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Robust Fuzzy Adaptive Control Based on Switch Control Method

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***Abstract*—In the field of adaptive fuzzy control, there has been a severe deficiency by assuming the premise variables will usually stay within the universe of discourse in the derivation of stability of the adaptive control system. To overcome this deficiency, we develop a switching adaptive control scheme using only essential qualitative information of the plant to attain asymptotical stability of the adaptive control system for a typical nth-order nonlinear system without imposing the mentioned severe assumption. The switching adaptive control system consists of an adaptive VSS controller for coarse control, an adaptive fuzzy controller for fine control, and a hysteresis switching mechanism. An adaptive VSS control scheme is proposed to force the state to enter the universe of discourse in finite time. While the premise variable is within the universe of discourse, an adaptive fuzzy control is proposed to learn the capability to stabilize the plant. At the boundary of the universe of discourse, a hysteresis switching scheme between the two controllers will be proposed. We show that after finite times of switching, the premise variables of the fuzzy system will remain within the universe of discourse and stability of the closed-loop system can be attained.**

Index Terms: Adaptive fuzzy control, adaptive VSS control, switching adaptive control, T-S fuzzy model

I. Introduction

Recently, fuzzy adaptive control has become a popular method for nonlinear adaptive control. However, in most of the related literature [1]-[14], it is assumed that the trajectories of the premise variables are located in the universe of discourse of the fuzzy systems so that the universal approximation property can be invoked in the analysis of system behavior to guarantee system stability. This assumption is infeasible in an adaptive control system since the system must pass through a learning period in which the system behavior can not be known in advance. To attack the above mentioned problem, the so called semi-global stability is induced in the field of adaptive fuzzy control. Typically with the semi-global stability as done in [15], the universe of discourse depends on unknown system parameters and the initial states. One deficiency is that we can not explicitly define the universe of discourse in advance so as to ensure the premise variables will remain in the corresponding universes of discourse.

To attack the problem mentioned in the previous paragraph, we shall develop a switching adaptive control scheme to attain stability of the adaptive control system for a typical nth-order integral-chain nonlinear system. We shall only make some essential qualitative assumptions of the plant, instead of requiring some quantitative information of the plant, to construct an adaptive controller. The proposed switching adaptive control system consists of an adaptive VSS controller for coarse control, an adaptive fuzzy controller for fine control, and a hysteresis switching mechanism for switching of the previous two controllers. The adaptive VSS controller is used to force the premise variable to enter the universe of discourse in finite time. While the premise variable is kept within the universe of discourse, the adaptive fuzzy controller will tune its parameters and gradually learn the capability to stabilize the plant. However, during the learning period of the adaptive fuzzy controller, infinite switching between the above two control algorithms may happen at the boundary of the universe of discourse. Therefore, at the boundary of the universe of discourse, a hysteresis switching scheme between the adaptive VSS control law and the adaptive fuzzy control law will be proposed. We shall show that after finite times of switching, the premise variable of the fuzzy system will remain in the universe of discourse and stability of the adaptive control system will be attained.

The remainder of this work is organized as follows. The problem to be attacked and the hysteresis switching adaptive control scheme are described in Section II. The adaptive VSS controller is proposed and analyzed in Section III. Then, an adaptive fuzzy control is presented in Section IV. Analysis of the switching control system is made in Section V. Finally, conclusions and discussions are given in Section VI. **Due to space constraint, all the proofs of the derived lemmas and theorems will be omitted.**

II. Problem Formulation of The Hysteresis Switching Adaptive Control

A. Plant Model and Assumptions

In this study, we consider the $n-$th order plant

$$\dot{z} = \bar{A}z + \bar{B}(\bar{f}(z) + \bar{u}) \tag{1}$$

where

$$\bar{A}=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\\vdots&\vdots&\vdots&\ddots&0\\0&0&0&\cdots&1\\0&0&0&0&0\end{bmatrix},\bar{B}=\begin{bmatrix}0\\0\\\vdots\\0\\1\end{bmatrix}$$

where $\bar{f}(z)$ is an unknown scalar nonlinear function of the state vector

$$z=\begin{bmatrix}z_1&\cdots&z_n\end{bmatrix}^T\in R^n$$

and $\bar{u}\in R^1$ is the system input. Note that even if the dynamics of state $z_n(t)$ defined in (1) is asymptotically stable, the state, $z_i(t)$ for $i=2,\ldots,n$, defined as the integral of $z_{i+1}(t)$ for $i=1,\ldots,n-1$, respectively, may not be asymptotically stable. To overcome this deficiency, a coordinate transformation will be considered and a controller for the plant in (1) is chosen as

$$\bar{u}=u+Kz \tag{2}$$

where $K=\begin{bmatrix}k_1&\cdots&k_n\end{bmatrix}\in R^{1\times n}$ is a gain matrix and u is an adaptive control law to be specified later. Using the above proposed controller structure, the closed-loop system becomes

$$\dot{z}=\bar{A}_c z+\bar{B}\left[f(z)+u\right] \tag{3}$$

where

$$\bar{A}_c=\bar{A}+\bar{B}K=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\\vdots&\vdots&\vdots&\ddots&0\\0&0&0&\cdots&1\\k_1&k_2&k_3&\cdots&k_n\end{bmatrix}$$

