simulations.

Key Words : Fuzzy-model-based controller, sliding-mode control, genetic algorithms

1. Introduction

During the past several years, fuzzy logic control has become one of the most useful approaches for utilizing the qualitative knowledge of a system to design a controller. Fuzzy logic control is generally applicable to plants that are mathematically poorly modeled and where the qualitative knowledge of experienced operators is available for qualitative control. In other words, fuzzy logic controller is particularly suitable for systems whose dynamics are uncertain or complex. Design approaches of fuzzy logic controllers may be divided into two categories: One is model-free and the other is model-based. The specific design of a fuzzy logic controller, however, has difficulties in the acquisition of experts knowledge and relies to a great extent on empirical and heuristic knowledge which, in many cases, cannot be justified. Therefore, the performance of the controllers can be degraded in the case of plant parameter variations or unpredictable incidents which a designer may have ignored. Moreover, the parameters of fuzzy logic controllers obtained by experts control action may not be optimal. To overcome these difficulties in recent years, many researchers have devoted their efforts to the development of systematic analysis and design procedure for fuzzy control systems [1-2, 4].

In 1985, Takagi and Sugeno proposed a new kind of fuzzy inference system, called the Takagi Sugeno (TS) fuzzy model today. It can combine the flexibility of fuzzy logic theory and the rigorous mathematical analysis tools into a unified framework. Since it employs linear functions in the consequent parts, it is convenient to apply the conventional linear systems theory for analysis. Based on the TS fuzzy model, various kinds of TS fuzzy model based controllers have been suggested. For example, Takagi and Sugeno [1] represents a nonlinear system as a combination of linear functions of inputs and then applied their method to the control of water cleaning process and steel-making process. Cao et al. [11] applied modern control theory for analysis and design of some general fuzzy model based controllers. Tanaka and Kosaki [13] implemented a fuzzy model based controller for an articulated vehicle and performed stability analysis. In these methods, sets of fuzzy rules are used to construct suitable local linear state models from which local controllers can be determined. The stability of the overall system is then determined by a Lyapunov stability analysis. These kinds of design approaches suffer mainly from a few limitations: (1) A common positive definite matrix must be found to satisfy the Lyapunov equation, which can be difficult especially when the number of fuzzy rules required to give a good plant model is large. (2) The performance of the closed-loop system is difficult to predict. (3) The stability is guaranteed only for those simplified TS fuzzy models although they have successfully applied to the original underlying nonlinear systems. (4) Tracking problem is not explicitly addressed. (5) If the original nonlinear system is partially known, then it is difficult, if not impossible, to determine the stability of the overall fuzzy system. Although LMI based approaches have been used to determine the existence of a common

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positive definite matrix [8, 13, 15], other problems still remain unresolved. In the analyis

On the other hand, it is well known that sliding mode control (or variable structure control) can provide very robust performance [18]. There have been quite a lot of research on the combination of sliding model control and fuzzy control in order to improve the robustness and performance of the fuzzy logic controllers [19-20]. These approaches generally focused on the design of sliding surface via fuzzy logic theory.

Along this line of approach, the author have developed a new kind of fuzzy-model-based controller combined with sliding mode control theory to improve the tracking performance and stability of the conventional fuzzy-model-based controller. It has been shown that the performance and the stability of the proposed method can be effectively verified via some rigorous mathematical proofs. However, some parameters of the resulting fuzzy controller should be finely tuned for better performance the overall closed-loop system, and the conventional mathematical design procedure sometimes fails to determine the values of the parameters for the required performance.

Genetic algorithms (GAs), on the other hand, have shown to be flexible and robust optimization tools for many nonlinear optimization problems, where the relationship between adjustable parameters and the resulting objective function is assumed to exist but mathematical relationship is not clear. Thus, the aforementioned design problem is effectively solvable by GAs if the design problem can be converted to an appropriate nonlinear optimization problem.

In the present paper, we propose a GA-based controller design technique for the control of complex continuous-time nonlinear systems with the fuzzy-model-based controllers aided by sliding mode control theory. The design procedure is composed of two stages; first, the coarsely tuned parameters of the sliding-mode fuzzy-model-based controller is determined by the conventional mathematical design procedure. Then, the controller parameters are finely tuned by converting the design problem to the nonlinear optimization problem, to which GAs are applied.

Using the proposed method, one can design a globally stable fuzzy logic controller with good stabilizing and tracking performances simultaneously. Moreover, it guarantees the stability of the original nonlinear system. Simulation examples have been performed to show the effectiveness and feasibility of the proposed fuzzy control method.

