Research Article

Fuzzy Adaptive Prescribed Performance Control for MIMO Uncertain Chaotic Systems in Nonstrict Feedback Form

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This paper presents a fuzzy adaptive control method for MIMO uncertain chaotic systems in nonstrict feedback form, which is capable of guaranteeing the prescribed performance bounds. For the prescribed performance bounds, we mean that the tracking error should converge to a predefined arbitrarily small set, with convergence rate no more than a prescribed value. A novel output error transformation is introduced to transform the original constrained system into an equivalent unconstrained one, and it is proved that the stabilization of the unconstrained system is sufficient to solve the problem. Based on the error transformation technique, a fuzzy adaptive controller is designed for the unconstrained system. For updating the parameters of the fuzzy logic systems, a proportional-integral adaptation law is proposed. Finally, an illustrative example is given to demonstrate the effectiveness of the proposed results.

1. Introduction

Chaotic systems have complex dynamical behaviors that possess some special features such as having bounded trajectories in the phase space with positive leading Lyapunov exponent and being extremely sensitive to small variations of initial conditions. Nowadays, chaos has lots of useful applications in information processing, secure communication, biological engineering, lasers, chemical processing, and many other areas [1–3]. However, chaotic behavior can also result in destructive effects; therefore, the undesired chaotic phenomenon needs to be suppressed. The problem of chaos control was firstly studied by Ghezzi and Piccardi [4]. Since then, several control techniques have been successfully applied for the control of chaotic systems, including PID control, observer-based control, adaptive feedback control, sliding mode control, adaptive fuzzy control, and adaptive backstepping control [5–7]. Most of the aforementioned methods have assumed that the model of the chaotic system is known. However, from the viewpoint of practice, most of the chaotic systems are disturbed by external disturbances and model uncertainties. It is worth mentioning that the existence of uncertainties may lead to notable performance

degradations or even instability of the control system. So it is more advisable to take the effects of the system uncertainties and external disturbances into account.

Another important issue associated with the adaptive control of nonlinear system is tracking error performance. Traditionally, nonlinear adaptive control designs guarantee convergence of the tracking error to a residual set, whose size depends on explicit design parameters and some unknown bounded terms. However, on the one hand, no systematic procedure exists to accurately compute the required upper bounds. The problem has been relaxed for feedback linearizable systems in [8, 9]. On the other hand, performance issues on transient behavior (i.e., overshoot and undershoot convergence rate) are hard to be established analytically, even if the nonlinearities are completely known. In [10], L_2 norm of the tracking error which is derived to be a function of initial estimation errors and design parameters is studied. Contributions in guaranteeing prescribed transient and steady state output error bounds can be found in [11–15]. In [11, 12], the tracking error can converge to a neighborhood of prescribed radius $\lambda > 0$, while, in [13], funnel control is established in the light of which the achieved transient behavior is governed by a dynamic gain involving the required transient response

characteristics. In [14], a robust adaptive control scheme for SISO strict feedback nonlinear systems is proposed, which is capable of guaranteeing prescribed performance bounds. In [15], a universal prescribed performance controller is designed for cascade systems involving dynamic uncertainty, unknown nonlinearities, and exogenous disturbances.

To the best of our knowledge, there are few literatures dealing with the prescribed performance control problem for MIMO uncertain chaotic systems in nonstrict feedback form. Inspired by the works in [14, 15], we investigate the tracking control with guaranteed prescribed performance for MIMO uncertain chaotic systems. The unknown nonlinear functions are approximated by fuzzy logic systems. Compared with the related works, the main contributions are listed as follows. (1) The system we consider is not only MIMO but also in nonstrict feedback form. (2) An adaptation PI law based on e -modification is proposed to update the fuzzy parameters. (3) External perturbations are considered in the system.

The rest of this paper is organized as follows. The problem formulation and preliminaries are given in Section 2. The adaptive fuzzy control design with prescribed performance is proposed in Section 3. Section 4 provides a simulation example to illustrate the effectiveness of our results. Finally, Section 5 gives some concluding remarks.

2. Problem Formulation and Preliminaries

Consider the following chaotic dynamic system:

$$\begin{aligned} \dot{x}_1 &= f_1(x) + \sum_{j=1}^n g_{1j}u_j + d_1(t), \\ &\vdots \\ \dot{x}_n &= f_n(x) + \sum_{j=1}^n g_{nj}u_j + d_n(t), \end{aligned} \quad (1)$$

where $x = [x_1, x_2, \dots, x_n]^T \in R^n$ is the system state vector which is assumed to be available for measurement. $u = [u_1, \dots, u_n]^T \in R^n$ is the control input and $d_i(t)$, $i = 1, \dots, n$, are external perturbations. $f_i(x)$, $i = 1, \dots, n$, are unknown nonlinear functions, and g_{ij} , $i, j = 1, \dots, n$, are known constant control gains.

