http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (1): 186-191, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.186.191
© 2013 Asian Network for Scientific Information

An Adaptive Fuzzy Control Algorithm for Unknown Multivariable Unknown Non-affine Systems

Chunzhi Yang, Heng Liu and Ning Li
Department of Mathematics and Computational Science,
Huainan Normal University, Huainan, 232038, China

Abstract: A new scheme was proposed for the design of fuzzy adaptive control for a class of non-affine systems with unknown control direction. To facilitate the controller design based on the affine-like equivalent model, a Taylor series expansion was used to transform unknown non-affine system into an affine system. The adaptive laws were derived in the Lyapunov sense to ensure the asymptotic stability and tracking of the controlled system. To prove the validity of the proposed method, the simulation results were illustrated in this study.

Key words: Non-affine system, fuzzy controller, adaptive control, fuzzy logic system

INTRODUCTION

The fuzzy controllers emerged to give a new technology to obtain a good performance without having accurate models of process to be controlled. Generally, the basic objective of adaptive control was consistent with the performance, to keep the system in the presence of these uncertainties (Wang, 1994). Direct adaptive fuzzy control was based on the deviation between the actual system performance and ideal performance, through a certain method to adjust the parameters of the controller (Chekireb *et al*., 2003). Adaptive laws to adjust the parameters, the artificial output tracked the reference mode output. Adaptive control was the social nature of the internal control system and improve the areas of research. In the literature (Labiod and Guerra, 2007; Chekireb *et al*., 2003; Wang, 1994), many of the results had been reported capable of preserving stability and robustness for some nonlinear systems.

In recent decades, uncertain nonlinear systems, adaptive fuzzy control theory is increasingly becoming a hot issue. The theory had made many achievements in the control field of the affine nonlinear system. But in practice, there were many non-affine structure of nonlinear systems, such as biochemical processes, so the study of non-affine system control has a practical significance (Labiod and Guerra, 2007; Liu *et al*., 2009).

A direct adaptive fuzzy controller based on any observers for a class of SISO (Single-Input-Single-Output) affine nonlinear system had been proposed by Boulkroune *et al.* (2008). Three fuzzy adaptive controllers for a class of MIMO (Mult-Input-Mult-Output) uncertain nonlinear systems were introduced by Boulkroune *et al.* (2010a), some similar class of MIMO non-affine systems had been considered by Park and Park (2003), Park and Kim (2004), Park *et al*. (2005) and Doudou and Khaber (2012). A class of MIMO uncertain nonlinear system was adaptive and fuzzy, its output tracking control be discussed by Liu *et al*. (2009). In order to estimate the true control direction, a unique Nussbaum-type function had been especially employed for dealing with the unknown control direction by Boulkroune *et al.* (2012).

In this study, an adaptive fuzzy controller was proposed, this controller was a class of uncertain multivariable non-affine systems with unknown control direction. Taylor series expansion of higher order terms fuzzy approximation error to compensate for a dynamic and robust adaptive control. The fuzzy system was employed to approximate the unknown nonlinear function, the adaptive law updated the parameters of the Lyapunov stability analysis of the model so that finite-time convergence of tracking error and closed-loop stability can be guaranteed.

PROBLEM DESCRIPTION

Consider the following equation that can be used to describe a class of non-affine nonlinear uncertain systems:

$$\begin{cases} \dot{y}_1 = f_1(x,u) + \Delta_1(t) \\ \dot{y}_2 = f_2(x,u) + \Delta_2(t) \\ \quad \vdots \\ \dot{y}_n = f_n(x,u) + \Delta_n(t) \end{cases} \tag{1}$$

Corresponding Author: Chunzhi Yang, Department of Mathematics and Computational Science, Huainan Normal University, Huainan, 232038, China

where, $x = [x^T_1, ..., x^T_n]^T \in R^n$ is the state vector which is assumed available for measurement. $u = [u_1, ..., u_n]^T \in R^n$ is the control input vector and f_i (x, u), i = 1,2, ..., n are smooth unknown nonlinear functions, $\Delta_i(t)$, i = 1, ..., n are unknown bounded disturbance.

