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On the Design of Simple-structured Adaptive Fuzzy Logic Controllers

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Abstract

One of the methods to simplify the design process for a fuzzy logic controller (FLC) is to reduce the number of variables representing the rule antecedent. This in turn decreases the number of control rules, membership functions, and scaling factors. For this purpose, we designed a single-input FLC that uses a sole fuzzy input variable. However, it is still deficient in the capability of adapting some varying operating conditions although it provides a simple method for the design of FLC's. We here design two simple-structured adaptive fuzzy logic controllers (SAFLC's) using the concept of the single-input FLC. Linguistic fuzzy control rules are directly incorporated into the controller by a fuzzy basis function. Thus some parameters of the membership functions characterizing the linguistic terms of the fuzzy control rules can be adjusted by an adaptive law. In our controllers, center values of fuzzy sets are directly adjusted by an adaptive law. Two SAFLC's are designed. One of them uses a Hurwitz error dynamics and the other a switching function of the sliding mode control (SMC). We also prove that 1) their closed-loop systems are globally stable in the sense that all signals involved are bounded and 2) their tracking errors converge to zero asymptotically. We perform computer simulations using a nonlinear plant.

Key words : Fuzzy Logic Control, Adaptation Law, Sliding Mode Control, Lyapunov Function. Hurwitz Polynomial

1. Introduction

Fuzzy logic controllers are useful in situations where 1) there is no acceptable mathematical model for the plant to be controlled and 2) there are experienced human operators who can adequately control the plant by some qualitative control rules. Most FLC's use the error and the change-of-error as antecedent variables of if-then rules regardless of the complexity of the controlled plants. Either control input or incremental control input is typically used as a consequent variable [1]. Such FLC's are suitable for simple lower order plants. All process states are typically required for a good performance of complex higher order plants. Recently Choi et *al.* proposed a single-input FLC that uses a sole input variable consists in all state variables [2]. It gave a useful method to simplify the design process for a proper FLC.

Although the FLC has a kind of adaptability in itself, it still lacks in the case of some complicated situations, where the operating conditions can be subject to change. Wang developed an adaptive fuzzy logic control method that ensures the stability of the overall system using a Lyapunov-based learning law [3]. He presented here a fuzzy basis function that provides a natural framework for combining numerical and linguistic information in a uniform fashion. Despite its advantages it has some drawbacks: it can occur a kind of high control action due to its supervisory control input, and it must adapt itself to every change of the reference signal. Su and Stepanenko introduced a modified version of this approach that incorporates a variable structure controller to keep the system state within defined boundaries [4]. Fischle and Schroder [5] presented some improved stable adaptive fuzzy control methods for resolving some drawbacks existed in [3]. Besides these direct adaptive FLC's, many indirect or hybrid adaptive FLC's also published in the related fields [6-9].

In this paper we design two stable adaptive FLC's equipped with Lyapunov-based adaptation algorithms. Some linguistic fuzzy information from experienced human operators is incorporated into the closed-loop control system through a fuzzy basis function. This is especially useful to the complex systems with high nonlinearities and uncertainties and improves some control performance.

We first explain a simple-structured FLC that uses a sole variable in the antecedent part of the fuzzy control rule [2], and then propose two stable adaptive FLC's that automatically adjust some parameters of the simple-structured FLC. One is designed by using a Hurwitz error dynamics and the other a switching function of the SMC. We perform computer simulations using a nonlinear plant and compare the control performance between the simple-structured FLC and two SAFLC's.

This paper is organized as follows. We simply describe the design strategy for the simple-structured FLC in Section Ⅱ. In Section Ⅲ, two SAFLC's are designed by using a Hurwitz error dynamics and utilizing a switching function of the SMC, respectively. In Sections Ⅳ and Ⅴ, we represent computer

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simulations and general discussions, respectively.

2. Simple-structured FLC

Most FLC's use the error and the change-of-error as antecedent variables of their if-than rules. The control rule tables have a skew-symmetric property in the case of minimum phase plants. This fact allows to design a simple-structured FLC.

