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Function Vector Synchronization of Uncertain Chaotic Systems with Parameters Variable

Ning Li, Heng Liu, Wei Xiang and Hui Lv
Department of Mathematics and Computer Science, Huainan Normal University,
Huainan 232038, China

Abstract: In this study, a state variable Function Vector Synchronization (FVS) of two non-identical chaotic systems with both varying parameters and delay is investigated. Based on feedback principle and Lyapunov stability theory, the adaptive fuzzy controller is constructed. The synchronization for the state variable function vector of systems can be reached by using the proposed controller. The control is robust for varying parameters and disturbance of systems. Compared with the traditional synchronization, aided by appropriate state variable function vectors of master and slave systems instead of state variables, signal transmission security can be improved. The simulation results shows the effectiveness of the method.

Key words: Chaotic system, fuzzy control, synchronization, function vector synchronization

INTRODUCTION

Since the synchronization problem of two chaotic systems with different initial conditions was investigated (Pecora and Carroll, 1990), the main interest in chaotic synchronization stemmed from its potential applications such as secure communication, digital communication, power electronic devices, biological systems, chemical reaction and design and so on. There were several schemes proposed for the chaotic systems synchronization such as complete (or anti) synchronization (Agiza, 2004; Wang, 2009), phase synchronization (Rosenblum *et al*., 1996), lag synchronization (Chen *et al*., 2007; Miao *et al*., 2009), generalized synchronization (Wang and Guan, 2006; Mainieri and Rehacek, 1999), intermittent lag synchronization (Boccaletti and Valladares, 2000), modified function projective synchronization (Mainieri and Rehacek, 1999). Wang and Liu (2010), Nong and Jian-Fen (2011) investigated modifying function projective synchronization problem of a class of chaotic systems by designing a suitable response system. Shou-Sang and Hang-Feng (2011) proposed a method of time-delay generalized projective synchronization for a class of piece wise modified Lorenz-Stenflo chaotic system. The synchronization of non-autonomous time-varying delay chaotic systems via delayed feedback control was investigated (Betmart *et al*., 2012). By using periodically intermittent nonlinear feedback control, the synchronization scheme for a class of nonlinear delay chaotic systems was proposed (Yu *et al*., 2012). However, based on much potential applications of the synchronizations, investigating more general synchronization strategies become more challenging.

Disturbance was the common phenomenon in engineering. The system parameters could be also varying. To the best of our knowledge, the works studied about the varying parameters are very few. Thus, designing controller for nonlinear systems with parameter variable remained an open problem.

In this study, the state signal function vectors lag synchronization for non-identical master-slave chaotic systems was proposed. The main contributions of this work include:

- The state variable function vector synchronization of a class of chaotic systems with varying parameters was proposed firstly. It was the generalization of literatures (Agiza, 2004; Wang, 2009; Rosenblum *et al*., 1996; Chen *et al*., 2007; Miao *et al*., 2009; Wang and Guan, 2006; Miainieri and Rehacek, 1999; Wang and Liu, 2010; Nong and Jian-Fen, 2011; Shou-Song and Hong-Feng, 2011)
- Proposed master-slave systems contain not only external disturbance but also varying parameters (i.e., parameters have perturbance) and it is evident inevitably in real system running

Corresponding Author: Ning Li, Department of Mathematics and Computer Science, Huainan Normal University, Huainan 232038, China

PROBLEM DESCRIPTION

Consider following master-slave systems:

$$\dot{x} = f(x) + \Delta f(x,p) + \Delta_1(t) \quad (1)$$

$$\dot{y} = g(y) + \Delta g(y,q) + \Delta_2(t) + u \quad (2)$$

In the above equations $x \in R^n$ and $y \in R^n$ are the state vectors. $f(\cdot) \in R^n$ and $g(\cdot) \in R^n$ are nonlinear function vectors. The perturbations:

$$\Delta f(\cdot) = [\Delta f_1(\cdot), \ldots, \Delta f_n(\cdot)]^T \in R^n$$

and

$$\Delta g(\cdot) = [\Delta g_1(\cdot), \ldots, \Delta g_n(\cdot)]^T \in R^n$$

are uncertain bounded continuous function vectors, ρ and q are master and slave systems parameters disturbances. The system disturbances $\Delta_1(t) \in R^n$ and are $\Delta_2(t) \in R^n$ unknown bounded functions. u is the control input.