Denote

$$\begin{aligned} f(x) &= [f_1(x), \dots, f_n(x)]^T, \quad d(t) = [d_1(t), \dots, d_n(t)]^T, \\ G &= \begin{bmatrix} g_{11} & \cdots & g_{1n} \\ \vdots & \ddots & \vdots \\ g_{n1} & \cdots & g_{nn} \end{bmatrix}. \end{aligned} \quad (2)$$

Then, system (1) can be rewritten as

$$\dot{x} = f(x) + Gu + d(t). \quad (3)$$

Remark 1. It should be noted that lots of chaotic systems can be described as the form of (3), such as Lorenz system, Chen

system, unified chaotic system, multiscroll chaotic systems, Chua's circuit, and many others.

The objective of this paper is to construct a fuzzy adaptive controller such that

- (P1) the system state x tracks the reference signal $x_d \in R^n$, and all the signals in the closed-loop system remain bounded;
- (P2) the prescribed transient and steady state behavioral bounds on the tracking error $e_i(t) = x_i(t) - x_{di}(t)$, $i = 1, 2, \dots, n$, are achieved.

To meet the objective, we make the following assumptions.

Assumption 2. The control gain matrix G is positive definite.

Assumption 3. The desired trajectory $x_d(t)$ is a known bounded differentiable function.

Remark 4. In fact, there are many physical systems, such as robotic systems and electrical machines, which satisfy Assumption 2. In addition, Assumption 3 is reasonable as well. Similar assumptions can be found in [2, 6, 16, 17].

2.1. Description of the Fuzzy Logic System. The basic configuration of a fuzzy logic system consists of a fuzzifier, some fuzzy IF-THEN rules, a fuzzy inference engine, and a defuzzifier. The fuzzy inference engine uses the fuzzy IF-THEN rules to perform a mapping from an input vector $x = [x_1, x_2, \dots, x_n]^T \in R^n$ to an output $\alpha(x) \in R$. The i th fuzzy rule is written as

$$\text{Rule } i: \text{ if } x_1 \text{ is } F_1^i, \dots, x_n \text{ is } F_n^i \text{ then } \alpha(x) \text{ is } \alpha_i, \quad (4)$$

where $F_1^i, F_2^i, \dots, F_n^i$ are fuzzy sets and α_i is the fuzzy singleton for the output in the i th rule. By using the singleton fuzzifier, product inference, and the center-average defuzzifier, the output of the fuzzy system can be expressed as follows:

$$\alpha(x) = \frac{\sum_{j=1}^N \alpha_j \prod_{i=1}^n \mu_{F_i^j}(x_i)}{\sum_{j=1}^N \left[\prod_{i=1}^n \mu_{F_i^j}(x_i) \right]} = \theta^T \psi(x), \quad (5)$$

where $\mu_{F_i^j}(x_i)$ is the degree of membership of x_i to F_i^j , N is the number of fuzzy rules, $\theta = [\alpha_1, \dots, \alpha_N]^T$ is the adjustable parameter vector, and $\psi(x) = [p_1(x), p_2(x), \dots, p_N(x)]^T$, where

$$p_j(x) = \frac{\prod_{i=1}^n \mu_{F_i^j}(x_i)}{\sum_{j=1}^N \left[\prod_{i=1}^n \mu_{F_i^j}(x_i) \right]} \quad (6)$$

is the fuzzy basis function. It is assumed that fuzzy basis functions are selected so that there is always at least one active rule.

FIGURE 1: Tracking error prescribed performance.

3. Adaptive Fuzzy Control Design with Prescribed Performance

P2 is introduced in the analysis with the help of the performance function which translates the prescribed performance characteristics into tracking error constraints.

Definition 5. A smooth function $y : R_+ \rightarrow R_+ - \{0\}$ is called a performance function if $y(t)$ is decreasing and $\lim_{t \rightarrow \infty} y(t) = y_\infty > 0$.

Hence, we can guarantee P2 by satisfying

$$-y(t) \leq e(t) \leq y(t), \quad (7)$$

for all $t \geq 0$ and $y(t)$ is a performance function associated with the tracking error $e(t)$. The constant y_∞ represents the maximum allowable size of the tracking error $e(t)$ at the steady state, and the decreasing rate of the performance function $y(t)$ represents a lower bound on the required speed of convergence of $e(t)$. The aforementioned statements are shown in Figure 1.