Let the controlled process be a system with n-th order (linear or nonlinear) state equation:

$$x^{(n)} = f(\mathrm{x}, t) + b(\mathrm{x}, t)u(t) + d(t), \quad y = x, \tag{1}$$

with

$$\mathrm{x} = [x_1, x_2, \cdots, x_n]^T = [x, \dot{x}, \cdots, x^{(n-1)}]^T,$$

where $f(\mathrm{x}, t)$ and $b(\mathrm{x}, t)$ are partially known continuous functions, $d(t)$ is the unknown external disturbance, and $u(t) \in R$ and $y(t) \in R$ are the input and output of the system, respectively. $\mathrm{x}(t) \in R^n$ is the process state vector.

The control problem is to force $y(t)$ to follow a given bounded reference input signal $x_d(t)$. Let $e(t)$ be the tracking error vector as follows:

$$\mathrm{e}(t) = \mathrm{x}(t) - \mathrm{x_d}(t) = [e, \dot{e}, \cdots, e^{(n-1)}]^T. \tag{2}$$

The rule form for the conventional FLC using two fuzzy input variables of the error and the change-of-error is as follows:

R^{ij}_{old} : If e is LE^i and $\dot{e}$ is LDE^j, then u is LU^{ij}

where $i = 1, 2, \cdots, M$, $j = 1, 2, \cdots, N$, and LE, LDE, and LU are the linguistic values taken by the process state variables e, $\dot{e}$, and u, respectively.

The control rule form for a simple-structured FLC is summarized as follows [2]:

R^k_{new} : If d_s is LDL^k then u is LU^k ,

where $d_s = \frac{\dot{e} + \lambda e}{\sqrt{1+\lambda^2}}$, and LDL^k is the linguistic value of the signed distance in the k-th rule. That is, the rule table can be established on an one-dimensional space like Table 1.

Table 1. Rule table for a simple-structured FLC.

d_s	LDL_{-2}	LDL_{-1}	LDL_0	LDL_1	LDL_2
u	LU_2	LU_1	LU_0	LU_{-1}	LU_{-2}

In Table 1, subscripts -2, -1, 0, 1, and 2 denote fuzzy linguistic values of Negative Big (NB), Negative Small (NS), ZeRo (ZR), Positive Small (PS), and Positive Big (PB), respectively.

This scheme was easily extended to the general case that used more than three variables in the antecedent part of a fuzzy control rule. In this case d_s was replaced by D_s defined as follows [2]:

$$D_s = \frac{e^{(n-1)} + \lambda_{n-1}e^{(n-2)} + \cdots \lambda_2\dot{e} + \lambda_1 e}{\sqrt{1 + \lambda_{n-1}^2 + \cdots \lambda_2^2 + \lambda_1^2}}. \tag{3}$$

3. Simple-structured Adaptive FLC's

A fuzzy IF-THEN rule can directly be expressed by a rigorous mathematical equation. Let LDL^k be a fuzzy set in U, then the fuzzy logic system with the singleton fuzzifier, product inference, and the height defuzzifier is of the following form:

$$u(D_s) = \frac{\sum_{k=1}^{K} \bar{u}^k (\mu_{LDL^k}(D_s))}{\sum_{k=1}^{K} (\mu_{LDL^k}(D_s))} \tag{4}$$

where $\bar{u}^k$ is the point in R at which μ_{LU^k} achieves its maximum value (assume that $\mu_{LU^k}(\bar{u}^k) = 1$), and K is the number of one-dimensional control rules. And the fuzzy basis function (FBF) is summarized as:

$$\xi^k(D_s) = \frac{\mu_{LDL^k}(D_s)}{\sum_{k=1}^{K} (\mu_{LDL^k}(D_s))} \tag{5}$$

Therefore an one-dimensional fuzzy control rule R^k_{new} can be expressed as a rigorous mathematical formula:

$$u(D_s) = \Theta_u^T \Xi_u(D_s), \tag{6}$$

where $\Theta_u = [\bar{u}^1, \bar{u}^2, \cdots, \bar{u}^K]^T$ is an adjustable parameter vector, and $\Xi_u(D_s) = [\xi^1(D_s), \xi^2(D_s), \cdots, \xi^K(D_s)]^T$ is a regressive vector.

The control purpose is to determine a feedback control input

$$u = u_f(D_s|\Theta_u) + u_a \tag{7}$$

such that the tracking error should be as small as possible under some constraints, where u_f is a control law by the simple-structured FLC and u_a is an auxiliary control input to ensure the closed-loop stability.