2. The TS Fuzzy Model

Consider a class of SISO nonlinear dynamic system :

$$x^{(n)} = f(\mathbf{x}) + g(\mathbf{x})u \qquad (1)$$

where, the scalar x is the output state variable of interest, scalar u is the system control input, and $\mathbf{x}=[x\ \dot{x}\ \dots\ x^{(n-1)}]^T$ is the state vector. In equation (1), $f(\mathbf{x})$ is a known nonlinear continuous function of $\mathbf{x}$, and the control gain $g(\mathbf{x})$ is a known nonlinear continuous and locally invertible function of $\mathbf{x}$. This SISO nonlinear system can be approximated by the TS fuzzy model, proposed in [1], which combines the fuzzy inference rules and local linear state models [2-5]. The ith rule of the TS fuzzy model, representing the complex SISO system (1), is the following:

Plant rule i :

IF x(t) is F_1^i and ... and $x^{(n-1)}$ is F_n^i

$$\text{THEN } \dot{\mathbf{x}} = A_i\mathbf{x}(t) + B_i u(t) \qquad (2)$$
$$(i = 1, 2, \dots, q)$$

where, Rule i denotes ith fuzzy inference rule, F_j^i $(j=1,2,\dots,n)$ are fuzzy sets, $\mathbf{x}(t)\in R^n$ is the state vector, $u(t)\in R^1$ is the control vector, and $A_i\in R^{n\times n}$, $B_i\in R^{n\times 1}$, and q is the number of fuzzy rules.

By using the fuzzy inference method with a singleton fuzzifier, product inference, and center average defuzzifier, the dynamic fuzzy model (2) can be expressed as the following global model:

$$\dot{\mathbf{x}}(t) = \frac{\sum_{i=1}^{q} w_i(\mathbf{x}(t))(A_i\mathbf{x}(t)+B_i u(t))}{\sum_{i=1}^{q} w_i(\mathbf{x}(t))} = A(\mu(\mathbf{x}(t)))x(t) + B(\mu(\mathbf{x}(t)))u(t) \qquad (3)$$

where,

$$w_i(\mathbf{x}(t)) = \prod_{j=1}^{n} F_j^i(\mathbf{x}^{(j-1)}(t))$$
$$\mu_i(\mathbf{x}(t)) = \frac{w_i(\mathbf{x}(t))}{\sum_{i=1}^{q} w_i(\mathbf{x}(t))}$$
$$\mu(\mathbf{x}(t)) = (\mu_1(\mathbf{x}(t)),\dots,\mu_n(\mathbf{x}(t)))$$
$$A(\mu(\mathbf{x}(t))) = \sum_{i=1}^{q}\mu_i(\mathbf{x}(t))A_i$$
$$B(\mu(\mathbf{x}(t))) = \sum_{i=1}^{q}\mu_i(\mathbf{x}(t))B_i$$

and, $F_j^i(x^{(j-1)}(t))$ is the grade of the membership of $x^{(j-1)}(t)$ in F_j^i.

3. GA-based design of sliding-mode fuzzy-model-based controllers

3.1 Sliding-mode fuzzy-model-based controller

The control problem is to design a controller u to drive the state vector x to track a specific trajectory, $x_d=[x_d\ \dot{x}_d \cdots x_d^{(n-1)}]^T$. In order to control the given nonlinear system (1) based on the TS fuzzy model (2), we adopt and extend the concept of PDC [2] to design a TS fuzzy-model-based controller. The basic idea of PDC is to design a compensator for each rule of the TS fuzzy model (2). This PDC, however, requires finding a common positive definite matrix to guarantee the stability of the overall closed-loop system and this stability condition can be applied only to the approximate TS fuzzy model. In addition, it cannot deal with the tracking problem. Therefore, the author proposed a new type of fuzzy-model-based controllers to resolve such problems [28].