Define the synchronization error:

$$e = F(x_\tau, t_\tau) - G(y,t) \quad (3)$$

where, $F(\cdot) \in R^n$, $G(\cdot) \in R^n$ are the known smooth function vectors and $x_\tau = x(t_\tau) = x(t-\tau)$, $t_\tau = t-\tau$, $\tau = \tau(t)$ is the system delay, satisfying: $0 \le \tau \le 1$.

Definition 1: Considering the chaotic systems (1) and (2), the systems (1) and (2) are said to be the state signal function vectors primary synchronization (SFVPS), if:

$$\lim_{t\to\infty} \|e\| = \lim_{t\to\infty} \|F(x_\tau, t_\tau) - G(y,t)\| = \varepsilon$$

with ε>0 is small constant and we can say that the systems (1) and (2) are the state Signal Function Vectors Synchronization (SFVS), when ε = 0.

Remark 1: $F(\cdot)$, $G(\cdot) \in R^n$ in Eq. 3 are designed by both sides of the communication, therefore, and they could be modified. The degrees of the freedom of $F(\cdot)$ and $G(\cdot)$ are much great, so, the variability and the randomness of the signals could be increased uncommonly, it is hard to decode than traditional algorithms through signal communication.

Remark 2: We can clearly see that the SFVS is the synchronization, when $F(x_\tau, t_\tau) = x$, $G(y,t) = y$. The FVS is the synchronization of the literature (Nong and Jian-Fen, 2011), as $F(x_\tau, t_\tau) = x$, $G(y,t) = My$, or $F(x_\tau, t_\tau) = Mx$, $G(y,t) = y$.

Remark 3: How little the positive constant ε of system (4) is can be contingent on the specific condition.

Remark 4: The unknown nonlinear function vectors $\Delta f(x, p)$, $\Delta g(y, q)$ in system (1), (2) contain the system parameter disturbances p,q.

The objective of this study is to design a controller such that synchronizing two state variable function vectors of non-identical chaotic systems with varying parameters.

Design of the fuzzy logic system, (FLS): The basic configuration of a fuzzy logic system contains a fuzzifier, some fuzzy IF-THEN rules, a fuzzy inference engine and a defuzzifier. The fuzzy inference engine uses the fuzzy rules to perform a mapping from an input vector x to an output f.

The ith fuzzy rule is written as:

- R^l: If x_1 is F^l_n, x_2 is, F^l_n, ..., x_n is, F^l_n then, f is G^l, l = 1, ..., N.

$x = [x_1, \ldots, x_n]^T$ and f are the input and output of the fuzzy logic system, F^l_n, G^l are the fuzzy sets. Fuzzy logic system could be expressed as follows:

$$f(x) = \frac{\sum_{l=1}^N w_l \prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N [\prod_{i=1}^n \mu_{F_i^l}(x_i)]} \quad (4)$$

Where:

$$w_j = \max_{\overline{w} \in R} \mu_{GJ}(\overline{w})$$

the fuzzy basis function is defined as:

$$\xi_j = \frac{\prod_{i=1}^n \mu_{F_i^l}(x_i)}{\sum_{l=1}^N [\prod_{i=1}^n \mu_{F_i^l}(x_i)]} \quad (5)$$

Define $w = [w_1, \ldots, w_N]^T$, $\xi = [\xi_1, \ldots, \xi_N]^T$, then, fuzzy system could be written as:

$$f(x) = w^T \xi \quad (6)$$

According to fuzzy logic rules, the universal function approximating theorem is given as following:

Lemma 1: g (x) is the continuous function defined at the tight set Ω, then ∀ε>0, there exists the fuzzy system (6), such that:

$$\sup_{x\in\Omega}|g(x)-f(x)|\le\varepsilon \tag{7}$$

MAIN RESULTS

Considered the error (3), the time derivative of e becomes:

$$\begin{aligned}\dot e &= \dot F_{x_\tau}(x_\tau,t_\tau)\dot x_\tau(1-\dot\tau)-\dot G_y(y,t)\dot y+\dot F_{t_\tau}(x_\tau,t_\tau)(1-\dot\tau)-\dot G_t(y,t)\\ &=\dot F_{x_\tau}(x_\tau,t_\tau)(1-\dot\tau)(f(x_\tau)+\Delta f(x_\tau,p)+\Delta_1(t_\tau))\\ &+\dot F_{t_\tau}(x_\tau,t_\tau)(1-\dot\tau)-\dot G_y(y,t)(g(y)+\Delta g(y,q)\\ &+\Delta_2(t)+u)-\dot G_t(y,t))\end{aligned} \tag{8}$$