(1) Design by Hurwitz Error Dynamics :

$$u_1 = u_{f1}(D_s|\Theta_{u1}) + u_{a1}$$

Let $\mathrm{c} = [c_n, c_{n-1}, \cdots, c_1]^T \in R^n$ be a real valued vector such that all roots of the polynomial $h(s) = s^n + c_1 s^{n-1} + \cdots + c_n$ are in the open left-half plane, where s is the Laplace variable.

If the functions f, b, and d are known in the controlled plant (1), then the control law is as follows:

$$u_1^* = b^{-1}(-f - d + x_d^{(n)} - c^T e), \quad (8)$$

where e is the tracking error vector that is given by Eq. (2). Substituting Eq. (8) into Eq. (1), the following error dynamics is obtained.

$$e^{(n)} + c_1 e^{(n-1)} + \cdots + c_n e = 0. \quad (9)$$

Since Eq. (9) is a Hurwitz from the definition of the constant parameter vector c, $\lim_{t\to\infty} e(t) = 0$.

However, we don't know exact information about the functions f, b, and d, except for the sign of $b(x, t)$. Substituting Eq. (7) into Eq. (1) and adding and subtracting bu_1^* in the right hand side, Eq. (1) is summarized as follows:

$$\begin{aligned} x^{(n)} &= f + b(u_{f1} + u_{a1}) + d + bu_1^* - bu_1^* \\ &= b(u_{f1} - u_1^*) + bu_{a1} + x_d^{(n)} - c^T e. \end{aligned} \quad (10)$$

It can also be rewritten as Eq. (11).

$$\dot{e} = Ce + B(u_{f1} - u_1^*) + Bu_{a1}, \quad (11)$$

where

$$C = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ & & \vdots & & \\ -c_n & -c_{n-1} & -c_{n-2} & \cdots & -c_1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ b \end{bmatrix}. \quad (12)$$

Now we define the optimal parameter Θ_{u1}^* and the minimum approximation error related to the control input ε_{u1} as follows:

$$\Theta_{u1}^* = \arg\min_{\Theta_{u1}} [\sup_x |u_{f1}(D_s|\Theta_{u1}) - u_1^*|] \quad (13)$$

and

$$\varepsilon_{u1} = u_{f1}^* - u_1^* \quad (14)$$

where $u_{f1}^* = u_{f1}(D_s|\Theta_{u1}^*)$. Furthermore ε_{u1} will maintain a very small value due to the universal approximating property of the fuzzy logic system [10]. That is,

$$|\varepsilon_{u1}| = |u_{f1}^* - u_1^*| \le \varepsilon, \quad (15)$$

where $\varepsilon > 0$ is a small value. Then the error equation (10) can be rewritten as

$$\begin{aligned} \dot{e} &= Ce + B(u_{f1} - u_{f1}^*) + B\varepsilon_{u1} + Bu_{a1} \\ &= Ce + B\Phi_{u1}^T \Xi_{u1} + B\varepsilon_{u1} + Bu_{a1}. \end{aligned} \quad (16)$$

where $\Phi_{u1} = \Theta_{u1} - \Theta_{u1}^*$ and Ξ_{u1} is the FBF.

Now we replace the $u_{f1}(D_s|\Theta_{u1})$ by a fuzzy logic system (6) and develop an adaptive law to update the parameter vector Θ_{u1}. It is obtained by the followings:

Theorem 1 : Consider a control law (8) and a stable error dynamics (9). If we choose the auxiliary control input u_{a1} as

$$u_{a1} \le -sgn(e^T PB)|\varepsilon_{u1}|, \quad (17)$$

then the proposed system is stable in the sense of the Lyapunov and the parameter adaptation law is given as

$$\dot{\Theta}_{u1} = -sgn(b)\gamma_1 e^T P_n \Xi_{u1}, \quad (18)$$

where P is a positive definite symmetric $n \times n$ matrix that satisfies the Lyapunov equation

$$C^T P + PC = -Q. \quad (19)$$

Here, Q is an arbitrary positive definite matrix. $\gamma_1 > 0$ is a constant that determines a kind of learning rate, and P_n is the last column of P.

