Scientific Journal of Information Engineering
October 2016, Volume 6, Issue 5, PP.112-118

Robust Fuzzy Adaptive Control Design for a Class of Nonlinear Systems*

LI Xiaoqiang[1†], XU Meiyu[2], FU Zhumu[1]

1. Information Engineering College, Henan University of Science and Technology, Luoyang 471023, PR China

2. Electrical Engineering College, Henan University of Science and Technology, Luoyang 471023, PR China

†Email: sxxqli@126.com

Abstract

A fuzzy robust adaptive control design scheme is developed for a class of nonlinear system represented by input-output models with unknown control direction. The control law and update laws are constructed by on-line approximating the unknown nonlinear functions and using Nussbaum control gain technique. The Lyapunov method based stability analysis shows that all the signals in the closed-loop are stable. A simulation example is presented to demonstrate the method.

Keywords: Nonlinear Systems; Fuzzy Logic System; Nussbaum Function

INTRODUCTION

During the last decades, a great deal of progress in the feedback control of nonlinear systems has been achieved. At the same time, fuzzy logic systems have been found to be an useful tool for solving the nonlinear system control problems with uncertainty or un-modelled dynamics [1-3]. Adaptive control for nonlinear systems with parameter uncertainty and uncertain nonlinearity are studied by many researchers.

In [4], an adaptive fuzzy controller is developed for a class of nonlinear systems with uncertainty. The nonlinear system in [4] is a single-input single-output system in which the uncertain nonlinear functions depend on the output and a number of its derivatives of the system. Different from [4], another class of nonlinear systems where the states are the input, the output and a number of their derivatives is considered in [5] and the system's parameters are uncertain. Since the states of the augmented system contain the input and its derivatives, the control design of the system in [5] is a challenging problem. In the work of [5], a semi-global controller is designed to achieve asymptotic output tracking for reference signals which are bounded and have bounded derivatives up to the nth order.

In a later paper [6], the same system is considered and the uncertainties in the system are nonlinear functions and satisfying a condition that a smooth nonlinear function must be known such that the unknown nonlinear function in the system is bounded by the product of the known nonlinear function and an unknown constant.

This condition of the unknown functions in [6] is removed in [7]. In [7], by on-line approximating the un-modelled dynamics using radial basis function (RBF) neural network, the feedback linearization technique and the neural network based adaptive control technique are combined to develop a robust adaptive controller design method.

In the control design procedure of [4-7], the sign of the control gain in the system is assumed to be known. When the gain sign is unknown, the stability problem is more difficult. Nussbaum control gain technique was introduced in [8]. This technique has been used to settle the control problem of every kinds of the system with the unknown control gain whose sign is unknown [9-10].

In this paper, we further consider the system in [4-7] with the unknown control gain whose sign is unknown. Combining on-line approximation with Nussbaum control gain technique, control law and update law are constructed. Stability analysis based on Lyapunov theory shows that all the signals in the closed-loop are bounded

* This work was partially supported by the Key Program of Department of Education of Henan Provincial (No. 13A470254), the Project of Science and Technology Department of Henan Provincial(No. 142300410292).

and the tracking errors converge to the epsilon neighborhood of zero. The theoretic results are illustrated through a simulation example.

PROBLEM FOR MULATIONS AND PRELIMINARIES

We consider a single-input single-output nonlinear system described by:

$$\begin{aligned} y^{(n)} &= f(y(t), \dot{y}(t), \cdots y^{(n-1)}(t), u(t), \dot{u}(t), \cdots u^{(m-1)}(t)) \\ &\quad + g(y(t), \dot{y}(t), \cdots y^{(n-1)}(t), u(t), \dot{u}(t), \cdots u^{(m-1)}(t)) u^{(m)}(t) \end{aligned} \tag{1.1}$$

where y is the output of system, $y^{(i)}$ is the $ith(1 \le i \le n)$ derivative of y, u is the control input of system and $u^{(j)}$ is $jth(1 \le j \le m)$ derivative of u; f, g are unknown smooth nonlinear functions and $g \ne 0$; f is denoted as the un-modeled dynamics and unknown nonlinearity of the system.