Denote:

- $\dot{y} = [\dot{y}_1, \cdots, \dot{y}_n]^T$
- $F(x,u) = [f_1(x,u), \cdots, f_n(x,u)]^T$
- $\Delta(t) = [\Delta_1(t), \cdots, \Delta_n(t)]^T$

The system (1) can be rearranged in the following compact form:

$$\dot{y} = F(x,u) + \Delta(t) \tag{2}$$

The objective of this study is to design a control law u_i such that the output vector asymptotically tracks a time varying desired trajectory $y_d = [y_{d1}, ..., y_{dn}]^T \in R^n$ with all signals in the closed-loop system remain bounded uncertainty and bounded external disturbances. Throughout this study the following assumptions and made:

Assumption 1: The desired trajectory $x_d(t) = [y_{d1}, \dot{y}_{d1}, ..., y_{dn}, \dot{y}_{dn}]^T$ is continuous, bounded and available for measurement, x_d is a known compact set.

Assumption 2: The matrix:

$$\frac{\partial F(x,u)}{\partial u}$$

is no-singular, its sign is positive definite or negative definite.

Define the tracking error is:

$$e_1 = y_{d1} - y_1$$
$$\vdots$$
$$e_n = y_{dn} - y_n$$

and $e = [e_1, ..., e_n]^T$.

The time derivative of e is given by:

$$\dot{e} = \dot{y}_d - \dot{y} = \dot{y}_d - [F(x,u) + \Delta(t)] \tag{3}$$

Now, in order to facilitate the control system design for the system (2), the non-affine system (2) can be transformed into the affine system (4).

$$F(x,u) = F(x,u^*(x)) - \frac{\partial F(x,u)}{\partial u}\Big|_{u=u^*(x)} u^*(x) + \frac{\partial F(x,u)}{\partial u}\Big|_{u=u^*(x)} + H(x,u) = F(x) + G(x)u + H(x,u) \tag{4}$$

Where:

$$F(x) = F(x,u^*(x)) - \frac{\partial F(x,u)}{\partial u}\Big|_{u=u^*(x)} u^*(x) = [F_1(x), \cdots, F_n(x)]^T$$
$$G(x) = \frac{\partial F(x,u)}{\partial u}\Big|_{u=u^*(x)} = [g_{ii}(x)]$$

H (x, u) is the higher order terms of the Taylor series expansion, u = u* (x) is an unknown optimal control and an unknown smooth function minimizing the higher order terms.

In order to study the controller design and stability analysis, the following important lemma and realistic assumption are considered.

Lemma 1: Any real matrix $G(x) \in R^{n\times n}$ with non-zero leading principal minors can be decomposed follows:

$$G(x) = G_e(x)DT(x) \tag{5}$$

where, $G_e(x) \in R^{n\times n}$ is a symmetric positive-definite matrix, $D \in R^{n\times n}$ is a diagonal matrix whose elements are +1 or -1 and T(x) is a unity upper triangular matrix. Moreover, the diagonal elements d_{ii} of D are nothing else than the ratios of the signs of the leading principal minors of G(x).

Proof of lemma 1: See the proof in Ge and Wang (2002a, b).

Assumption 3:

- The sign of G(x) is unknown, but it must be positive-definite or negative-definite
- Ge(x) and

$$\frac{d}{dt}G_e^{-1}(x)$$

are continuous functions

- $\frac{\partial g_{ij}(x)}{\partial y_j} = 0 \ \forall i = 1, \cdots, n, j = 1, \cdots, n$

Remark 1:

- Assumption 3 is satisfied many affine physical systems, namely robotic systems and electric machines
- The required property on the partial derivatives of the control gain matrix ensure that

$$\frac{d}{dt}G_e^{-1}(x)$$

does not depend on the system inputs.