(8) can be written as:

$$\dot e = H-\dot G_y(y,t)u+\Delta \tag{9}$$

where,

$$\begin{aligned}H&=(\dot F_{x_\tau}(x_\tau,t_\tau)f(x_\tau)+\dot F_{t_\tau}(x_\tau,t_\tau))(1-\dot\tau)\\ &-\dot G_y(y,t)g(y)-\dot G_t(y,t)\end{aligned} \tag{10}$$

$$\begin{aligned}\Delta&=[\Delta_1,\ldots,\Delta_n]^T\\ &=\dot F_{x_\tau}(x_\tau,t_\tau)(1-\dot\tau)(\Delta_1(t_\tau)+\Delta f(x_\tau,p))\\ &-\dot G_y(y,t)(\Delta g(y,q)+\Delta_2(t))\end{aligned} \tag{11}$$

In the controller design, we need the following assumptions.

Assumption 1:

$$\|\dot F_x(x,t)\|\le\eta_F$$
$$\|\dot G_y(x,t)\|\le\eta_1$$

where, are constants.

Assumption 2: $\|\Delta_1(t)\|\le\rho_1$, $\|\Delta_2(t)\|\le\rho_2$, where $\rho_1>0$, $\rho_2>0$ are unknown constants.

Assumption 3: G_y (y,,t) is non-singular matrix and the constant matrix $A\in R^{n\times m}$ is positive definite, i.e., there exists the λ>0, such that A>λI, I is n dimension identity matrix.

Assumption 4: For unknown function Δf_i (x,p), Δg_i (y,q), there exist the continuous functions:

$$\Delta\bar f_i(x) \text{ and } \Delta\bar g_i(y)$$

such that:

$$|\Delta f_i(x,p)|\le\Delta\bar f_i(x)$$
$$|\Delta g_i(y,q)|\le\Delta\bar g_i(y)$$

Remark 5: Assumption 1 and 3 are not restrictive, because the F (x, t) and G (y, t) are designed by both sides of the communication.

Remark 6: The unknown constants ρ_1, ρ_2 in Assumption 2 can be estimated by the adaptive law.

Remark 7: Note that the disturbance vectors p, q are bounded, so the continuous function Δf_i (x, p) and Δg_i (y, q) are bounded too, Hence, Assumption 4 is by no means restrictive, since such functions: $\Delta\bar f_i(x)$, $\Delta\bar g_i(y)$ always exist.

Let us denote:

$$\bar\Delta_i=\eta_1(\Delta\bar f_i(x_\tau)+|\Delta_{1i}(t_\tau)|)+\eta_2(\Delta\bar g_i(y)+|\Delta_{2i}(t)|) \tag{12}$$

then:

$$|\Delta_i|\le\bar\Delta_i, i=1,\ldots,n \tag{13}$$

According to lemma 1, we have:

$$\bar\Delta_i=w_i^{*T}\xi_i+\delta_i \tag{14}$$

where, $|\delta_i|\le\varepsilon_i$, ε_i is unknown constants, w_i^* is the optimal values of w_i, they are assumed to be constant and unknown, with:

$$\tilde w_i=w_i^*-\hat w_i, \tilde k_i=\delta_i-\hat k_i, \quad i=1,\ldots,n \tag{15}$$

The designed controller is following as:

$$u=\dot G_y^{-1}(y,t)(H-\bar u) \tag{16}$$

Where:

$$\bar u=[\bar u_1,\ldots,\bar u_n]^T,$$

with:

$$\bar u_i=\text{sign}(e_i)(-\hat w_i^T\xi_i-\hat k_i)-\lambda_i e_i, \quad i=1,\ldots,n \tag{17}$$

From above discussion, we can get the following conclusions:

Theorem 1: The SFVPS between the master system (1) slave system (2) can be reached, under control law (16).