Since the pair $(\bar{A},\bar{B})$ is controllable, the gain matrix K can be selected so that the eigenvalues of matrix $\bar{A}_c$ can be arbitrarily assigned. By specifying a set of distinct stable real eigenvalues $\{\mu_i\}_{i=1}^n$ of matrix $\bar{A}_c$, a real matrix K can be determined by using Ackerman's formula [16].

Lemma 1: There exists a coordinate transformation matrix $\widetilde{V}$ as defined later in the proof such that under the coordinate transformation $z=\widetilde{V}x$, the dynamic system in (1) can be transformed into

$$\dot{x}=Ax+B\left[f(x)+u\right] \tag{4}$$

where $f(x)=\bar{f}(z)\big|_{z=\widetilde{V}x}$,

$$B=\widetilde{V}^{-1}\bar{B}=\bar{B}, \tag{5}$$

and $A=\widetilde{V}^{-1}\bar{A}_c\widetilde{V}$ is an upper triangular matrix for which

$$A=\begin{bmatrix}\mu_1&1&0&\cdots&0\\0&\mu_2&1&\cdots&0\\\vdots&\vdots&\ddots&\vdots&\vdots\\0&0&0&\mu_{n-1}&1\\0&0&0&0&\mu_n\end{bmatrix}. \tag{6}$$

■

Denote the new state vector x as $x=\begin{bmatrix}x_1&\cdots&x_n\end{bmatrix}^T\in R^n$. From Lemma 1, it is obvious that if the state $x_n(t)$ is asymptotically stable by applying an appropriate control law u, then the remaining states $x_2(t),\ldots,x_n(t)$ will be asymptotically stable. Owing to this advantage, design and analysis of the adaptive control system with respect to (1) can be simpler than that with respect to (3).

In this study, a hysteresis switching scheme between the adaptive VSS control law and the adaptive fuzzy control law will be proposed. Let Ω_x with $0\in\Omega_x$ be the universe of discourse of the fuzzy system used to define the adaptive fuzzy control law. For the nonlinear function $f(x)$, we make the following assumptions.

Assumption 1: Assume that $f(x)$ is a continuous function on R^n and $f(0)=0$. ■

Assumption 2: There is an upper bound $\psi(x)$ of $f(x)$ satisfying

$$|f(x)|\le\sum_{i=1}^m c_i^*\psi_i(x)=\psi(x),\ \text{for } x\notin\Omega_x \tag{7}$$

where $\{c_i^*\}_{i=1}^m$ is a set of unknown positive parameters and $\{\psi_i(x)\}_{i=1}^m$ is a set of known functions with $\psi_i(x)\ge 0$. Without loss of generality, it is assumed that $\psi_1(x)=1$ and $\psi_i(0)=0$ for $i=2,\ldots,m$. ■

B. Problem Formulation

In this study, we shall consider the case that the structure of the nonlinear function $f(x)$ is unknown and a fuzzy approximator $F(x|\theta)$ will be used to approximate an ideal stabilizing controller in the universe of discourse Ω_x as $\Omega_x=\{x_2\in R|\,|x_2|\le 1\}$. Basically, when the state trajectory $x(t)$ is outside the universe of discourse Ω_x, by utilizing the structure information of $f(x)$ given in (7) in Assumption 2, we shall develop an adaptive VSS control law $u_{VSS}(t)$ to force the state trajectory entering Ω_x. On the other hand, if the state trajectory $x(t)$ is staying within Ω_x, an adaptive fuzzy control law $u_{fuzzy}(t)$ will be applied to further ensure that the system will be ultimately asymptotically stable. Since switching between these two control laws with infinite frequency at the boundary of the region Ω_x may happen, we shall use a hysteresis switching control as described in the following to avoid this problem. Let h, with $0<h<1$, be the size of the hysteresis zone Ω_h defined as $\Omega_h=\{x_2\in R|1-h\le|x_2|\le 1\}$. The hysteresis switching control structure, as shown in Fig. 1, is described as follows. At $t=0$, the control effort is defined as

$$u(0)=\begin{cases}u_{VSS}(0), & \text{if } |x_2(0)|>1-h\\ u_{fuzzy}(0), & \text{if } |x_2(0)|\le 1-h\end{cases} \tag{8}$$