Substituting Eq. 5 into the tracking error dynamics Eq. 3, it yields:

$$\dot{e} = \dot{y}_d - F(x) - G_e(x)DT(x)u(t) - H(x,u) - \Delta(t) \quad (6)$$

Equation 6 can be arranged as follows:

$$G_1(x)\dot{e} = F_1(x,u) - Du - H_1(x,u,\Delta) \quad (7)$$

Posing

- $G_1(x) = G_e^{-1}(x)$
- $F_1(x,u) = G_1(x)[\dot{y}_d - F(x)] - [DT(x) - D]u$
- $H_1(x,u,\Delta) = G_1(x)(H(x,u) + \Delta(t))$

Equation 7 can be written as:

$$\begin{aligned} G_1(x)\dot{e} + \frac{1}{2}\dot{G}_1(x)e &= F_1(x,u) + \frac{1}{2}\dot{G}_1(x)e - Du - H_1(x,u,\Delta) \\ &= \alpha(\bar{z}) - Du - H_1(x,u,\Delta) \end{aligned} \quad (8)$$

Where:

$$\alpha(\bar{z}) = [\alpha_1(\bar{z}),\cdots,\alpha_n(\bar{z})]^T = F_1(x,u) + \frac{1}{2}\dot{G}_1(x)e$$

with $\bar{z} = [\bar{z}_1^T,\cdots,\bar{z}_n^T]^T$. By carefully examining the expressions of $F_1(x, u)$, $\alpha(\bar{z})$, the vectors $\bar{z}_i$ can be determined as follows:

$$\begin{aligned} \bar{z}_1 &= [x^T, u_2,\cdots,u_n]^T \\ \bar{z}_2 &= [x^T, u_3,\cdots,u_n]^T \\ &\vdots \\ \bar{z}_{n-1} &= [x^T, u_n]^T \\ \bar{z}_n &= x \end{aligned}$$

It is clear from the property of the matrix Dt(x) -D, that $\bar{z}_1$ depends on control in puts u_2, ..., u_n, $\bar{z}_2$ depends on control in puts u_3, ..., u_n and so on. The nonlinearity $\alpha(\bar{z})$ has an upper triangular control structure, allowing there by for algebraic loop free sequential determination of the control variables u_i, for i = 1, 2, ..., n.

Remark 2: In the Eq. 8, the nonlinear functions $\alpha(\bar{z})$, H_1 (x, u, Δ) are unknown, moreover H_1 (x, u, Δ) depends explicitly on the input u, the control system design to asymptotically stabilize the dynamics is very difficult, so we will use an adaptive fuzzy system to approximate the unknown nonlinear function $\alpha(\bar{z})$ and a dynamic adaptive robust control to dynamically compensate for the effect of the uncertain nonlinearity H_1 (x, u, Δ).

DESIGN OF THE FUZZY LOGIC SYSTEM

Since the function α(x) is unknown, the control system design to asymptotically stabilize the dynamics is very difficult. In this study, fuzzy systems are employed to approximate the equivalent controller. Using the product-inference rule, singleton fuzzifier and center-average defuzzifier then the output of the fuzzy system can be defined as:

$$\alpha(x) = \frac{\sum_{j=1}^{N}\theta_j \Pi_{i=1}^{n}\mu_{F_i^j}(x_i)}{\sum_{j=1}^{N}[\Pi_{i=1}^{n}\mu_{F_i^j}(x_i)]} \quad (9)$$

where, N is the number of total fuzzy rules, x is the input vector, $\mu_{F_i^j}$ is x_i's membership of jth rule and θ_j is the centroid of the jth consequent set. Equation 9 can be rewritten as following equation:

$$\alpha(x) = \theta^T\psi(x) \quad (10)$$

with:

$$\theta = [\theta_1,\cdots,\theta_N]^T \quad \psi(x) = [p_1(x), p_2(x),\cdots,p_N(x)]^T$$

and the fuzzy basis function can be writing as:

$$p_j(x) = \frac{\Pi_{i=1}^{n}\mu_{F_i^j}(x_i)}{\sum_{j=1}^{N}[\Pi_{i=1}^{n}\mu_{F_i^j}(x_i)]}$$

So, by applying the introduced fuzzy systems in Eq. 10 and N fuzzy rules:

Rule i: if x_1 is F_1^i and ... and x_n is F_n^i then α(x) is B_i, i = 1, 2, ..., N. Then $\alpha(\bar{z})$ can be approximated, over compact set $\Omega_{\bar{z}i}$, by the fuzzy system Eq. 10 as:

$$\hat{\alpha}(\bar{z},\theta) = \theta^T\psi(\bar{z}) \quad (11)$$

Define the ideal parameters of θ_i as:

$$\theta_i^* = \underset{\theta_i}{\arg\min}[\sup_{\bar{z}_i \in \Omega_{\bar{z}_i}} |\alpha_i(\bar{z}_i) - \hat{\alpha}_i(\bar{z}_i,\theta_i)|]$$