Controller Rule i :

IF x(t) is F_1^i and ... and $x^{(n-1)}(t)$ is F_n^i,

$$\text{THEN } u(t) = -K_i\,\mathbf{x}(t) + u_f(t) \qquad (4)$$
$$(i = 1, 2, ..., r)$$

The first term $-K_i\,\mathbf{x}(t)$ of $u(t)$ is the same as the conventional PDC, and the second term $u_f(t)$ is introduced as supervisory control to guarantee global system stability. Equation (4) can be rewritten as

$$\begin{aligned} u(t) &= \frac{\sum_{i=1}^{q} w_i(-K_i\,\mathbf{x}(t) + u_f(t))}{\sum_{i=1}^{q} w_i} \\ &= -\sum_{i=1}^{q} \mu_i K_i\,\mathbf{x}(t) + \sum_{i=1}^{q} \mu_i u_f(t) \qquad (5) \\ &= -K(\mu)\,\mathbf{x}(t) + u_f(t) \end{aligned}$$

where, $\mu_i = w_i / \sum_{i=1}^{r} w_i$ and $K(\mu) = \sum_{i=1}^{q} \mu_i K_i$. The closed-loop system is obtained from the feedback interconnection of the nonlinear system (1) and the controller (6), as

$$x^{(n)}(t) = F(\mathbf{x}(t)) + g(\mathbf{x}(t))u_f(t) \qquad (6)$$

where,

$$F(\mathbf{x}(t)) = f(\mathbf{x}(t)) - g(\mathbf{x}(t))K(\mu)\,\mathbf{x}(t)$$

The scalar input $u_f(t)$, which is introduced to guarantee system stability, is determined based on the well known sliding mode control theory [8] as follows.

Let $\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_d$ be the tracking error and let

$$\tilde{\mathbf{x}} = \mathbf{x} - \mathbf{x}_d = [\,\tilde{x} \ldots \tilde{x}^{(n-1)}]^T \qquad (7)$$

In order to incorporate the sliding mode control technique into the fuzzy-model-based controller, we first define a time-varying surface, $S(t)$, in the state space by imposing the scalar equation $s(\mathbf{x};t) = 0$, with

$$\begin{aligned} s(\mathbf{x};t) &= \left(\frac{d}{dt} + \lambda\right)^{(n-1)} \tilde{x} \\ &= \tilde{x}^{(n-1)} + a_1\,\tilde{x}^{(n-2)} + \ldots + a_{n-1}\,\tilde{x} \end{aligned} \qquad (8)$$

where, λ is a strictly positive constant.

Given an initial condition, the problem of tracking x_d reduces to that of keeping the scalar function s at zero. More precisely, the nth order tracking problem in x can be replaced by first order stabilization problem in s.

The simplified first order problem of keeping the scalar s at zero can now be achieved by choosing the control law such that

$$\frac{d}{dt} s^T s \le -\eta |s| \text{ outside of } S(t) \qquad (9)$$

Differentiating $s(\mathbf{x};t)$ with respect to time and using (6), we obtain

$$\begin{aligned} \dot{s} &= \overline{F}(\mathbf{x}) + g(\mathbf{x})u_f(t) \\ \overline{F}(\mathbf{x}) &= F(\mathbf{x}) - x_d^{(n)} + \tilde{x}^{(n-1)} \\ &\quad + a_1\,\tilde{x}^{(n-2)} + \ldots + a_{n-1}\,\tilde{x} \end{aligned} \qquad (10)$$

Having designed the sliding mode control via the design of switching functions, the next step is to design the reaching mode and the overall control law. This gives not only the desired sliding mode but also the desired system dynamics in the reaching mode. The main requirement in this design is that the control law should satisfy the reaching condition, which, in turn, guarantees the existence of the sliding mode on the switching manifold. For this purpose, we adopt the reaching law method [10]. A general form of the reaching law is

$$\begin{aligned} \dot{s} &= -Qsgn(s) - Kh(s) \\ sgn(s) &= \begin{cases} 1 & \text{if } s \ge 0 \\ -1 & \text{if } s < 0 \end{cases} \end{aligned} \qquad (11)$$

where, Q and K are strictly positive constants, $sh(s) > 0$ for all $s \ne 0$, and $h(0) = 0$.

Having selected the reaching law equation (11), the control law can be determined by equating (10) and (11):

$$\dot{s} = \overline{F}(\mathbf{x}) + g(\mathbf{x})u_f(t) = -Qsgn(s) - Kh(s) \qquad (12)$$

This equation is solved for the sliding mode control law, yielding

$$u_f(t) = -g(\mathbf{x})^{-1}(\overline{F}(\mathbf{x}) + Qsgn(s) + Kh(s)) \qquad (13)$$

Consequently, the sliding condition (9) is satisfied:

$$\frac{d}{dt} s^T s = -2s^T Qsgn(s) - 2sKh(s) < 2Q|s| < 0$$

Therefore, the closed-loop fuzzy control system (6) is asymptotically stable.