Proof : Consider the following Lyapunov function candidate

$$V_1 = \frac{1}{2} e^T Pe + \frac{|b|}{2\gamma_1} \Phi_{u1}^T \Phi_{u1}. \quad (20)$$

Then,

$$\begin{aligned} \dot{V}_1 &= -\frac{1}{2} e^T Qe + e^T PB(\Phi_{u1}^T \Xi_{u1} + \varepsilon_{u1} + u_{a1}) \\ &\quad + \frac{|b|}{\gamma_1} \Phi_{u1}^T \dot{\Phi}_{u1} \\ &= -\frac{1}{2} e^T Qe + \frac{|b|}{\gamma_1} \Phi_{u1}^T (\dot{\Phi}_{u1} + sgn(b)\gamma_1 e^T P_n \Xi_{u1}) \\ &\quad + e^T PB\varepsilon_{u1} + e^T PBu_{a1}. \end{aligned} \quad (21)$$

From Eq. (21) we can get the following parameter adaptation law:

$$\dot{\Phi}_{u1} = -sgn(b)\gamma_1 e^T P_n \Xi_{u1}. \quad (22)$$

Since $\dot{\Phi}_{u1} = \dot{\Theta}_{u1}$, Eq. (22) is equivalent to the adaptation law (18). Also if we choose the auxiliary control input such that the given condition (17) is satisfied, then Eq. (21) is summarized as follows:

$$\dot{V}_1 \le -\frac{1}{2} e^T Qe. \quad (23)$$

Thus, the proposed SAFLC is stable in the sense of the Lyapunov. □

(2) Design by Switching Function of SMC :

$$u_2 = u_{f2}(D_s|\Theta_{u2}) + u_{a2}$$

A method designed above requires some tuning parameters such as c_i $(i = 1, 2, \cdots, n)$, and it makes the design of an adaptive FLC somewhat difficult. So we propose another method. It uses a switching function of the sliding mode control. Then the number of tuning parameters is also reduced.

Consider the following switching function $S_l = 0$ that is used in SMC:

$$\begin{aligned} S_l &= 0 \\ &= e^{(n-1)} + \lambda_{n-1} e^{(n-2)} + \cdots + \lambda_2 \dot{e} + \lambda_1 e. \end{aligned} \quad (24)$$

We first determine the control law u_2^* when the functions f, b, and d of the controlled plant (1) are known. Here two cases must independently be considered: $S_l = 0$ and $S_l \neq 0$.

In the case of $S_l = 0$, the control law is easily determined by the following equation.

$$u_2^* = b^{-1}(-f - d + x_d^{(n)} - \sum_{i=1}^{n-1} \lambda_i e^{(i)}). \tag{25}$$

As $S_l \neq 0$, the control law can be derived from the concept of the SMC. That is, it can be determined by the following sliding condition:

$$S_l \dot{S}_l \leq -\eta |S_l|, \tag{26}$$

where η is a positive constant. From Eq. (24),

$$\begin{aligned} \dot{S}_l &= e^{(n)} + \lambda_{n-1} e^{(n-1)} + \cdots \lambda_1 \dot{e} \\ &= f + bu_2 + d - x_d^{(n)} + \sum_{i=1}^{n-1} \lambda_i e^{(i)}. \end{aligned} \tag{27}$$

Multiplying both sides of Eq. (27) by S_l,

$$\begin{aligned} S_l \dot{S}_l &= S_l \Big(f + bu_2 + d - x_d^{(n)} + \sum_{i=1}^{n-1} \lambda_i e^{(i)} \Big) \\ &= -\eta |S_l|. \end{aligned} \tag{28}$$

From Eq. (28),

$$\begin{aligned} u_2^* &\leq b^{-1}\Big(-f - d + x_d^{(n)} - \sum_{i=1}^{n-1} \lambda_i e^{(i)} - \eta \Big) \quad \text{for } S_l > 0, \\ u_2^* &\geq b^{-1}\Big(-f - d + x_d^{(n)} - \sum_{i=1}^{n-1} \lambda_i e^{(i)} + \eta \Big) \quad \text{for } S_l < 0. \end{aligned} \tag{29}$$

Combining Eq. (25) and (29), we obtain the following closed form for the control law.

$$u_2^* = b^{-1}\Big(-f - d + x_d^{(n)} - \sum_{i=1}^{n-1} \lambda_i e^{(i)} - \rho\, sgn(S_l)\, \eta_m \Big), \tag{30}$$

where $\rho = \begin{cases} 1 & \text{for } S_l \neq 0 \\ 0 & \text{for } S_l = 0 \end{cases}$ and $\eta_m \geq \eta$.