3.1. Error Transformation. In order to meet the control objective, we introduce an error transformation technique, which can transform the original nonlinear system into an equivalent unconstrained system.

Define

$$e_i(t) = y_i(t) s_i(z_i), \quad i = 1, 2, \dots, n, \quad (8)$$

where $y_i(t)$ are performance functions, z_i are the transformed errors, and $s_i(\cdot)$ are smooth, strictly increasing functions and satisfy the following conditions:

$$\begin{aligned} -1 \leq s_i(z_i) \leq 1, \quad \lim_{z_i \rightarrow -\infty} s_i(z_i) &= -1, \\ \lim_{z_i \rightarrow +\infty} s_i(z_i) &= 1. \end{aligned} \quad (9)$$

Obviously, if z_i is bounded, we can obtain $-1 < s_i(z_i) < 1$. Therefore, we have $-y(t) < e(t) < y(t)$. That is to say, if z_i are kept bounded, we can guarantee (7).

Note that $s_i(z_i)$ are strictly increasing functions, and we have the following inverse transformation:

$$z_i = s_i^{-1} \left(\frac{e_i(t)}{y_i(t)} \right), \quad i = 1, 2, \dots, n. \quad (10)$$

Differentiating (10) with respect to time yields

$$\begin{aligned} \dot{z}_i &= \frac{\partial s_i^{-1}}{\partial (e_i(t)/y_i(t))} \frac{1}{y_i(t)} \\ &\times \left[f_i(x) + d_i(t) + \sum_{j=1}^n g_{ij} u_j - \dot{x}_{di} - \frac{e_i(t) \dot{y}_i(t)}{y_i(t)} \right]. \end{aligned} \quad (11)$$

Let us define

$$r_i = \frac{\partial s_i^{-1}}{\partial (e_i(t)/y_i(t))} \frac{1}{y_i(t)} > 0, \quad v_i = -\dot{x}_{di} - \frac{e_i(t) \dot{y}_i(t)}{y_i(t)}. \quad (12)$$

Then (11) can be rewritten as

$$\dot{z}_i = r_i \left[f_i(x) + d_i(t) + \sum_{j=1}^n g_{ij} u_j + v_i \right], \quad i = 1, 2, \dots, n. \quad (13)$$

Let $z = [z_1, \dots, z_n]^T$, $v = [v_1, \dots, v_n]^T$, $\Gamma = \text{diag}[r_1, \dots, r_n]$, $\gamma(x) = f(x) + d(t)$. Then (13) can be written as the following compact form:

$$\dot{z} = \Gamma [\gamma(x) + Gu + v]. \quad (14)$$

Remark 6. There exist smooth and strictly increasing functions $s_i(\cdot)$ which satisfy condition (9). For example, we can choose the function $s_i(z_i) = \tanh(z_i) = (e^{z_i} - e^{-z_i}) / (e^{z_i} + e^{-z_i})$.

3.2. Adaptive Fuzzy Control Design. Since the nonlinear function $\gamma(x)$ is unknown, we employ fuzzy systems to approximate it. By the fuzzy logic systems (5), the nonlinear function $\gamma_i(x)$ can be approximated as

$$\hat{\gamma}_i = \theta_i^T \psi(x), \quad i = 1, 2, \dots, n, \quad (15)$$

where $\gamma_i(x)$ is the i th element of the nonlinear function $\gamma(x)$. Let us define the ideal parameters of θ_i as

$$\theta_i^* = \arg \min_{\theta_i} [\sup |\gamma_i(x) - \hat{\gamma}_i(x)|]. \quad (16)$$

Define the parameter estimation errors and the fuzzy approximation errors as follows:

$$\tilde{\theta}_i = \theta_i - \theta_i^*, \quad (17)$$

$$\varepsilon_i(x) = \gamma_i(x) - \hat{\gamma}_i(x, \theta_i^*),$$

with $\hat{\gamma}_i(x, \theta_i^*) = \theta_i^{*T} \psi(x)$. As in the literature [2], we can assume that the fuzzy approximation error is bounded for all x ; that is, $|\varepsilon_i(x)| < \bar{\varepsilon}_i$, where $\bar{\varepsilon}_i$ is unknown constant. Let $\varepsilon = [\varepsilon_1(x), \dots, \varepsilon_n(x)]^T$, $\bar{\varepsilon} = [\bar{\varepsilon}_1, \dots, \bar{\varepsilon}_n]^T$. Then we can get $|\varepsilon(x)| \leq \bar{\varepsilon}$. From the above analysis, we have