Let $x_1 = y,\ x_2 = \dot{y}, \cdots, x_n = y^{(n-1)}, z_1 = u,\ z_2 = \dot{u}, \cdots, z_m = u^{(m-1)}$. System (1.1) can be represented by:

$$\begin{cases} \dot{x}_i = x_{i+1} \quad 1 \le i \le n-1 \\ \dot{x}_n = f(x(t), z(t)) + g(x(t), z(t)) v \\ \dot{z}_i = z_{i+1}, 1 \le i \le m-1 \\ \dot{z}_m = v \end{cases} \tag{1.2}$$

where $v = u^{(m)}(t)$ is the control input of the augmented system (1.2), and $x = [x_1, \cdots, x_n]^T$, $z(t) = [z_1(t), z_2(t), \cdots, z_m(t)]^T$ is the state of the system (1.2).

The initial states of the integrators are chosen such that $(x(0), z(0)) \in Z_0$ and $Z_0 \subset R^{m+n}$.

Our objective is to design a robust adaptive state feedback controller for (1.2) such that the closed-loop system is stable and the output $y(t)$ of the system tracks the reference signal $y_r(t)$ with high quality in the presence of the unknown nonlinear function.

Let $e_1 = x_1 - y_r, e_2 = x_2 - \dot{y}_r,\ \cdots,\ e_n = x_n - y_r^{(n-1)},\ e = [e_1, e_2, \cdots, e_n]^T$, Define a new index variable e_f as follows:

$$e_f = (\frac{d}{dt} + \beta)^{n-1} e_1 = [\Lambda \quad 1] e \tag{1.3}$$

where $\beta > 0$ is a constant and $\Lambda = [\beta^{n-1}, (n-1)\beta^{n-2}, \frac{(n-1)(n-2)}{2!}\beta^{n-3}, \cdots, (n-1)\beta]^T$. It has been shown in [11,12] that $e \to 0$ as $e_f \to 0$. That is, if $e_f \to 0$, we can beat the target of this paper.

According to (1.42) and (1.3), we get that:

$$\dot{e}_f = f(x, z) + g(x, z) v + \alpha - y_r^{(n)} \tag{1.4}$$

where $\alpha = [0 \quad \Lambda^T] e$. For the design of the controller, we give some assumptions as follows:

Assumption 1: The states of the system (1.2) are available for feedback.

According to the assumption 1 and $g(x) \ne 0$, we can know that system (1.2) input–output is linearized by full state feedback for all x.

It also guarantees that for every x, there is a globally defined normal form for x. Especially, Let:

$$\begin{cases} \omega_i = z_i - x_{n-m+i}, & 1 \le i \le m-1 \\ \omega_m = g z_m - x_n \end{cases}$$

We have:

$$\begin{cases} \dot{\omega}_i = \omega_{i+1}, & 1 \le \mathrm{i} < m-2 \\ \dot{\omega}_{m-1} = z_m - x_n \\ \dot{\omega}_m = \dot{g} z_m - f(x,z)\Big|_{z_i = \omega_i + x_{n-m+i}, z_m = (\omega_m + x_n)/g} \end{cases} \tag{1.5}$$

Together with the first n state equations of (1.2), (1.5) defines the global normal form. We further make the following assumption which includes a minimum-phase condition.

Assumption 2: The system (1.5) has the property that for any $z(0) \in Z_0$ and any bounded $x(t)$, the state ω_i is bounded.

From assumption 2, we conclude that z_i is bounded.

Assumption 3: The reference signal $y_r(t)$ is bounded with bounded derivatives up to the nth order and $y_r^{(n)}(t)$ is piecewise continuous.

Before introducing our control design method, we first recall the approximation property of the fuzzy logic system and Nussbaum control type function.

B. Fuzzy logic system

Various types of fuzzy logic system have been proved to be universal approximators in that they can uniformly approximate any continuous functions defined on compact domains to any degree of accuracy [13]. Next is the description of the structure of the Mamdani fuzzy logic system.