Proof: From system (3), (9) and (16), we have:

$$\begin{aligned} e^T\dot{e} &= \sum_{i=1}^{n} e_i\bar{u}_i + \sum_{i=1}^{n} e_i\Delta_i \le \sum_{i=1}^{n} e_i\bar{u}_i + \sum_{i=1}^{n}|e_i|\bar{\Delta}_i \\ &= -\sum_{i=1}^{n}|e_i|(\hat{w}_i^T\xi_i + \hat{\varepsilon}_i) - \sum_{i=1}^{n}\lambda_i e_i^2 \\ &+ \sum_{i=1}^{n}|e_i|(w_i^{*T}\xi_i + \varepsilon_i) \\ &= \sum_{i=1}^{n}|e_i|(\tilde{w}_i^T\xi_i + \tilde{\varepsilon}_i) - \sum_{i=1}^{n}\lambda_i e_i^2 \end{aligned} \tag{18}$$

Let us consider the following Lyapunov function:

$$V = \frac{1}{2}e^Te + \frac{1}{2}\sum_{i=1}^{n}\frac{1}{\gamma_{0i}}\tilde{w}_i^T\tilde{w} + \frac{1}{2}\sum_{i=1}^{n}\frac{1}{\gamma_{0i}}\tilde{k}_i^2 \tag{19}$$

The time derivative of V is given by:

$$\begin{aligned} \dot{V} &= e^T\dot{e} - \sum_{i=1}^{n}\frac{1}{\gamma_{0i}}\tilde{w}_i^T\dot{\hat{w}}_i - \sum_{i=1}^{n}\frac{1}{\gamma_{1i}}\tilde{k}_i\dot{\hat{k}}_i \\ &\le \sum_{i=1}^{n}|e_i|(\tilde{w}_i^T\xi_i + \tilde{\varepsilon}_i) - \sum_{i=1}^{n}\lambda_i e_i^2 \\ &- \sum_{i=1}^{n}\frac{1}{\gamma_{0i}}\tilde{w}_i^T\dot{\hat{w}}_i - \sum_{i=1}^{n}\frac{1}{\gamma_{0i}}\tilde{k}_i\dot{\hat{k}}_i \end{aligned} \tag{20}$$

with:

$$\dot{\hat{w}}_i = \gamma_{0i}|e_i|\xi_i + \gamma_{0i}m_{0i}\hat{w}_i,\ \dot{\hat{k}}_i = \gamma_{1i}|e_i| + \gamma_{1i}m_{1i}\hat{k}_i \tag{21}$$

where, γ_{0i}, γ_{1i}, m_{0i}, m_{1i}, γ_{0i}, γ_{1i} are non negative constants, (20) could be written by:

$$\dot{V} \le -\sum_{i=1}^{n}(m_{0i}\tilde{w}_i^T\hat{w}_i + m_{1i}\tilde{k}_i\hat{k}_i,) - \sum_{i=1}^{n}\lambda_i e_i^2 \tag{22}$$

We could easily check that:

$$\begin{aligned} -m_{0i}\tilde{w}_i^T\hat{w}_i &\le -\frac{1}{2}\tilde{w}_i^T\tilde{w}_i + \frac{1}{2}\hat{w}_i^T\hat{w}_i \\ -m_{1i}\tilde{k}_i\hat{k}_i &\le -\frac{1}{2}\tilde{k}_i^2 + \frac{1}{2}\hat{k}_i^2 \end{aligned}$$

(22) becomes:

$$\dot{V} \le -aV + b \tag{23}$$

where:

$$a = \min_i\{2\lambda_i, \gamma_{0i}m_{0i}, \gamma_{1i}m_{1i}\}$$

$$b = \frac{1}{2}\sum_{i=1}^{n}\hat{w}_i^T\hat{w}_i + \frac{1}{2}\sum_{i=1}^{n}\hat{k}_i^2$$

Integrating (22) over $[t_0,t]$, we have:

$$V(t) \le (V(t_0) - \frac{b}{a})e^{-a(t-t_0)} + \frac{b}{a},\ t \ge t_0 \tag{24}$$

Let V (t_0) = 0, then:

$$V(t) \le \frac{b}{a} \tag{25}$$

Remark 8: From system (23,25), we can see that the error e can be exponentially stable quickly by choosing λ_i as much as possible and m_{0i}, m_{1i} as little as possible. When $m_{0i} = m_{1i} = 0$, the error e can converge to zero. However, if λ_i was too great, the burden of the controller could be increased, so, the λ_i must be chosen suitable.