For $t>0$, while $x(t)$ is outside the hysteresis zone Ω_h, the control input $u(t)$ is defined as

$$u(t)=\begin{cases}u_{VSS}(t), & \text{if } |x_2(t)|>1\\ u_{fuzzy}(t), & \text{if } 0\le|x_2(t)|<1-h\end{cases} \tag{9}$$

and on the contrary, while $x(t) \in \Omega_h$, $u(t)$ is defined as

$$u(t) = \begin{cases} u_{VSS}(t), & \text{if } u(t_-) = u_{VSS}(t_-) \\ u_{fuzzy}(t), & \text{if } u(t_-) = u_{fuzzy}(t_-) \end{cases} \quad (10)$$

We note that while applying the adaptive VSS control law u_{VSS}, the tuning parameters in the adaptive fuzzy control will be kept invariant. On the other hand, while applying the adaptive fuzzy control law u_{fuzzy}, the tuning parameters in the adaptive VSS control will be frozen.

The problem to be attacked is formulated as follows. Based on the mentioned switching mechanism, for the plant in (4) under **Assumption** 1 and **Assumption** 2, we shall construct an adaptive VSS controller and an adaptive fuzzy controller so that the tuning parameters in the two adaptive controllers are bounded and $x(t) \to 0$ as $t \to \infty$.

III. Design and analysis of the adaptive VSS control

In this section, an adaptive VSS controller will be proposed for the plant in (4) such that boundedness of the tuning parameters and asymptotical stability of the states will be ensured. First, we represent the uncertain function $\psi(x)$ in (7) as a linear regression form given by

$$\psi(x) = \phi^T(x)\theta_c^*$$

where

$$\begin{aligned} \phi(x) &= \begin{bmatrix} \psi_1(x) & \psi_2(x) & \cdots & \psi_m(x) \end{bmatrix}^T \\ \theta_c^* &= \begin{bmatrix} c_1^* & c_2^* & \cdots & c_m^* \end{bmatrix}^T \end{aligned}$$

Meanwhile, partition the closed-loop dynamics in (4) as

$$\begin{bmatrix} \dot{\bar{x}} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \bar{x} \\ x_n \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} [f(x) + u]$$

where $\bar{x} = \begin{bmatrix} x_1 & \cdots & x_{n-1} \end{bmatrix}^T \in R^{(n-1)\times 1}$.

Lemma 2: Since the pair (A, B) in (4) is controllable, so is the pair (A_{11}, A_{12}). ■

To design the adaptive VSS control law, we need to construct $\hat{c}_i$ which are the estimates of c_i^* and construct an estimate of the uncertain function $\psi(x)$ as

$$\begin{aligned} \hat{\psi}(x) &= \phi^T(x)\hat{\theta}_c \\ \hat{\theta}_c &= \begin{bmatrix} \hat{c}_1 & \hat{c}_2 & \cdots & \hat{c}_m \end{bmatrix}^T \end{aligned}$$

Then the difference between $\hat{\psi}(x)$ and $\psi(x)$ can be expressed as

$$\hat{\psi}(x) - \psi(x) = \phi^T(x)\tilde{\theta}_c \quad (11)$$

where the parametric error vector $\tilde{\theta}_c$ is defined as

$$\tilde{\theta}_c = \hat{\theta}_c - \theta_c^*$$

Now define a sliding surface as

$$s(x) = 0$$

where

$$s(x) = C\bar{x} + x_n, C \in R^{1\times(n-1)}$$

Note that by Lemma 2, since (A_{11}, A_{12}) is a controllable pair, the gain matrix C can be chosen such that $A_{11} - A_{12}C$ is a Hurwitz matrix and there exists a unique positive matrix $\overline{P}$ such that

$$(A_{11} - A_{12}C)^T \overline{P} + \overline{P}(A_{11} - A_{12}C) = -\overline{Q} \quad (12)$$

for any positive matrix $\overline{Q} \in R^{(n-1)\times(n-1)}$ [17].