Let S is a compact simply connected set in R^n. With a map $f: S \to R^m$, $f \in C_m$ and define C_m to be the function space such that f is continuous. Consider a fuzzy logic system to uniformly approximate a continuous multidimensional function $y = f(x)$, where x is a vector with n independent variables $x = (x_1, \cdots, x_n)$, $x_i \in [a_i, b_i]$. In order to construct a fuzzy system, the interval $[a_i, b_i]$ is divided into N_i subintervals $a_i = C_{i1} \le \cdots C_{iN_i} = b_i$. On each interval $[a_i, b_i]$, the jth set $[C_{ii}, C_{(i+1)i}]$ is denoted by ϕ_i^j, and ϕ_i^j is defined to fuzzify x_i. The membership function of ϕ_i^j is denoted by $\mu_i^j(x_i)$, which can be represented by triangular, trapezoid, generalized bell or Gaussian type and so on. In this paper, the membership function is represented by Gaussian type .

The fuzzy rule base consists of a collection of fuzzy IF-THEN rule:

R_l : *If* x_1 is ϕ_1^j and x_2 is ϕ_2^j and …and x_n is ϕ_n^j, *Then*, y_l is Ω_l. $l = 1,2,\cdots,L$. $1 \le j_1, j_2, \cdots j_n \le \max N_i + 1$ .where Ω_l denotes an output fuzzy set. The output of the fuzzy system in the vector form is given by:

$Mamdani: \hat{f}(x) = \sigma^T \xi(x)$

where $\sigma = [\sigma_1, \cdots, \sigma_L]^T$ is a collection of consequent parameters in the fuzzy rule and $\xi(x) = [\xi_1(x), \cdots, \xi_L(x)]^T$ is a collection of so-call fuzzy basis function, and

$$\xi_l(x) = \prod_{i=1}^{n} \mu_{j_l}^l(x_i) / (\sum_{l=1}^{L} \prod_{i=1}^{n} \mu_{j_l}^l(x_i)) \tag{1.6}$$

where L denotes rule number. If Ω_l denotes output fuzzy set, the fuzzy logic system is a Mamdani fuzzy logic system; if $\Omega_l = f_l(x_1, x_2, \cdots, x_n)$, the fuzzy logic system(FLS) is a T-S (Takagi-Sugeno) fuzzy logic system.

For any continuous function $f(x)$, there exists some type fuzzy system to approximate it to an arbitrary accuracy. Following is a lemma proved by Wang [13].

Lemma 1 Suppose that the input universal of discourse U is a compact set in R^n. Then, for any given real continuous function $f(x)$ on U and $\forall \varepsilon \ge 0$, there exists a FLS in the form (2.10) such that: $\sup_{x \in U} \| f(x) - \hat{f}(x, \theta) \| \le \varepsilon$

B. Nussbaum type function

An even differentiable function is called Nussbaum-type function if it has the following properties:

$\limsup_{s\to+\infty}\frac{1}{s}\int_0^s N(\zeta)d\zeta=+\infty \qquad \liminf_{s\to+\infty}\frac{1}{s}\int_0^s N(\zeta)d\zeta=-\infty$

The continuous functions $\zeta^2\cos\zeta, e^{\zeta^2}\cos(\frac{\pi\zeta}{2})$ have those two properties and they are Nussbaum functions. In this paper, Nussbaum function $\zeta^2\cos\zeta$ is exploited.

Lemma 2[10]:Let $V(\cdot),\zeta(\cdot)$ be smooth functions defined on $[0,t_f)$ with $V(t)\geq 0, \forall t\in[0,t_f)$ and $N(\zeta)$ is an even smooth Nussbaum-type function. The following inequality holds for $\forall t\in[0,t_f)$:

$$0\leq V(t)\leq c_0+e^{-c_1t}\int_0^s(G(x(\tau))N(\zeta)+1)\dot{\zeta}e^{c_1\tau}d\tau \tag{1.7}$$

where $c_1>0$ and c_0 represents some suitable constant, $G(x)$ is a time-varying function or parameter,and $G(x)\in[g_{\min},g_{\max}]$, $0\notin[g_{\min},g_{\max}]$, $V(t)$, $\zeta(t)$ and $\int_0^s G(x(\tau))N(\zeta)\dot{\zeta}d\tau$ is bounded on $[0,t_f)$.