Simulation studies: In this section, we provide an example to show the effectiveness of the proposed method.

Choose Lorenz-Stenflo chaotic system as the master system and Lu's system as the slave system, respectively.

Consider Lorenz-Stenflo chaotic system as following:

$$\begin{cases} \dot{x}_1(t) = a_1(x_2(t) - x_1(t)) + d_1x_4(t) \\ \dot{x}_2(t) = x_1(t)(c_1 - x_3(t)) - x_2(t) \\ \dot{x}_{3(t)} = x_1(t)x_{2(t)} - b_1x_3(t) \\ \dot{x}_4(t) = -x_1(t) - a_1x_4(t) \end{cases} \tag{26}$$

The initial conditions are x (0) = $[0.1, 0.3, -0.1, -0.2]^T$. when a = 1, b = 0.7, c = 26, d = 1.5, the system is hyper-chaotic. Considering the system with delay, disturbance and varying parameter vectors, the master system could be described as:

$$\begin{cases} \dot{x}_1(t_\tau) = \tilde{a}_1(x_2(t_\tau) - x_1(t_\tau)) + \tilde{d}_1x_4(t_\tau) + d_{11}(t_\tau) \\ \dot{x}_2(t_\tau) = x_1(t_\tau)(\tilde{c}_1 - x_3(t_\tau)) - x_2(t_\tau) + d_{12}(t_\tau) \\ \dot{x}_3(t_\tau) = x_1(t_\tau)x_2(t_\tau) - \tilde{b}_1x_3(t_\tau) + d_{13}(t_\tau) \\ \dot{x}_4(t_\tau) = -x(t_\tau)_1 - \tilde{a}_1x_4(t_\tau) + d_{14}(t_\tau) \end{cases} \tag{27}$$

Where:

$$\tilde{a}_1 = a_1 + \bar{a}_1, \tilde{b}_1 = b_1 + \bar{b}_1, \tilde{c}_1 = c_1 + \bar{c}_1$$

and:

$$\tilde{d}_1 = d_1 + \bar{d}_1,\ \bar{a}_1, \bar{b}_1, \bar{c}_1$$

and $\bar{d}_1$ are the disturbances of the parameter a_1, b_1, c_1 and d_1. We choose:

$$\begin{aligned}&\bar{a}_1 = 0.5\sin 2t, \bar{b}_1 = 0.5\sin t\\&\bar{c}_1 = 0.4\sin 3t, \bar{d}_1 = 0.4\sin 2t\\&d_{11}(t_\tau) = \sin(\pi t_\tau),\ d_{12}(t_\tau) = 0.2\cos(5\pi t_\tau)\\&d_{13}(t_\tau) = \sin(4\pi t_\tau), d_{14}(t_\tau) = 0.6\cos(3\pi t_\tau)\end{aligned}$$

and $\tau = 0.2$

Consider Lu's system as follows:

$$\begin{cases}\dot{y}_1(t) = a_2(y_2(t) - y_1(t)) + y_4(t)\\ \dot{y}_2(t) = y_{1(t)}y_3(t) - c_2y_2(t)\\ \dot{y}_3(t) = y_1(t)y(t)_2 - b_2y_3(t)\\ \dot{y}_4(t) = y_1(t)y_3(t) - r_2y_4(t)\end{cases} \quad (28)$$