Note that the ideal parameter θ_i^* is introduced only for the purposes of analysis and its value is not needed when implementing the controller. Define the parameter estimation error and the fuzzy approximation error as follows:

$$\tilde{\theta}_i = \theta_i - \theta_i^* \quad (12)$$

and

$$\varepsilon_i(\bar{z}_i) = \alpha_i(\bar{z}_i) - \hat{\alpha}_i(\bar{z}_i, \theta_i^*) \tag{13}$$

with $\hat{\alpha}_i(\bar{z}_i, \theta_i^*) = \theta_i^{*T}\psi_i(\bar{z}_i)$.

As in literature (Boulkroune *et al*., 2008, 2010a, b, 2011, 2012), assumed the fuzzy approximation errors is bound for all $\bar{z}_i \in \Omega_{\bar{z}i}$, i.e., $|\varepsilon_i(\bar{z})| \le \bar{\varepsilon}_i$, $\bar{\varepsilon}_i$ is unknown constant.

Now, denote:

$$\begin{aligned}\hat{\alpha}(\bar{z},\theta) &= [\hat{\alpha}_1(\bar{z}_1,\theta_1),\cdots,\hat{\alpha}_n(\bar{z}_n,\theta_n)]^T \\ &= [\theta_1^T\psi_1(\bar{z}_1),\cdots,\theta_n^T\psi_n(\bar{z}_n)]^T\end{aligned}$$

$$\varepsilon(\bar{z}) = [\varepsilon_1(\bar{z}_1),\cdots,\varepsilon_n(\bar{z}_n)]^T$$

$$\bar{\varepsilon} = [\bar{\varepsilon}_1,\cdots,\bar{\varepsilon}_n]^T$$

From above analysis, it yields:

$$\begin{aligned}\hat{\alpha}(\bar{z},\theta) - \alpha(\bar{z}) &= \hat{\alpha}(\bar{z},\theta) - \hat{\alpha}(\bar{z},\theta^*) + \hat{\alpha}(\bar{z},\theta^*) - \alpha(\bar{z}) \\ &= \hat{\alpha}(\bar{z},\theta) - \hat{\alpha}(\bar{z},\theta^*) - \varepsilon(\bar{z}) = \tilde{\theta}^T\psi(\bar{z}) - \varepsilon(\bar{z})\end{aligned} \tag{14}$$

Where:

$$\tilde{\theta}^T\psi(\bar{z}) = [\tilde{\theta}_1{}^T\psi_1(\bar{z}_1),\cdots\tilde{\theta}_n{}^T\psi_n(\bar{z}_n)]^T$$

and $\tilde{\theta}_i = \theta_i - \theta_i^*$, for i = 1, ..., n.

From Eq. 14 and Eq. 8 can be written as:

$$\begin{aligned}&\frac{d}{dt}[\frac{1}{2}e^TG_1(x)e] = e^T[\alpha(\bar{z}) - Du - H_1(x,u,\Delta)] \\ &= -e^T\tilde{\theta}^T\psi(\bar{z}) + e^T\varepsilon(\bar{z}) + e^T\alpha(\bar{z},\theta) - e^TDu - e^TH_1(x,u,\Delta)] \\ &= -e^T\tilde{\theta}^T\psi(\bar{z}) + e^T\alpha(\bar{z},\theta) - e^TDu + e^T[\varepsilon(\bar{z}) \\ &-H_1(x,u,\Delta) + \vartheta^*\text{sign}(e)] - \frac{1}{2}\sum_{i=1}^{n}\sigma_{\theta_i}|e_i|\|\theta_i^*\|^2\end{aligned} \tag{15}$$

Where:

$$\vartheta^* = \text{diag}[\frac{1}{2}\sigma_{\theta_1}\|\theta_1^*\|^2,\cdots,\frac{1}{2}\sigma_{\theta_n}\|\theta_n^*\|^2]$$

$\sigma_{\theta i}$ is positive design constants.