If the solution of the resulting closed-loop system is bounded, then $t_f=\infty$ [14].

ROBUST ADAPTIVE CONTROLLER DESIGN

In this section, the control law and the update laws of the considered system are given. Give a compact set $\Omega_{(e+Y_r,z)}\in R^{n+m}$, for any $(e+Y_r,z)\in\Omega_{(e+Y_r,z)}$ and continuous function $f(x)$, according the lemma 1, there exist σ^* and ε^*, we have:

$$f(e+Y_r,z)+\alpha=\sigma^{*T}\xi(e+Y_r,z)+\varepsilon^*. \tag{2.1}$$

where $|\varepsilon^*|\leq\varepsilon,\forall\varepsilon>0$.

Choose a controller as follows:

$$v=N(\zeta)(\hat{\sigma}^T\xi+y_r^{(n)}-ke_f) \tag{2.2}$$

where $\dot{\zeta}=\hat{\sigma}^T\xi e_f+y_r^{(n)}e_f-ke_f^2$; and $k>0$ is a suitable design constant.

$\hat{\sigma}$ is the estimate of σ^* and is updated as follows:

$$\dot{\hat{\sigma}}=\Gamma(e_f\xi-\mu\hat{\sigma}) \tag{2.3}$$

With any constant matrix $\Gamma=\Gamma^T\geq 0,\mu>0$ and μ is a design constant.

Theorem 1: Under assumptions 1-3, for any $x(0)$, $z(0)$ and Y_r satisfying $(e+Y_r,z)\in\Omega_{(e+Y_r,z)}$, the proposed robust adaptive state feedback controller (2.2) and the adaptive laws (2.3) guarantee that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded. Choosing suitable parameter, the output of the given system (1.1) converges to the reference signal $Y_r(t)$ in the presence of un-modeled dynamics and unknown nonlinearity.

Proof: Let $\tilde{\sigma}=\sigma^*-\hat{\sigma}$

Consider Lyapunov function candidate:

$$V=e_f^2/2+\tilde{\sigma}^T\Gamma^{-1}\tilde{\sigma}/2 \tag{2.4}$$

The time derivative of V along (1.1) is:

$$\dot{V}=e_f\dot{e}_f-\tilde{\sigma}^T\Gamma^{-1}\dot{\hat{\sigma}}=e_f(f+gv-y_r^{(n)}+\alpha)-\tilde{\sigma}^T\Gamma^{-1}\dot{\hat{\sigma}} \tag{2.5}$$

Substituting （1.1） and v into (2.5), we have:

$$\begin{aligned}\dot{V}&=e_f(f+gN(\zeta)(\hat{\sigma}^T\xi+y_r^{(n)}-ke_f)+\alpha)-\tilde{\sigma}^T\Gamma^{-1}\dot{\hat{\sigma}}\\&=e_f(\sigma^{*T}\xi+\varepsilon^*)-e_fy_r^{(n)}+gN(\zeta)\dot{\zeta}+\dot{\zeta}-\dot{\zeta}-\tilde{\sigma}^T\Gamma^{-1}\dot{\hat{\sigma}}\\&=-ke_f^2+e_f\varepsilon^*+e_f\tilde{\sigma}^T\xi+(gN(\zeta)+1)\dot{\zeta}-\tilde{\sigma}^T\Gamma^{-1}\dot{\hat{\sigma}}\end{aligned}$$