$$\begin{aligned} \hat{\gamma}(x, \theta) - \gamma(x) &= \hat{\gamma}(x, \theta) - \hat{\gamma}(x, \theta^*) + \hat{\gamma}(x, \theta^*) - \gamma(x) \\ &= \tilde{\theta}^T \psi(x) - \varepsilon(x), \end{aligned} \quad (18)$$

where $\hat{\gamma}(x, \theta) = [\hat{\gamma}_1(x, \theta_1), \dots, \hat{\gamma}_n(x, \theta_n)]^T$. Then the controller can be constructed as

$$u = G^{-1} [-\theta^T \psi(x) - v - Kz + u_r], \quad (19)$$

with

$$u_{ri} = -\text{sign}(z_i) r_i \hat{\varepsilon}_i, \quad i = 1, 2, \dots, n, \quad (20)$$

where $K = \text{diag}[k_1, \dots, k_n]$ with $k_i > 0, i = 1, 2, \dots, n$, are free positive constants of the design. $\hat{\varepsilon}_i$ are the design parameters.

Multiplying z^T to (14) and using (18)–(20), we obtain that

$$\begin{aligned} z^T \dot{z} = & -\sum_{i=1}^n r_i k_i z_i^2 - \sum_{i=1}^n r_i z_i \tilde{\theta}_i^T \psi(x) \\ & + \sum_{i=1}^n r_i z_i \varepsilon_i(x) - \sum_{i=1}^n z_i u_{ri}. \end{aligned} \quad (21)$$

In order to meet the control objective, $\hat{\varepsilon}_i$ and the fuzzy parameters θ_i are updated by

$$\theta_i = \int_0^t [-\sigma_i \gamma_{0i} |z_i| \theta_i + \gamma_{0i} z_i \psi(x)] d\tau - \gamma_{1i} \delta_i, \quad (22)$$

with $\delta_i = \sigma_i |s_i| \theta_i - s_i \psi(x)$, and $\gamma_{0i}, \gamma_{1i}, \sigma_i > 0$ are design constants.

Remark 7. It should be noted that, compared with the related literatures, a new PI adaption law (22) is proposed in this paper. In (22), the term $-\sigma_i \gamma_{0i} |z_i| \theta_i$, which is borrowed from the e -modification concept, has the task of keeping the parameter bounded, and δ_i are proportional terms which can make the fuzzy parameters a fast convergence.

Now we turn back to our original problem that designing a controller in the form of (19) such that P1 and P2 are satisfied. The solution of this problem is given by the following theorem.

Theorem 8. Consider system (3). Suppose that Assumptions 2 and 3 are satisfied. Then controller (19) with the adaption law given by (22) can guarantee the transient and steady state tracking error behavioral bounds introduced by the performance function $y(t)$ and the output transformation (10). Furthermore, the transformed system is sufficient to guarantee the prescribed performance.

Proof. Consider the following Lyapunov function:

$$V = \frac{1}{2} z^T z + \frac{1}{2} \sum_{i=1}^n \frac{r_i}{\gamma_{0i}} (\tilde{\theta}_i + \gamma_{1i} \delta_i)^T (\tilde{\theta}_i + \gamma_{1i} \delta_i). \quad (23)$$

The time derivative of V is given by

$$\dot{V} = z^T \dot{z} + \sum_{i=1}^n \frac{r_i}{\gamma_{0i}} (\tilde{\theta}_i + \gamma_{1i} \delta_i)^T (\dot{\tilde{\theta}}_i + \gamma_{1i} \dot{\delta}_i) = \dot{V}_1 + \dot{V}_2. \quad (24)$$

From (21) and (22), we have

$$\begin{aligned} \dot{V}_1 = z^T \dot{z} \leq & -\sum_{i=1}^n r_i k_i z_i^2 - \sum_{i=1}^n r_i z_i \tilde{\theta}_i^T \psi(x) \\ & + \sum_{i=1}^n r_i |z_i| \bar{\varepsilon}_i - \sum_{i=1}^n z_i u_{ri}. \end{aligned} \quad (25)$$