Posing $H_2(x, u, e) = \varepsilon(\bar{z}) - H_1(x, u, \Delta) + \partial^* \text{sing}(e)$.

In the sequel, the following realistic assumption is necessary.

Assumption 4: The following inequality is assumed to form:

$$|H_2(x,u,e)| \le k^*\bar{H}(x,u)$$

with $\bar{H}(x, u) = 1+\|x\|+\|u\|$. where, $k^* = [k^*_1,\ldots, k^*_n]^T$ is an unknown constant vector.

For the system (1), the following fuzzy adaptive controller can be considered:

$$u = D[\hat{\alpha}(\bar{z},\theta) + Ke + k_A\text{sign}(e)] \tag{16}$$

Where:

$$D = D^{-1} = \text{diag}[d_{11},\cdots,d_{mn}]$$

After substituting the control law Eq. 16 into Eq. 15, it yields:

$$\begin{aligned}\frac{d}{dt}[\frac{1}{2}e^TG_1(x)e] &\le e^T\alpha(\bar{z}) - e^T[\hat{\alpha}(\bar{z},\theta) + Ke + -k_A\text{sign}(e)] + |e^T|k^*\bar{H}(x,u) \\ &= e^T\alpha(\bar{z}) - e^T\hat{\alpha}(\bar{z},\theta) - e^TKe - |e^T|k_A + |e^T|k^*\bar{H}(x,u) \\ &= e^T[\alpha(\bar{z}) - \hat{\alpha}(\bar{z},\theta)] + |e^T|\bar{H}(x,u)k^* - \sum_{i=1}^{n}k_ie_i^2 - |e^T|k_A \\ &= e^T\varepsilon(\bar{z}) - e^T\tilde{\theta}^T\psi(\bar{z}) + |e^T|\bar{H}(x,u)k^* - \sum_{i=1}^{n}k_ie_i^2 - |e^T|k_A \\ &= e^T\varepsilon(\bar{z}) - |e^T|k_A - e^T\tilde{\theta}^T\psi(\bar{z}) + |e^T|\bar{H}(x,u)k^* - \sum_{i=1}^{n}k_ie_i^2\end{aligned} \tag{17}$$

Adaptation laws associated to the proposed controller Eq. 16 are given by:

$$\dot{\theta}_i = \gamma_ie_i\psi_i(\bar{z}_i) \text{ for } i = 1,\cdots,n \tag{18}$$

where, γ_i is positive design constant.

The main result is summarized by the following theorem.

Theorem 1: Consider system (1), suppose that Assumption 1 is satisfied. Then the control law defined by Eq. 16 guarantees the following properties: (1) All signals in the closed loop system are bounded. (2) The tracking errors and their derivatives decrease asymptotically to zero i.e.:

$$e_i(t) \to 0 \text{ as } t \to \infty \text{ for } i = 1, ..., n$$

Proof of theorem 1: Since $G_1(x)$ is symmetric positive-definite, the following Lyapunov function is defined:

$$V = \frac{1}{2}e^TG_1(x)e + \frac{1}{2}\sum_{i=1}^{n}\frac{1}{\gamma_i}\tilde{\theta}_i^T\tilde{\theta}_i \tag{19}$$

where, $\tilde{\theta}_i = \theta_i - \theta_i^*$ for i = 1, ..., n.

The time derivative of V is given by:

$$\dot{V} = \frac{d}{dt}[\frac{1}{2}e^TG_1(x)e] + \sum_{i=1}^{n}\frac{1}{\gamma_i}\tilde{\theta}_i^T\dot{\theta}_i \tag{20}$$