For the plant in (4), the parameter tuning law and the proposed adaptive VSS controller are proposed as

$$\begin{aligned} \dot{\hat{\theta}}_c &= |s|\,\Gamma_1\phi(x),\ \hat{c}_i(0) = 0 & (13) \\ u &= -\left(A_{12}^T\overline{P} + CA_{11}\right)\bar{x} - (CA_{12} + \mu_n)\,x_n \\ &\quad -\left[\hat{\psi}(x) + \eta\right]\text{sign}(s) & (14) \end{aligned}$$

where η is a positive number, Γ_1 is a positive definite matrix with

$$\Gamma_1 = \begin{bmatrix} \gamma_1 & 0 & \cdots & 0 \\ 0 & \gamma_2 & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \gamma_m \end{bmatrix},$$

and the sign function sign(s) is defined as

$$\text{sign}(s) = \begin{cases} 1, & \text{if } s > 0 \\ 0, & \text{if } s = 0 \\ -1, & \text{if } s < 0 \end{cases}$$

The tuning laws in (13) of the parameters $\hat{c}_i(t)$ for $1 \le i \le m$ are given by

$$\dot{\hat{c}}_i = \gamma_i\,|s|\,\psi_i(x) \quad (15)$$

The sliding condition for an adaptive VSS control system is defined as

$$s(t)\dot{s}(t) < 0 \text{ if } s(t) \neq 0 \quad (16)$$

for all $t \ge t_0 + T'$ where T' is a finite positive number. Recall that the adaptive VSS control system will operate under the sliding mode if there is a finite time T with $T \ge T'$ such that for $t \ge t_0 + T$,

$$\begin{aligned} s(t) &= 0, \\ \dot{s}(t) &= 0. \end{aligned}$$

While the adaptive VSS control system is not operating under the sliding mode, the closed-loop dynamics can be expressed as

$$\begin{aligned} \dot{x} &= Ax + B\left[-CA_{11}\bar{x} - (CA_{12} + \mu_n)\,x_n\right] \\ &\quad + B\left[f(x) - A_{12}^T\overline{P}\bar{x} - \hat{\psi}(x)\text{sign}(s)\right] & (17) \\ \dot{\hat{\theta}}_c &= |s|\,\Gamma_1\phi(x) & (18) \end{aligned}$$

On the other hand, if the adaptive VSS control system is operating under the sliding mode since a finite time

t_0+T, the closed-loop dynamics can be derived from the condition $s(t)=0$ as

$$\begin{aligned} \dot{\bar{x}} &= (A_{11}-A_{12}C)\,\bar{x}, x_n = -C\bar{x} && (19)\\ \dot{\hat{\theta}}_c &= 0 && (20)\end{aligned}$$

for $t \geq t_0+T$ and the equivalent control u_{eq} under the sliding mode can be derived from the condition $\dot{s}(t)=0$ as

$$u_{eq} = -C\left(A_{11}\bar{x}+A_{12}x_n\right) - \left(\mu_n x_n + f(x)\right)$$

Lemma 3: Let $g(t)$ be a uniformly continuous function on $[t_0,\infty)$ with $g(t)\geq 0$. Suppose that

$$\int_{t_0}^{\infty} g(t)dt < \infty$$

Then, (i) $g(t)$ is uniformly bounded on $[t_0,\infty)$, and (ii) $\lim_{t\to\infty} g(t)=0$. ■

Lemma 4: [15] If $V(t,x)$ is positive definite and $\dot{V}\leq -k_1V+k_2$ where $k_1>0$ and $k_2\geq 0$ are bounded constants, then

$$V(t,x)\leq \frac{k_2}{k_1}+(V(0)-\frac{k_2}{k_1})e^{-k_1t}$$

for all t. Also it is obvious that

$$\lim_{t\to\infty} V(t,x)\leq \frac{k_2}{k_1}$$

■

Lemma 5: Consider a positive definite function V_a defined as

$$V_a = \frac{1}{2}\bar{x}^T\overline{P}\bar{x}+\frac{1}{2}s^2+\frac{1}{2}\tilde{\theta}_c^T\Gamma_1^{-1}\tilde{\theta}_c. \qquad (21)$$

Assume that $\dot{V}_a$ is differentiable on $[t_0,\infty)$ and $\bar{x}(t)$ is uniformly continuous on $[t_0,\infty)$. If the following inequality

$$\dot{V}_a \leq -\frac{1}{2}\bar{x}^T\overline{Q}\bar{x} \qquad (22)$$

holds over $[t_0,\infty)$, then it follows that

$$\lim_{t\to\infty}\bar{x}(t)=0.$$

■

Theorem 1: Consider the plant in (4) and the VSS controller in (13)-(14). For each i with $i=1,2,\ldots,m$, the tuning parameter $\hat{c}_i(t)$ is a non-decreasing function of t with

$$\lim_{t\to\infty}\hat{c}_i(t)=\hat{c}_i(\infty)$$

where $\hat{c}_i(\infty)$ is a finite positive value and

$$\lim_{t\to\infty}x(t)=0.$$

Moreover, there is a finite time T_1 such that the adaptive VSS control system operates under the sliding mode for $t\geq t_0+T_1$ so that the tuning parameter vector $\hat{\theta}_c(t)$ will be kept invariant and $x(t)$ exponentially converges to the origin for $t\geq t_0+T_1$. ■