However we don't know exact information about the controlled plant (1) except for the sign of b(x,t). Adding and subtracting bu_2^* in the right side of Eq. (27),

$$\begin{aligned} \dot{S}_l &= f + b(u_{f2} + u_{a2}) + d - x_d^{(n)} + \sum_{i=1}^{n-1} \lambda_i e^{(i)} \\ &\quad + bu_2^* - bu_2^* \\ &= b(u_{f2} - u_2^*) + bu_{a2} - \rho\, sgn(S_l)\, \eta_m. \end{aligned} \tag{31}$$

Consider another optimal parameter Θ_{u2}^* and minimum approximation error related to the control input ε_{u2}:

$$\Theta_{u2}^* = \arg\min_{\Theta_{u2}} [\, \sup_x |u_{f2}(D_s|\Theta_{u2}) - u_2^*| \,], \tag{32}$$

and

$$\varepsilon_{u2} = u_{f2}^* - u_2^*, \tag{33}$$

where $u_{f2}^* = u_{f2}(D_s|\Theta_{u2}^*)$. ε_{u2} also has a very small value due to the universal approximating property of the fuzzy logic system [10]. That is,

$$|\varepsilon_{u2}| = |u_{f2}^* - u_2^*| \leq \varepsilon, \tag{34}$$

where $\varepsilon > 0$ is a small value. And Eq. (31) can be rewritten as

$$\begin{aligned} \dot{S}_l &= b(u_{f2} - u_{f2}^*) + b\varepsilon_{u2} + bu_{a2} - \rho\, sgn(S_l)\, \eta_m \\ &= b\Phi_{u2}^T \Xi_{u2} + b\varepsilon_{u2} + bu_{a2} - \rho\, sgn(S_l)\, \eta_m, \end{aligned} \tag{35}$$

where $\Phi_{u2} = \Theta_{u2} - \Theta_{u2}^*$ and Ξ_{u2} is the FBF.

Now we replace the $u_{f2}(D_s|\Theta_{u2})$ by a fuzzy logic system (6) and develop an adaptive law to update the parameter vector Θ_{u2}.

Theorem 2 : Consider a control law (30) and a switching function (24). If we choose the auxiliary control input u_{a2} as

$$u_{a2} \leq -sgn(bS_l)\, |\varepsilon_{u2}|. \tag{36}$$

then the proposed system is stable in the sense of the Lyapunov and the parameter adaptation law is given as

$$\dot{\Theta}_{u2} = -sgn(b)\, \gamma_2 S_l \Xi_{u2}, \tag{37}$$

where γ_2 is a positive constant that determines a kind of learning rate.

Proof: Consider the following Lyapunov function candidate:

$$V_2 = \frac{1}{2} S_l^2 + \frac{|b|}{2\gamma_2} \Phi_{u2}^T \Phi_{u2}. \tag{38}$$

Then,

$$\begin{aligned} \dot{V}_2 &= S_l (b\varepsilon_{u2} + bu_{a2} - \rho\, sgn(S_l)\, \eta_m) \\ &\quad + \frac{|b|}{\gamma_2} \Phi_{u2}^T (\dot{\Phi}_{u2} + sgn(b)\, \gamma_2 S_l \Xi_{u2}) \end{aligned} \tag{39}$$

From Eq. (39), we can easily obtain the parameter adaptation law (37) because $\dot{\Phi}_{u2} = \dot{\Theta}_{u2}$. Also if we choose the auxiliary control input such that the given condition (36) is satisfied, then Eq. (39) is summarized as follows:

$$\dot{V}_2 \leq -\rho\, \eta_m. \tag{40}$$

Thus, the proposed SAFLC is stable in the sense of the Lyapunov. □

4. Simulation Example

Now we reveal the performance of the proposed SAFLC's via computer simulations. We consider a tracking problem for the inverted pendulum system. Fig. 1 shows the plant composed of a pole and a cart. The cart moves on the rail tracks in horizontal direction.