By using the inequality $-2\tilde{\theta}_i^T \theta_i \leq -\sum_{i=1}^n \|\tilde{\theta}_i\|^2 + \sum_{i=1}^n \|\theta_i^*\|^2$, we have

$$\begin{aligned} \dot{V}_2 = & \sum_{i=1}^n \frac{r_i}{\gamma_{0i}} (\tilde{\theta}_i + \gamma_{1i} \delta_i)^T (-\sigma_i \gamma_{0i} |z_i| \theta_i + \gamma_{0i} z_i \psi(x)) \\ \leq & \sum_{i=1}^n r_i \tilde{\theta}_i^T \psi(x) z_i - \sum_{i=1}^n r_i \gamma_{1i} \|\delta_i\|^2 - \frac{1}{2} \sum_{i=1}^n r_i \sigma_i |z_i| \|\tilde{\theta}_i\|^2 \\ & + \frac{1}{2} \sum_{i=1}^n r_i \sigma_i |z_i| \|\theta_i^*\|^2. \end{aligned} \quad (26)$$

Then we have

$$\begin{aligned} \dot{V} \leq & -\sum_{i=1}^n r_i k_i z_i^2 + \sum_{i=1}^n |z_i| r_i \bar{\varepsilon}_i + \frac{1}{2} \sum_{i=1}^n r_i \sigma_i |z_i| \|\theta_i^*\|^2 \\ & - \sum_{i=1}^n |z_i| r_i \hat{\varepsilon}_i. \end{aligned} \quad (27)$$

If we choose $\hat{\varepsilon}_i \geq \bar{\varepsilon}_i + 0.5\sigma_i \|\theta_i^*\|^2$, then it yields that

$$\dot{V} \leq -\sum_{i=1}^n r_i k_i z_i^2. \quad (28)$$

Therefore, V is always negative, which implies that z_i and $\tilde{\theta}_i + \gamma_{1i} \delta_i \in L_\infty$. Since z_i keep bounded, we have $-y(t) < e(t) < y(t)$. This completes the proof. $\square$

Remark 9. In order to avoid the algebraic loop problem in (22), the adaption law can be rewritten as

$$\begin{aligned} \theta_i = & \frac{1}{1 + \gamma_{1i} \sigma_i |z_i|} \\ & \times \left(\int_0^t [-\sigma_i \gamma_{0i} |z_i| \theta_i + \gamma_{0i} z_i \psi(x)] d\tau + \gamma_{1i} z_i \psi(x) \right). \end{aligned} \quad (29)$$

Remark 10. Compared with the results in [8, 9], the external perturbations are considered in the paper. Meanwhile, the system we considered is of nonstrict feedback form.

4. Simulation Results

In this section, a simulation example is given to illustrate the effectiveness of the proposed methods. Let us consider the well-known Lü chaotic system which is known as a bridge between the Lorenz system and Chen system [18–20]:

$$\dot{x}(t) = Ax(t) + f(x) + d(t) + Gu(t), \quad (30)$$

FIGURE 2: Tracking errors response.

FIGURE 3: The control inputs.

where

$$A = \begin{pmatrix} -36 & 36 & 0 \\ 0 & 20 & 0 \\ 0 & 0 & -3 \end{pmatrix}, \quad f = \begin{pmatrix} 0 \\ -x_1 x_3 \\ x_1 x_2 \end{pmatrix}, \quad (31)$$

$$G = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

For each variable of the inputs, we define seven Gaussian membership functions uniformly distributed on the interval $[-10, 10]$. We choose the initial values of parameters of the fuzzy systems as $\theta_i = 0$, $i = 1, 2, 3$. The external disturbances are assumed to be $d_1(t) = 5 + \sin t$, $d_2(t) = 1 + \cos t$, $d_3(t) = \sin t + \cos t - 4$. The initial values of the system are selected as $x = [-1, 1, 3]^T$. The desired trajectory is $x_d(t) = [\sin t, \sin t, \sin t]^T$. The transient and steady state errors are prescribed through the performance functions $y_i(t) = 2e^{-0.7t} + 0.05$, $i = 1, 2, 3$, and the transformation functions are $s_i = (2/\pi) \arctan(z_i)$, $i = 1, 2, 3$. The design parameters are chosen as follows: $\gamma_{0i} = 500$, $\gamma_{1i} = 500$, $\sigma_i = 0.05$, $k_i = 1$, $\hat{\varepsilon}_i = 10$, $i = 1, 2, 3$.

The simulation results are shown in Figures 2 and 3, which show that the output tracking with prescribed performance has been achieved.

5. Conclusion

This paper has proposed a robust adaptive fuzzy control method for uncertain chaotic systems with unknown disturbances, which is capable of guaranteeing a prescribed performance. By using prescribed performance functions, we transform the system into an equivalent one, and it is sufficient to guarantee ultimate boundedness property of the transformed output error and a uniform boundedness of other signals in the closed-loop system. Simulation results have shown the effectiveness of the proposed scheme.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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