IV. Design of the Adaptive Fuzzy Control

For the plant in (4), the nonlinear function $f(x)$ only appears in the dynamics of $x_n(t)$. Moreover, if $x_n(t)$ converges to zero, then so do $x_i(t)$ for $i=2,\ldots,n$. Therefore, it is sufficient to construct a fuzzy system with the premise variable being $x_2(t)$. The universe of discourse Ω_x of the fuzzy system is defined as

$$\Omega_x = \{x\in R^n \,|\, |x_n|\leq 1\}.$$

The rule base of the T-S fuzzy system is defined as: for $1\leq l\leq L$,

$$\text{Rule } l: \text{If } x_n \text{ is } F_l, \text{ then } y=\theta_l.$$

where F_l is the fuzzy set with membership function $\mu_{F_l}(x_n)$ and θ_l is the value specified in the antecedent part of the $l-$th rule. The number L, which is the total number of rules, will be chosen as an odd number. A typical case for which x_n possesses five fuzzy sets is shown in Fig. 2. The set of IF-THEN rules will be complete, consistent, and continuous [18]. In this study, we shall use the triangular membership function for the fuzzy sets. For further analysis, denote A_i be the support of the membership function $\mu_{F_i}(x_n)$ for $1\leq i\leq L$, i.e.,

$$A_i = \left\{x\in\Omega_x \left| \mu_{F_i}(x_n)>0\right.\right\}$$

Based on the above rule base, the fuzzy system can be expressed as

$$F(x_n,\theta)=\xi^T(x_n)\theta \qquad (23)$$

where

$$\begin{aligned}\theta &= [\theta_1,...,\theta_L]^T,\\ \xi_l(x_n) &= \frac{\mu_{F_l}(x_n)}{\sum_i^L \mu_{F_l}(x_n)},\\ \xi(x_n) &= [\xi_1(x_n),...,\xi_L(x_n)]^T && (24)\end{aligned}$$

Since the triangular membership functions are adopted as shown in Fig. 2, we can observe that

$$\sum_{l=1}^{L}\mu_{F_l}(x_n)=1$$

and thus (24) is reduced to

$$\xi(x_n)=\left[\mu_{F_1}(x_n),...,\mu_{F_L}(x_n)\right]^T \qquad (25)$$

Using the fuzzy approximator $F(x_n,\theta)$ in (23), an adaptive fuzzy controller for the plant in (4) is chosen as

$$\begin{aligned}\dot{\hat{\theta}} &= x_n\xi(x_n) && (26)\\ u_{fuzzy} &= -\xi^T(x_n)\hat{\theta} && (27)\end{aligned}$$

where $\hat{\theta}(0)=0$.

V. Analysis of Switching Behavior

Based on the adaptive VSS controller in (13)-(14) and the adaptive fuzzy controller in (26)-(27), we shall study the proposed hysteresis switching robust adaptive control defined as in (9) and (10). According to the tuning law of $\hat{\theta}$ defined in (26) and the definition of the vector $\xi(x)$ in (25), some further properties of $\hat{\theta}$ can be discovered.

Lemma 6: (i) If $A_i \subset [0,1]$, then $\hat{\theta}_i(t) \geq 0$ and $\hat{\theta}_i(t)$ is a monotone increasing function of t. On the other hand, if $A_i \subset [-1,0]$, then $\hat{\theta}_i(t) \leq 0$ and $\hat{\theta}_i(t)$ is a monotone decreasing function of t. (ii) If $x(t) \in [1-h,1]$, then $\hat{\theta}^T(t)\xi(x_n(t)) \geq 0$. On the other hand, if $x(t) \in [-1,-(1-h)]$, then $\hat{\theta}^T(t)\xi(x_n(t)) \leq 0$. ■

Lemma 7: Assume that the adaptive fuzzy controller is applied at $t = t_1$. Then, it is impossible that the adaptive fuzzy controller is kept applied for all $t \geq t_1$ such that $\{x(t)\,|t \geq t_1\} \subset \Omega_h$.

In the following, we shall focus on discussing switching behavior of the switching adaptive control system at the boundaries of the hysteresis zone Ω_h. For further analysis, we shall need some definitions. First, due to Theorem 1 and Lemma 7, the following definition is well-posed.