According to $2ab \le a^2 + b^2$, we have $e_f \varepsilon^* \le e_f^2 + \frac{1}{4}\varepsilon^2$, then

$$\dot{V} \le -(k-1)e_f^2 + \frac{\varepsilon^2}{4} + e_f \tilde{\sigma}^T \xi + (gN(\zeta)+1)\dot{\zeta} - \tilde{\sigma}^T \Gamma^{-1} \dot{\hat{\sigma}} \le -(k-1)e_f^2 + \frac{\varepsilon^2}{4} + (gN(\zeta)+1)\dot{\zeta} - \tilde{\sigma}^T (\Gamma^{-1}\dot{\hat{\sigma}} - e_f \xi) \quad (2.6)$$

Substituting (2.3) into (2.6), we have:

$$\dot{V} \le -(k-1)e_f^2 + \frac{\varepsilon^2}{4} + (gN(\zeta)+1)\dot{\zeta} - \mu \tilde{\sigma}^T \hat{\sigma} \quad (2.7)$$

Noting $2\tilde{\sigma}^T \hat{\sigma} \ge \|\tilde{\sigma}\|^2 - \|\sigma^*\|^2$, we get:

$$\dot{V} \le -(k-1)e_f^2 + \frac{\varepsilon^2}{4} + (gN(\zeta)+1)\dot{\zeta} - \frac{\mu}{2}\|\tilde{\sigma}\|^2 + \frac{\mu}{2}\|\sigma^*\|^2 \le -(k-1)e_f^2 + \frac{\varepsilon^2}{4} + (gN(\zeta)+1)\dot{\zeta}^2$$

$$-\frac{\mu}{2\lambda_{\max}(\Gamma^{-1})}\tilde{\sigma}^T \Gamma^{-1} \tilde{\sigma} + \frac{\mu}{2}\|\sigma^*\|^2 \quad (2.8)$$

With $\lambda_{\max}(\Gamma^{-1})$ denoting as the largest eigenvalue of a square matrix Γ^{-1}.

Constants δ, η are defined as follows:

$$\delta = \min\{k-1, \frac{\mu}{2\lambda_{\max}(\Gamma^{-1})}\} \quad (2.9)$$

$$\eta = \frac{\varepsilon^2}{4} + \frac{\mu}{2}\|\sigma^*\|^2 \quad (2.10)$$

So, we get: $\dot{V} \le -\delta V + (gN(\zeta)+1)\dot{\zeta} + \eta$ (2.11)

Multiplying Eq. (2.11) by $e^{\delta t}$ yields: $(Ve^{\delta t})' \le e^{\delta t}[(gN(\zeta)+1)\dot{\zeta} + \eta]$ (2.12)

Integrating Eq.(2.12) over $[0,t]$, we have: $V(t) \le V(0) + \frac{\eta}{\delta} + e^{-\delta t}\int_0^t e^{\delta t}(gN(\zeta)+1)\dot{\zeta} d\tau$ (2.13)

According to Lemma 2, we get $V(t)$, $\zeta(t)$ and $\int_0^t gN(\zeta)\dot{\zeta} d\tau$ are semi-globally uniformly ultimately bounded on $[0,t_f)$. If the solution of the closed-loop system is bounded, then $t_f \to +\infty$.

Let A is the upper bound of $\int_0^t (gN(\zeta)+1)\dot{\zeta} d\tau$, $V(t) \le V(0) + \frac{\eta}{\delta} + A$. That is, $|e_f| \le \sqrt{2V(0) + \frac{\eta}{\delta} + A}$. So, we get that e_f is bounded on $[0,+\infty)$. So, we can get $e = [e_1, e_2, \cdots, e_n]^T$ is bounded on $[0,+\infty)$. According Barbalat Lemma [15], we can get $e_1 \to 0, t \to +\infty$. The proof is concluded.

SIMULATION EXAMPLE

Consider nonlinear system: $y^{(3)} = f(y, \dot{y}, \ddot{y}, u) + g(y, \dot{y}, \ddot{y})v$. F, g in this system are continuous smooth function. The tracking signal is $y_r(t) = \sin(0.1t)$. Let $x_1 = y$, $x_2 = \dot{y}$, $x_3 = \ddot{y}$, $z_1 = u$, $v = \dot{u}$, so we have:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = f(y, \dot{y}, \ddot{y}, z_1) + g(y, \dot{y}, \ddot{y})v \end{cases}$$

where $f = u + y - \ddot{y} + y\dot{y} + \dot{y}^2 + y\ddot{y}$, $g = 2 + \cos\dot{y}y$.