3.2 Optimization of the sliding-mode fuzzy-model-based controller using GAs

In the procedure in Section 3.2, the design parameters are sub-linear compensators K_i (i = 1, 2, ..., q), λ>0, Q>0, K>0, which are used to determine the sliding surface of the controller. The compensator gains K_i can be almost automatically obtained by using various kinds of design technologies such as linear matrix inequalities (LMIs) and algebraic Riccati equations (AREs). The remaining parameters are related to the sliding mode control part, whose values are determined empirically.

GA is an iterative adaptive general purpose search strategy based on the principle of natural selection. GAs explore a population of solutions in parallel. Each solution in the population is encoded as a chromosome, and a collection of chromosomes forms a generation. A new generation evolves by performing genetic operations, such as reproduction, crossover and mutation on strings in the current population and then placing the products into the new generation. Reproduction is a process in which individual strings are copied according to their fitness. After the members of the newly reproduced strings in the gene pool are mated at random, offsprings are constructed by copying the portion of parent strings designated by random crossover points with a crossover probability. As each bit is copied from parent to offspring, the bit has the probability of mutation, another GA operation for changing populations.

In this paper, we apply GAs to determine the parameters of the sliding mode control part for the fully automatic design of the sliding-mode fuzzy-model-based controller.

The procedure for the Automatic fuzzy modeling by GA is summarized as follows :

Step 1 : Set the crossover rate P_c, mutation rate P_m, the number of maximum generations G_m, and the population size P_s.

Step 2 : Determine the search space of the parameters K, Q, λ for GAs to be applied.

Step 3 : Generate initial populations $P(N)$, $N=1$, composed of randomly generated binary string codes.

Step 4 : Decode the chromosome of each population and determine the controller. Evaluate the determined fuzzy controller by (15) and assign the fitness value to each individual.

$$f_i = \omega \frac{\max_i(g_i) - g_i}{\max_i(g_i)} + (1-\omega)\frac{\max_i(h_i) - h_i}{\max_i(h_i)} \quad (15)$$

where,

$$g_i = \sqrt{\sum_{k=0}^{M} \frac{(y(kT) - y_d(kT))^2}{M}}$$

$$h_i = \sqrt{\sum_{k=0}^{M} \frac{(u(kT))^2}{M}}$$

and, ω_i is a weighting factor.

Step 5 : Evolve all populations by reproduction, crossover and mutation. Increase generation number by replacing old generation with new generation. During the replacement, preserve the population which has the maximum fitness value by the elitist reproduction.

Step 6 : Repeat Step 4~Step 5 until the satisfactory population appears or the generation number is over the maximum number of generations.

4. Simulation example

In this section, we present two simulation examples to illustrate the effectiveness of the proposed fuzzy controller design method.

Consider the problem of balancing an inverted pendulum on a cart. The dynamic equations of the pendulum are

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{g\sin(x_1) - amlx_2^2\sin(2x_1) - a\cos(x_1)u}{4l/3 - aml\cos^2(x_1)} \end{aligned} \quad (16)$$

where x_1 is the angle in rad of the pendulum from the vertical axis, x_2 the angular velocity in rad s-1, $g=9.8m/s^2$ the acceleration due to gravity, $m=2.0kg$ the mass of the pendulum, $a=(m+M)^{-1}$, $M=8.0kg$ the mass of the cart, $2l=1.0m$ the length of the pendulum, and u the force applied to the cart. Since the dynamic equations of the nonlinear system is available, a TS fuzzy model used to approximate this system can be manually calculated by simple linearization method. The resulting TS fuzzy model is

Plant Rule 1:

IF x_1 is about 0, THEN $\dot{\mathbf{x}} = A_1\mathbf{x} + B_1u$

Plant Rule 2:

IF x_2 is about $\pm\pi/2$, THEN $\dot{\mathbf{x}} = A_2\mathbf{x} + B_2u$

where,

$$A_1 = \begin{bmatrix} 0 & 1 \\ \frac{g}{4l/3 - aml} & 0 \end{bmatrix} \quad B_1 = \begin{bmatrix} 0 \\ -\frac{a}{4l/3 - aml} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 1 \\ \frac{2g}{\phi(4l/3 - aml\beta^2)} & 0 \end{bmatrix} \quad B_2 = \begin{bmatrix} 0 \\ -\frac{a\beta}{4l/3 - aml\beta^2} \end{bmatrix}$$

and, $\beta=\cos(88^\circ)$. The membership functions for Rule 1 and Rule 2 are shown in Fig. 1.