Using Eq. 17-20 can be bounded as follows:

$$\begin{aligned}\dot{V} &\le e^T\varepsilon(\bar{z}) - |e^T|k_A - e^T\tilde{\theta}^T\psi(\bar{z}) + |e^T|\bar{H}(x,u)k^* \\ &- \sum_{i=1}^{n} k_i e_i^2 + \sum_{i=1}^{n} e_i\tilde{\theta}_i^T\psi_i(\bar{z}_i) - \sum_{i=1}^{n} |e_i| k_i^* \bar{H}_i(x,u) \\ &\le -\sum_{i=1}^{n} k_i e_i^2 \le 0\end{aligned} \tag{21}$$

where, $k_A = \text{diag}[k_{A1}, ..., k_{An}]$, $k_{Ai}>0$, $i = 1, ..., n$. k_{Ai} is a adjustable constant, that ensures the following inequality Eq. 22 holds:

$$e^T\varepsilon(\bar{z}) + |e^T| k^* \bar{H}(x,u) - |e^T| k_A \le 0 \tag{22}$$

From Eq. 21 and using the Barbalat's lemma, It can be easily showed, $e_i \to 0$ when $t \to \infty$. Therefore, the tracking errors and their derivatives converge asymptotically to zero.

SIMULATION STUDIES

Here, simulation studies are carried out to show the effectiveness of the proposed adaptive fuzzy controller. we consider the tracking control problem of an academic non-affine uncertain system. The dynamic equations of this system are give by:

$$\begin{cases}\dot{x}_1 = x_1 x_2 + u_1 + (1 + x_2^2)u_2 + \Delta_1(t) \\ \dot{x}_2 = (x_1 + x_2)^2 - 0.5u_1 + (2 + \sin x_1)u_2 + \Delta_2(t)\end{cases} \tag{23}$$

where, $x = [x_1, x_2]^T$ is the state vector of the system, u_1 and u_2 are the control inputs. $\Delta(t)_1$ and $\Delta(t)_2$ are external disturbances, These are considered to be square waves having an amplitude ± 1 with a period of 2π(s). The control objective consists in allowing the system outputs x_1 and x_2 to track the desired trajectories $x_{d1} = \sin(t)$ and $x_{d2} = \sin(t)$, respectively.

The design parameters and initial conditions are chosen as follows:

$$\gamma_1 = \gamma_2 = 100,\ x_1(0) = 2,\ x_2(0) = -1.\ k_1 = k_2(0) = 1,$$
$$\theta_1(0) = \theta_2(0) = \text{null vector}$$

Simulation results in Fig. 1-3 are obtained by applying the design algorithm to the system (23). The time response of the state variables of the uncertain system are given in Fig. 1 and 2, a better tracking performance is achieved for the desired trajectories x_{d1} and x_{d2}. Boundedness and smoothness of the controllers u_1 and u_2 is described in Fig. 3. The simulation results show that the proposed method is successful in control unknown non-affine system and the states (x_1, x_2) quickly converge to respective desired trajectories (x_{d1}, x_{d2}) is nice.