Remark: This function is not used in constructing the controller and the update law except the assumption information. They just are used for simulating the plant.

In simulation, we set that $\beta = 2$, $\Gamma = 150I$, $\mu = 0.0001$, $k = 1$. The initial values of states (x, z) are all set to 0. The

controller and the update law are constructed as follows:

$v = \zeta^2 \cos\zeta((\hat{\sigma}^T \xi - \sin(0.1t) - e_f))$, $\dot{\hat{\sigma}} = 150I(e_f \xi - 0.0001\hat{\sigma})$.

The membership functions of x_1, x_2, x_3 are given as follows:

$\mu_i^1 = \exp[-(x-0.4)^2]$, $\mu_i^2 = \exp[-(x-0.2)^2]$, $\mu_i^3 = \exp(-x^2)$, $\mu_i^4 = \exp[-(x+0.2)^2]$, $\mu_i^5 = \exp[-(x+0.4)^2]$

Simulation results are shown in Figures 1-4. Figure 1 shows that the given control input is bounded. Figure 2 gives the output of the closed-loop system and the reference signal where the solid line denotes as the reference signal and the dash line denotes as the output of the system. The output of the closed-loop system tracks the reference input fairly well. After a short transient process, the output tracks the reference input at a high precision. Figure 3 is the tracking error and the good performance is shown again. Figure 4 shows that the parameter ζ is bounded also. The simulation results show that the designed controller is workable.

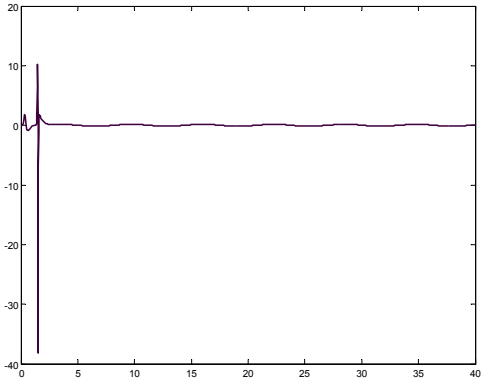

Fig. 1.CONTRAL INPUT

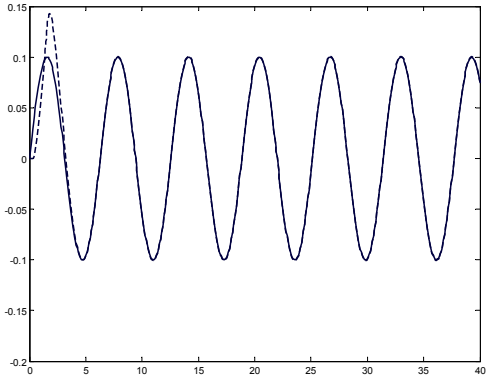

Fig. 2. OUTPUT OF THE CLOSED-LOOP SYSTEM (DASH LINE) AND THE REFERENCE SIGNAL(SOLID LINE)

CONCLUSION

Combining the feedback linearization technique and the fuzzy theory based adaptive control technique, in this work, we developed a robust adaptive controller design method for a class of non-affine nonlinear systems represented by input-output models. Using Mamdani fuzzy logic systems and Nussbaum control gain technique, our method can handle the class of systems with totally unknown nonlinear functions. Based on Lyapunov stability theorem, the stability analysis shows that the proposed control scheme guarantees that the signals in the closed-loop system are all semi-globally uniformly ultimately bounded.