The control objective is to balance the pole starting from an arbitrary condition by supplying a suitable force to the cart. For simplicity, we do not consider the position of the cart. The plant dynamics is then expressed as:

$$\ddot{\theta} = \frac{g \sin\theta + a\cos\theta - \mu_p w^2 l \cos\theta \sin\theta}{l(4/3 - \mu_p \cos^2\theta)}, \tag{41}$$

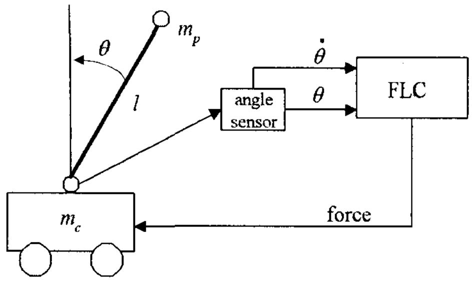


Fig. 1. The inverted pendulum system.

$$\mu_p = \frac{m_p}{m_p + m_c}, \tag{42}$$

$$a = \frac{F}{m_p + m_c}, \tag{43}$$

where g is an acceleration due to gravity ($=9.8\ m/\sec^2$), and F is the applied force. $m_c\ (=1.0\text{kg})$ and $m_p\ (=0.1\text{kg})$ are masses and $l\ (=0.5\text{m})$ is the pole length.

Fig. 2 represents the fuzzy sets for a control input u and a sole input variable d_s. In the SAFLC, the center values of membership functions for the control input are automatically adjusted by an adaptation law. Simulation conditions of SAFLC's are equally set to the case of the simple-structured FLC except for the addition of the parameter adaptation law. And we use the product inference and the height defuzzification.

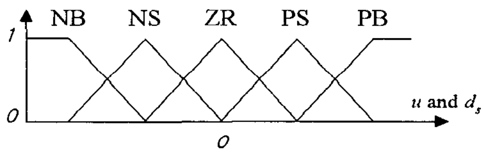
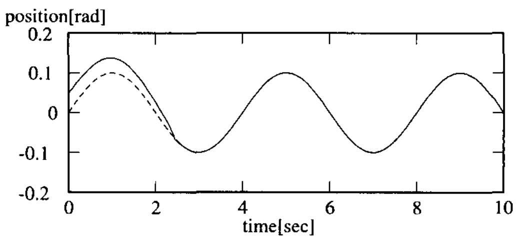
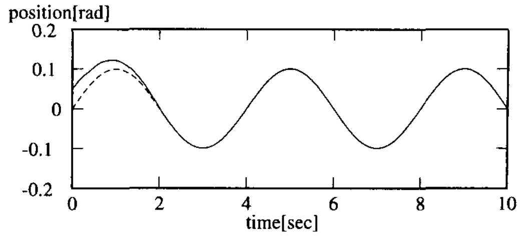


Fig. 2. The fuzzy sets for simulations.

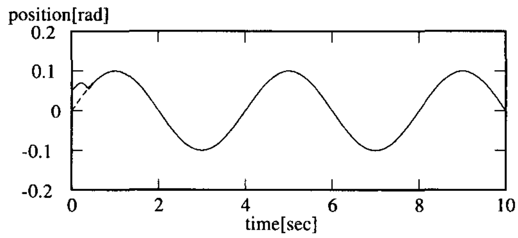
Figures 3, 4, and 5 show some simulation results of tracking performances, control inputs, and phase portraits, respectively. Here (a), (b), and (c) are the cases of the simple-structured FLC, and Methods 1 and 2 for the SAFLC, respectively. Fig. 6 shows the responses of the adaptive parameters of the SAFLC's, where (a) and (b) represents Methods 1 and 2, respectively. As shown in figures, the control performance of the SAFLC's is better than that of the simple-structured FLC. As a results, an adaptive scheme can improve the performance of the conventional case.



(a) single-input FLC.

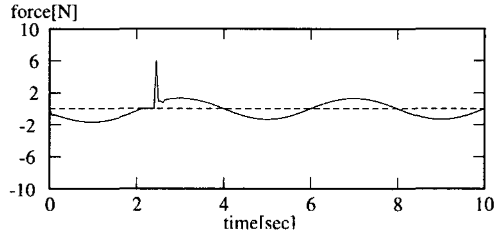


(b) SAFLC (1).

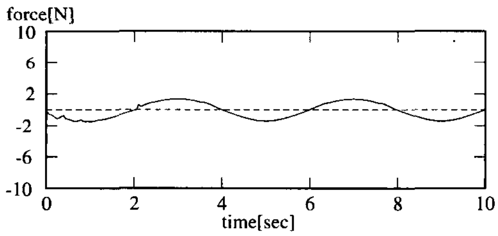


(c) SAFLC (2).