Definition 1: We say that a switching cycle at the positive boundary $x_n = 1 - h$ happens within the interval $[t_1, t_2]$ if there is a time instants t_1' and $\bar{t}_1 \in (t_1, t_2)$ such that (i) the adaptive fuzzy controller is applied for $t \in [t_1, \bar{t}_1]$ with $x_n(t_1) = 1 - h$, (ii) the adaptive VSS controller is applied within the interval $(\bar{t}_1, t_2)$ with $x_n(\bar{t}_1) = 1$ and $x_n(t_2) = 1 - h$, and the adaptive fuzzy control law is again applied after $t = t_2$. Along the same way, a switching cycle at the negative boundary $x_n = -(1-h)$ can be defined. ■

Definition 2: We say that a continuous switching of N times at the positive boundary $x_n = 1 - h$ happens since $t = t_1$ if there is a set of finite time instants $\{t_{i+1}\}_{i=1}^N$ such that a switching cycle at the positive boundary $x_n = 1 - h$ happens within the interval $[t_i, t_{i+1}]$ for $1 \leq i \leq N$. Similarly, a continuous switching of N times at the negative boundary $x_n = -(1-h)$ can be defined. Moreover, if $N \to \infty$, we shall say a continuous switching of infinite times at the positive boundary $x = 1 - h$ (or at the negative boundary $x_n = -(1-h)$) happens since $t = t_1$. ■

Definition 3: We say that there is no switching at the boundary $x_n = 1 - h$ (or at the boundary $x_n = -(1-h)$) happened since $t = t_1$ if (i) the adaptive VSS control is applied in (t_0, t_1) for some $t_0 < t_1$, (ii) the adaptive fuzzy control law is applied after $t = t_1$, and (iii) there is not a switching at the boundary $x_n = 1-h$ (or at the boundary $x_n = -(1-h)$) happens at $t = t_1'$ fro any $t_1' \geq t_1$. ■

Definition 4: We say that there is no switching at the boundary $x_n = 1 - h$ (or at the boundary $x_n = -(1-h)$) happened since $t = t_1$ if (i) the adaptive VSS control is applied in (t_0, t_1) for some $t_0 < t_1$, (ii) the adaptive fuzzy control law is applied after $t = t_1$, and (iii) there does not exist a finite time instant t_2 such that a switching cycle at the positive boundary $x_n = 1 - h$ (or at the negative boundary $x_n = -(1-h)$) happens within the interval $[t_1, t_2]$. ■

Lemma 8: It is impossible that a continuous switching of infinite times at the positive boundary $x_n = 1-h$ or at the negative boundary $x_n = -(1-h)$ happens since a finite time $t = t_1$. ■

Lemma 9: It is impossible that a switching at the positive boundary $x = 1 - h$ (or at the negative boundary $x_n = -(1-h)$) happens infinite times since any finite time $t = t_1$. ■

Lemma 10: For the proposed switching adaptive control system, we have

(i) there is a finite time t_{f_0} such that $x(t) \in \Omega_x$ and the adaptive fuzzy control is used for $t \geq t_{f_0}$ and

(ii) the tuning parameters $\hat{c}_i(t)$ for $i = 1, \ldots, m$ in the adaptive VSS control are uniformly bounded for $t \in [0, \infty)$. ■

Convergence analysis of the switching adaptive control system is concluded in the following theorem.

Theorem 2: For the proposed switching adaptive control system, we have

$$\lim_{t\to\infty} x_n(t) = 0.$$

and $\hat{\theta}(t)$ is uniformly bounded over $[0, \infty)$. Moreover, due the the special plant structure in (4), it follows that

$$\lim_{t\to\infty} x_i(t) = 0 \text{ for } i = 1, \ldots, n-1.$$

VI. Conclusion and Discussion

In the field of adaptive fuzzy control, there has been a severe deficiency by assuming the premise variables will usually stay within the universe of discourse in derivation of stability of the adaptive control system. To overcome this deficiency, we have developed a switching adaptive control scheme to attain asymptotical stability of the adaptive control system for a typical nth-order integral-chain nonlinear system without imposing the mentioned severe assumption. We only make some essential qualitative assumptions of the plant, instead of requiring quantitative information of the plant, to construct an adaptive controller. The switching adaptive control system consists of an adaptive VSS controller for coarse control, an adaptive fuzzy controller for fine control, and a hysteresis switching mechanism. An adaptive VSS control scheme is proposed to force the state to enter the universe of discourse Ω_x in finite time. The proposed adaptive VSS controller has a strong capability to drive the system trajectory within Ω_x, however, at the expense of high control signal. While the premise variable is kept within Ω_x, an adaptive fuzzy control will be proposed to learning the capability to stabilize the plant under control. We may say the adaptive fuzzy control is performed at the fine control stage since the control signal is usually smaller than that of the adaptive VSS control law.