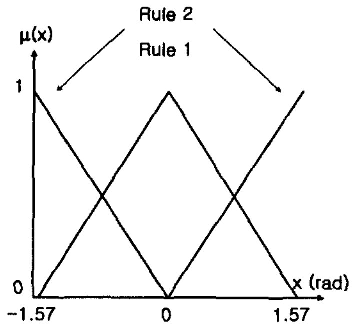


Fig. 1. Membership functions

In order to determine the parameters of the controller, we simply choose the closed-loop eigenvalues -2 and -2 for both $A_1 - B_1K_1$ and $A_2 - B_2K_2$. Then, we obtain

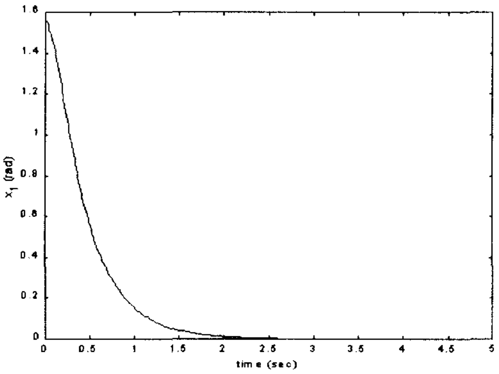
$$K_1 = [-120.6667 \quad -22.6667]$$

$$K_2 = [-2551.6 \quad -764.0]$$

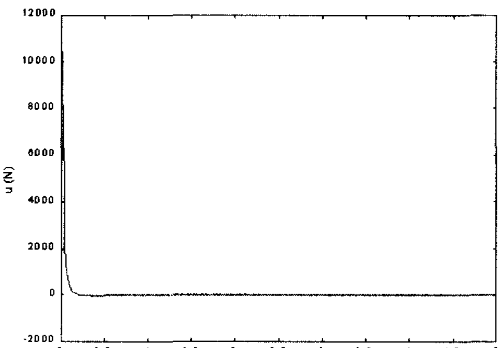
Initial parameters for running the GA-based design procedure are as follows. Maximum generation number G_m is 30, population size P_s is 20. During the population evolving, crossover rate P_c is 1.0, mutation rate P_m is 0.1, and the lenght of the string of the chromosome is 20. The search spaces of the design parameters λ, Q, K are $\lambda \in [0\ 50]$, $Q \in [0\ 5]$, and $K \in [0\ 100]$, respectively.

After whole design processes, we obtain the values of the design parameters as (λ, Q, K) = (2.6310, 2.4816, 6.7405). Figure 2 shows the simulation results with the GA-based sliding-mode fuzzy-model-based controller.

The control problem is to stabilize the system with the initial condition $\mathbf{x}(0) = [89\pi/180\ 0]^T$, of which assumption is that the pendulum is horizontally laid down. This control problem is physically impossible with realistic input constraints. However, we emphasize that this situation is selected to show the effectiveness of the proposed method in most extreme case. Fig. 2 (a) and (b) show the responses of the state x_1 and the control input u, respectively.



(a)



(b)

Fig. 2. (a) The responses of the conventional fuzzy-model-based controller (dashed line) and the proposed method (solid line) for the initial condition $\mathbf{x}(0) = [89\pi/180\ 0]^T$

(b) The control inputs of the conventional fuzzy-model-based controller (dashed line) and the proposed method (solid line) for the initial condition $\mathbf{x}(0) = [89\pi/180\ 0]^T$

The simulation results show that the proposed controller can stabilize the nonlinear system although the proposed design procedure is based on the TS fuzzy model instead of the original nonlinear plant. Furthermore, the maximum control input by the proposed method does not exceed 1.2×10^3, while that of the conventional method [28] exceeds 3.5×10^4, which shows that the proposed method is appropriate for the practical application of the designed controller.

5. Conclusion

In this paper, the design of sliding mode fuzzy-model-based controller using genetic algorithms has been proposed. In general, the construction of fuzzy logic controllers has difficulties for the lack of systematic design procedure. In the proposed method, the fuzzy model, which represents the local dynamic behavior of the given nonlinear system, is first constructed and used to design the controller. The overall controller consists of the local compensators which compensate the local dynamic linear model and the feed-forward controller which is designed via sliding mode control theory. Although the stability and the performance is guaranteed by the proposed method, some design parameters have to be chosen by the designer manually. This problem can be solved by using genetic algorithms. The proposed method tunes the parameters of the controller, by which the reasonable accuracy and the control effort is achieved. The validity and the efficiency of the proposed method are verified through simulations.

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