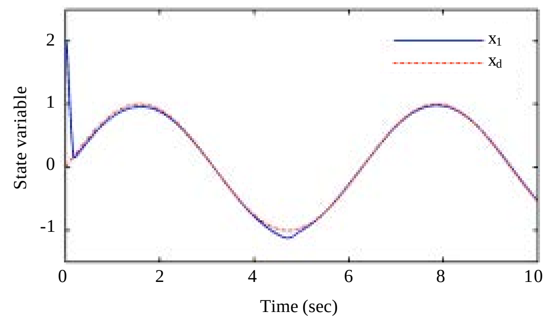

Fig. 1: The time response of the state variable x_1

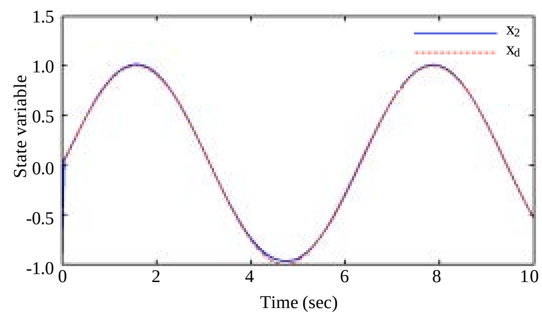

Fig. 2: The time response of the state variable x_2

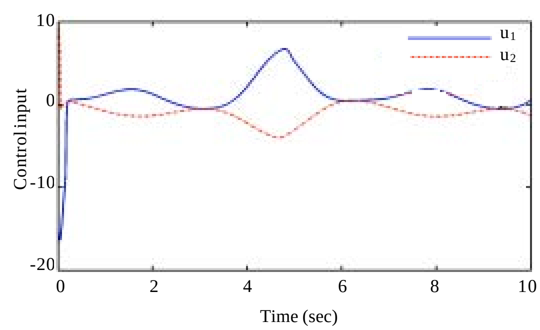

Fig. 3: The control input u

CONCLUSIONS

An adaptive fuzzy tracking control for a class of non-affine uncertain systems has been presented. In the designing of fuzzy adaptive controller, the nature of the control gain matrix factorization has been used. Be design of a fuzzy adaptive law can guarantee the tracking error converges to zero and all of the closed-loop system signal boundedness convergence . The simulation results show the effectiveness of the proposed controller .

ACKNOWLEDGMENTS

This research is jointly supported by the Foundation for the Natural Science Research in College of Anhui Province under Grant No. KJ2011Z357 and Scientific Research General Project of Huainan Normal University under Grant No. 2010QNL5. 2011LK79.

REFERENCES

Boulkroune, A., M. M'Saad, M. Tadjine and M. Farza, 2008. Adaptive fuzzy control for MIMO nonlinear systems with unknown Dead-zone. Proceedings of the 4th International IEEE Conference on Intelligent Systems, September 6-8, 2008, Varna, Bulgaria, pp: 4-45-4-55.

Boulkroune, A., M. Tadjine, M. M'Saad and M. Farza, 2010a. Fuzzy adaptive controller for MIMO nonlinear systems with known and unknown control direction. Fuzzy Sets Syst., 161: 797-820.

Boulkroune, A., M. M'Saad and H. Chekireb, 2010b. Design of a fuzzy adaptive controller for MIMO nonlinear time-delay systems with unknown actuator nonlinearities and unknown control direction. Inf. Sci., 180: 5041-5059.

Boulkroune, A., M. M'Saad and M. Farza, 2011. Adaptive fuzzy controller for multivariable nonlinear state Time-varying delay systems subject to input Non-linearities. Fuzzy Sets Syst., 164: 45-65.

Boulkroune, A., M. M'Saad and M. Farza, 2012. Adaptive fuzzy tracking control for a class of MIMO nonaffine uncertain systems. Neurocomputing, 93: 48-55.

Chekireb, H., M. Tadjine and D. Bouchaffra, 2003. Direct adaptive fuzzy control of nonlinear system class with applications. Control Intell. Syst., 31: 1-11.

Doudou, S. and F. Khaber, 2012. Direct adaptive fuzzy control of a class of MIMO non-affine nonlinear systems. Int. J. Syst. Sci., 43: 1029-1038.

Ge, S.S. and J. Wang, 2002a. Robust adaptive neural control for a class of perturbed strict feedback nonlinear systems. IEEE Trans. Neural Networks, 13: 1409-1419.

Ge, S.S. and C. Wang, 2002b. Adaptive NN control of uncertain nonlinear pure-feedback systems. Automatica, 38: 671-682.

Labiod, S. and T.M. Guerra, 2007. Adaptive fuzzy control of a class of SISO nonaffine nonlinear systems. Fuzzy Sets Syst., 158: 1126-1137.

Liu, Y.J., S.C. Tong and W. Wang, 2009. Adaptive fuzzy output tracking control for a class of uncertain nonlinear systems. Fuzzy Sets Syst., 160: 2727-2754.

Park, J.H. and S.H. Kim, 2004. Direct adaptive output feedback fuzzy controller for a nonaffine of nonlinear systems. IEEE Proc. Control Theory Appl., 151: 65-72.

Park, J.H., S.H. Huh, S.H. Kim, S.J. Seo and G.T. Park, 2005. Direct adaptive controller for nonaffine nonlinear systems using self-structuring neural networks. IEEE Trans. Neural Networks, 16: 414-422.

Park, J.Y. and G.T. Park, 2003. Robust adaptive fuzzy controller for non-affine nonlinear systems with dynamic rule activation. Int. J. Robust Nonlinear Control., 13: 117-139.

Wang, L.X., 1994. Adaptive Fuzzy Systems and Control: Design and Stability Analysis. Prentice-Hall, New Jersey, USA.