At the boundary of Ω_x, a hysteresis switching scheme between the adaptive VSS control law and the adaptive fuzzy control law will be proposed. The first advantage of using a hysteresis switching mechanism is to avoid switching of infinite frequency in the control input $u(t)$. The second one is that there is at least a fixed learning time interval for the the adaptive fuzzy control law when each switching happened. Since the adaptive fuzzy control law has the ability to enhance the system stability with at least a fix amount for each switching period, with switching of finite times in the hysteresis zone, the adaptive fuzzy control law will ultimately gain the capability to evade persistent switching in the hysteresis zone. We have shown that after some finite time, the premise variables of the fuzzy system are within the universe of discourse Ω_x without any control law switching. Then, asymptotical stability of the system states and boundedness of the tuning parameters can be ensured.

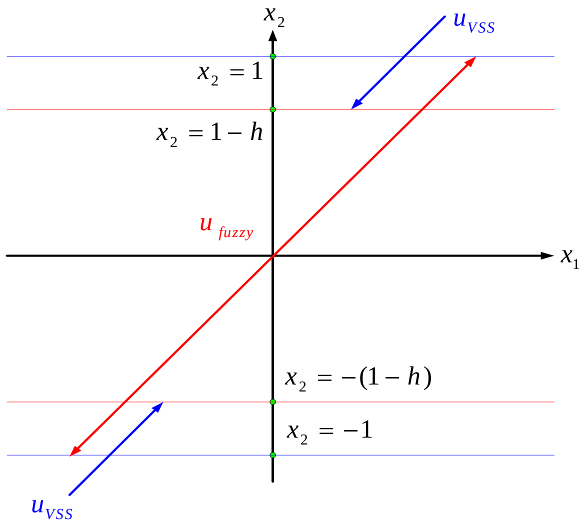

Fig. 1. Illustration of the hysteresis switching control.

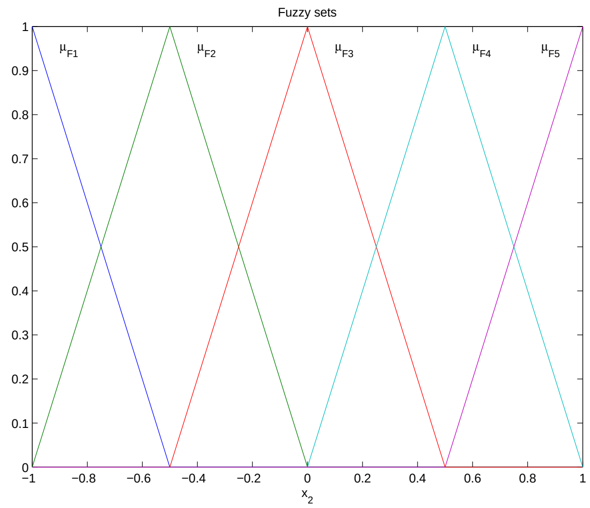

Fig. 2. A typical case of the fuzzy sets in the rule base for the situation of $n = 2$ where the premise variable is x_2.

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行政院國家科學委員會補助國內專家學者出席國際學術會議報告

100 年 07 月 27 日

附件三

報告人姓名	李柏坤	服務機構及職稱	中華大學電機系　教授
時間 會議 地點	100 年 7 月 10 日至 13 日 中國廣西桂林	本會核定補助文號	國科會 NSC 99-2221-E-216-001
會議名稱	（中文）2011 年機器學習與人工頭腦學國際研討會 (ICMLC 2011) （英文）2011 International Conference on Machine Learning and Cybernetics		
發表論文題目	（中文）切換適應 VSS/模糊控制之研究 （英文）A Switching Adaptive VSS/Fuzzy Control （中文）適應 VSS 控制之研究 （英文）On Adaptive VSS Control		

一、參加會議經過:

此次2011年機器學習與人工頭腦學國際研討會(2011 International Conference on Machine Learning and Cybernetics ，ICMLC 2011)，由河北大學、華南理工大學、IEEE SMC (System, Man, and Cybernetics) 協會等單位聯合主辦，於100年7月10日到100年7月13日，在中國廣西桂林市之喜來登酒店舉行。台灣的學者參與此研討會非常踴躍。

此次研討會所有論文都列入IEEE Explorer之資料庫，都屬於EI Index。研討會之網路首頁為http://www.icmlc.com/，整個研討會包含三個Plenary Talk：

[1] Fuzzy Forecasting Based on High-Order Fuzzy Time Series and Genetic Algorithms, Speaker: Professor Shyi-Ming Chen, IEEE Fellow, IET Fellow, IFSA Fellow, National Taiwan University of Science and Technology, Taiwan.