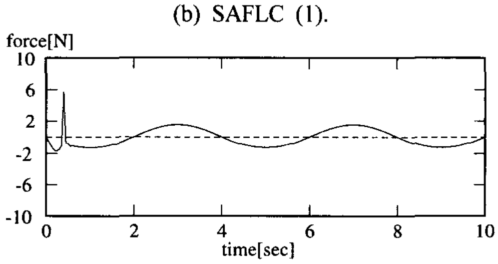
Fig. 3. Comparison of tracking performances.
(Solid line: Actual position, Dashed line: Desired position)



(a) single-input FLC.

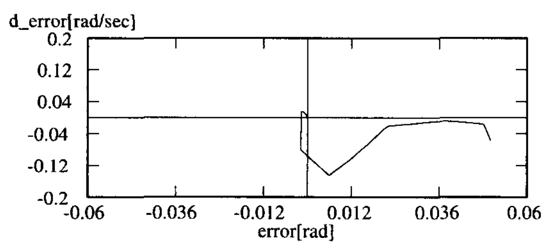


(b) SAFLC (1).

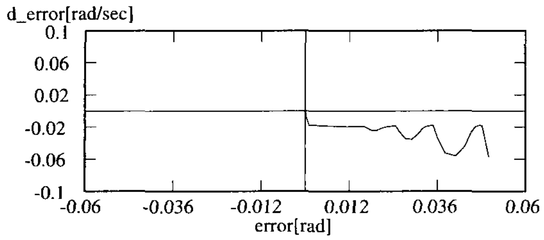


(c) SAFLC (2).

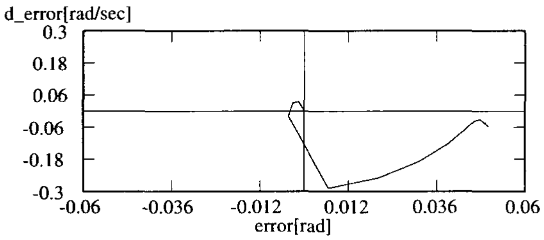
Fig. 4. Comparison of control inputs.



(a) single-input FLC.

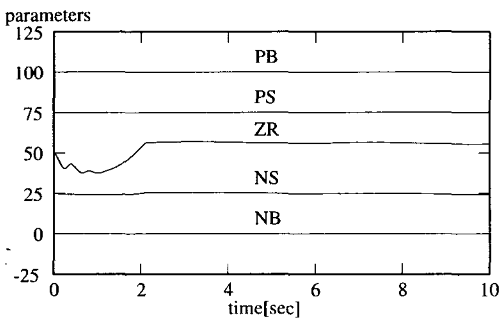


(b) SAFLC (1).

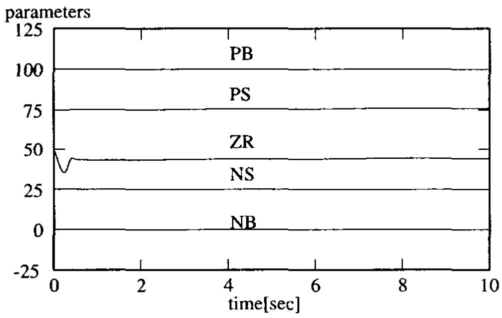


(c) SAFLC (2).

Fig. 5. Comparison of phase portraits.



(a) SAFLC (1).



(b) SAFLC (2).

Fig. 6. Adaptation responses of center values of membership functions.

5. Concluding Remarks

We briefly introduced a simple-structured FLC and then designed two simple-structured adaptive FLC's. A simple-structured FLC was naturally derived based on the skew-symmetric property of the control rule table for conventional FLC's. This can simply be extended to the general case of the n-th order complex systems. Since the simple-structured FLC uses a sole fuzzy input variable, it has many advantages.

We next designed two SAFLC's using the concept of the simple-structured FLC. One was designed based on a Hurwitz error dynamics and the other a switching function of the SMC. The closed-loop stability of both cases is ensured in the sense of the Lyapunov. We also derived the auxiliary control input u_a with a very small control action. Extremely, if we construct the rule base with sufficiently many rules, then the role of the auxiliary control input will disappear from the universal approximating property of a fuzzy logic system.

Finally, we performed computer simulations using an inverted pendulum system. Here we showed that the SAFLC's can improve the control performance of the simple-structured FLC.

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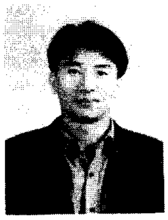

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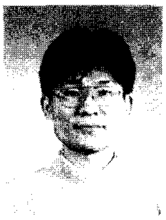

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