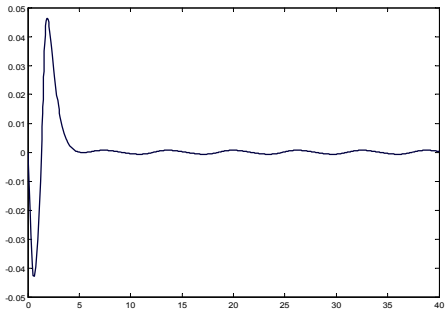

FIG. 3.TRACKING ERROR

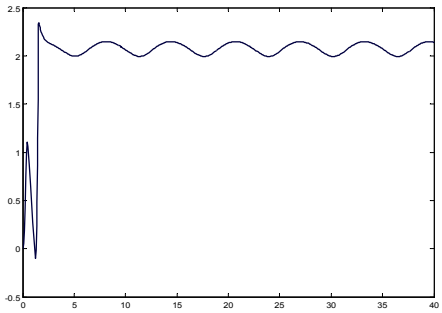

FIG. 4.THE CURVE OF ζ

REFERENCES

[1] Y. Li, S. Tong, T. Li, Adaptive Fuzzy Backstepping Control Design for a Class of Pure-Feed Switched Nonlinear Systems, Nonlinear Analysis: Hybrid Systems, 2015, 16: 72-80.

[2] T. Tao, S. Su, Moment Adaptive Fuzzy Control and Residue Compensation, IEEE Trans. ON Fuzzy Systems, 2014, 22(4): 803-816.

[3] Q. Zhou, C. Wu, X. Jing, L. Wang, Adaptive Fuzzy Backstepping Dynamic Surface Control for Nonlinear Input-delay Systems, Neurocomputing, 2016, 199(26): 58-65.

[4] H. Han, Ch. Su and Y. Stepanenko, Adaptive Control of a Class of Nonlinear Systems with Nonlinearly Parameterized Fuzzy Approximators, IEEE Trans. on Fuzzy Systems, 2001, 9(2): 315-323.

[5] H. K. Khalil, Adaptive Output Feedback Control of Nonlinear Systems Represented by Input-Output Models, IEEE Trans. on Automat. Contr., 1996, 41(2):177-188.

[6] Y. Liu and X.-Y. Li, Robust Adaptive Control of Nonlinear Systems Represented by Input-Output Models, IEEE Trans. on Automat. Contr., 2003, 48(6):1041-1045.

[7] D. Wang, J. Huang, W. Lan and X. Li, Neural Network Based Robust Adaptive Control of Nonlinear Systems with Unmodeled Dynamics, Mathematics and Computers in Simulation, Volume, 2009, 79(5): 1745-1753.

[8] R. D. Nussbaum, Some Remark on the Conjecture in parameter Adaptive Control, Systems Control Letter, 1983, 3:243-246.

[9] L. Liu and J. Huang, Global Stabilization of Lower Triangular Systems with Dynamic Uncertainties without Knowing the Control Direction, Proceedings of the 2007 American Control Conference, 2007: 5372-5377.

[10] Ge. S. S., Hong F. and Lee T. H., Adaptive Neural Control of nonlinear time-delay systems with unknown virtual control coefficient, IEEE Trans. on Systems, Man, and Cybermetics- Part B: Cybermetics, 2004, 34(1): 2004-2010.

[11] D. Wang and W. Lan, Adaptive Neural Control for a class of Uncertain Nonlinear Systems with Unknow Time-Delay, International Journal of Robust And Nonlinear Control, 2009, 19(7), 807-821.

[12] J. E. Slotine and W. P. Li. Applied Nonlinear Control. Englewood Cliffs, NJ: Prentice-Hall, 1991.

[13] L. X. Wang, A Course in Fuzzy Systems and Control. Englewood Cliffs, NJ: prentice-Hall, 1997.

[14] Ryan, E.p., An universal Adaptive Stabilizer for a Class of Nonlinear Systems, Systems and Control Letters, 1991,16(3): 209-218.

[15] H. K. Khalil. Nonlinear Systems, NJ: Prentice Hall, 2007.

AUTHORS

[1]LI Xiaoqiang(1979-), Doctor, lecturer, His research interests include nonlinear control theory and applications, neural networks, adaptive control. Email: sxxqli@126.com.