[2] Machine Learning Challenges for Human Brain Decoding
Speaker: Professor Seong-Whan Lee, IEEE Fellow, IAPR Fellow, Korean Academy of Science and Technology Fellow, Korea University, Korea

[3] Agent Technologies for Industrial Needs: Trends and Challenges
Speaker: Professor Vladimír Mařík, Editor-in-Chief of the IEEE Trans. on SMC, part C, Czech Technical University, Czech Republic.

此次研討會之主題包含：

1. Adaptive systems
2. Business intelligence
3. Biometrics
4. Bioinformatics
5. Data and web mining
6. Intelligent agent
7. Financial engineering
8. Inductive learning
9. Geoinformatics
10. Pattern Recognition
11. Logistics
12. Intelligent control
13. Media computing
14. Neural net and support vector machine
15. Hybrid and nonlinear system
16. Fuzzy set theory, fuzzy control and system
17. Knowledge management
18. Information retrieval
19. Intelligent and knowledge based system
20. Rough and fuzzy rough set

21. Networking and information security
22. Evolutionary computation
23. Ensemble method
24. Information fusion
25. Visual information processing
26. Computational life science

會議並安排一個 Panel Discussion，題目為 The Genesis of an Innovative Research Topic。另外有一個 Tutorials：Essentials of research methodology and an effective dissemination of research results, Speaker: Prof. Witold Pedrycz.

二、與會心得

(1) 從此次研討會所安排之主題來看，比較偏向人工智能於資訊工程之研究，各國有關人工智慧理論都有顯著的研究成果，幾個比較新的主題如 Media computing、Bioinformatics、Computational life science、Business intelligence，非常值得國內學界注意其發展。

(2) 除了認識許多中國之學者外，也認識了很多來自全世界各地的菁英學者，對於將來推動國際學術交流，有相當大的幫助。

(3) 大陸在人工智能領域之研究成果亦有長足之進步，在 IEEE SMC Society 之影響力也已超過台灣相關學界，國內應該即起直追。

三、考察參觀活動(無是項活動者省略)

四、建議

台灣應該多爭取舉辦國際研討會，使得全世界各地的菁英學者，能夠共聚一堂。大陸學術界的國際化，已經逐步生根，同時以此為基礎邁向國際之競爭，台灣學術界的國際化還有待大家的努力。

五、攜回資料名稱及內容

(1) 完整論文光碟片。

六、其他

無。

國科會補助計畫衍生研發成果推廣資料表

日期:2011/10/30

國科會補助計畫	計畫名稱: 基於切換控制方法之韌性模糊適應控制
	計畫主持人: 李柏坤
	計畫編號: 99-2221-E-216-001- 學門領域: 智慧型控制

無研發成果推廣資料

99 年度專題研究計畫研究成果彙整表

<table>
<tr><td colspan="3">計畫主持人：李柏坤</td><td colspan="5">計畫編號：99-2221-E-216-001-</td></tr>
<tr><td colspan="8">計畫名稱：基於切換控制方法之韌性模糊適應控制</td></tr>
<tr><td colspan="3" rowspan="2">成果項目</td><td colspan="3">量化</td><td rowspan="2">單位</td><td rowspan="2">備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）</td></tr>
<tr><td>實際已達成數（被接受或已發表）</td><td>預期總達成數(含實際已達成數)</td><td>本計畫實際貢獻百分比</td></tr>
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<tr><td>專任助理</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
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</table>

其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)	無

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

　　□實驗失敗

　　□因故實驗中斷

　　□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：□已發表 □未發表之文稿 ■撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

最近模糊適應控制已變成一個非常受歡迎的非線性適應控方法。然而，於絕大部分之相關文獻中皆假設前提變數的軌跡完全落於模糊系統之論文中，使得模糊系統之氾用近似性質能用於系統行為之分析，以保證系統穩定度。上述之假設在適應控制領域中是不合理的，因為系統必須經過一個參數學習階段，使得系統行為不能預先知道。為了克服此缺點，針對一個特殊的 n 階積分鏈非線性系統，於本研究中提出一個基於切換控制理論之適應控制法則。當前提變數落於論域外時，我們使用一個適應滑動模式控制器，以迫使前提變數進入論域中；另一方面，當前提變數落於論域內時，我們將建立一個適應模糊控制法則。然而在模糊系統之參數學習階段，在論域的邊界可能會發生上述兩種控制法則之無窮切換現象。於本研究中，我們提出一個磁滯切換機制，使得於有限次切換後，前提變數即完全落於論域內，並進而得到磁滯切換適應控制系統的穩定度。

本研究成果可使模糊適應控制之理論瓶頸獲得突破。