The initial conditions of the slave system are $y(0) = [1,-1, -1,1]^T$. When $a_2 = 36$, $b_2 = 3$, $c_2 = 20$, $-3.5 \le r_2 \le 1.3$ the system is hyper chaotic. Considering the system with the disturbance and varying parameter vectors, the slave system could be described as:

$$\begin{cases}\dot{y}_1(t) = \tilde{a}_2(y_2(t) - y_1(t)) + y_4(t) + d_{21}(t)\\ \dot{y}_2(t) = y_{1(t)}y_3(t) - \tilde{c}_2y_2(t) + d_{22}(t)\\ \dot{y}_3(t) = y_1(t)y(t)_2 - \tilde{b}_2y_3(t) + d_{23}(t)\\ \dot{y}_4(t) = y_1(t)y_3(t) - \tilde{r}_2y_4(t) + d_{24}(t)\end{cases} \quad (29)$$

where,

$$\tilde{a}_2 = a_2 + \bar{a}_2, \tilde{b}_2 = b_2 + \bar{b}_2, \tilde{c}_2 = c_2 + \bar{c}_2$$

and

$$\tilde{d}_2 = d_2 + \bar{d}_2 . \bar{a}_2, \bar{b}_2, \bar{c}_2$$

and $\bar{r}_2$ are the disturbances of the parameters a_2, b_2, c_2, and r_2. we choose:

$$\begin{aligned}&d_{21} = 0.4\sin(0.25\pi t),\ d_{22} = 0.1\cos(5\pi t)\\&d_{23} = 0.3\sin(\pi t),\ d_{24} = 0.5\cos(2\pi t)\\&\lambda_i = 50,\ i = 1,2,3,4\end{aligned}$$

and:

$$\bar{a}_2 = 0.5,\ \bar{b}_2 = 0.4,\ \bar{c}_2 = 0.2, \bar{d}_2 = 0.2$$

$$\begin{aligned}&F(x,t) = (0.1 + 0.05\sin(0.3\pi t))[0.5x_1 + 0.5x_2,\\&0.7x_2 - 0.3x_1, 0.6x_3 + 0.4x_4, x_4]^T\\&G(y,t) = [y_1, y_2, y_3, y_4]^T\end{aligned}$$

Then, we have:

$$\dot{F}_x(x) = (0.1 + 0.05\sin(0.3\pi t))\begin{bmatrix}0.5 & 0.5 & 0 & 0\\ 0 & 0.7 & -0.3 & 0\\ 0 & 0 & 0.6 & 0.4\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$\begin{aligned}&\dot{G}_y(y) = I, \dot{G}_y^{-1}(y) = I, \dot{G}_t(y,t) = 0, \tau = 0\\&\dot{F}_t(x,t) = 0.015\pi\cos(0.3\pi t)[0.5x_1 + 0.5x_2,\\&0.7x_1 - 0.3x_3, 0.6x_3 + 0.4x_4, x_4]^T\end{aligned}$$

For convenience, F_i (x, t) is denoted by F_i and G_i (y, t) by G_i i = 1,2,3,4.

The response of states x and the function vector F (x,t) of the system are depicted in Fig. 1 and 2, respectively. From Fig. 1 and 2, we can see that the response curves of the state vector x are different from ones of function vector F (x, t). Figure 3 indicates that the errors e_1, e_2, e_3 and e_4 are stable. Figure 4 shows that the

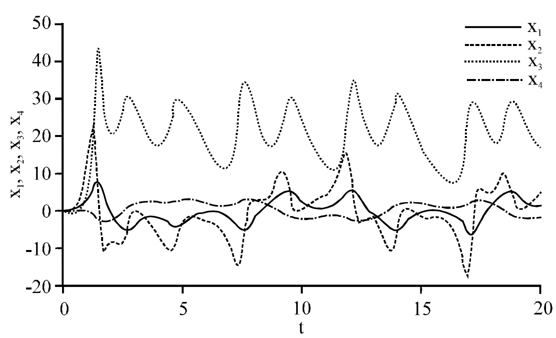

Fig. 1: The response of the states x_1, x_2, x_3 and x_4 of the master system

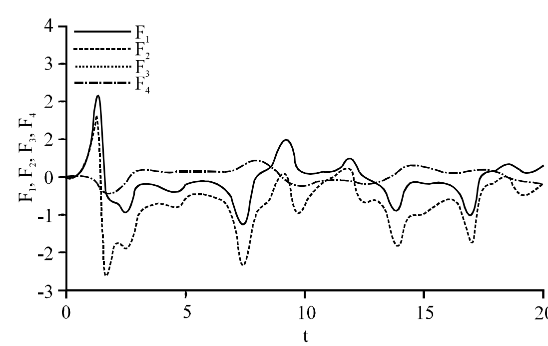

Fig. 2: The response of the state function vectors F_1, F_2, F_3 and F_4 of the master system

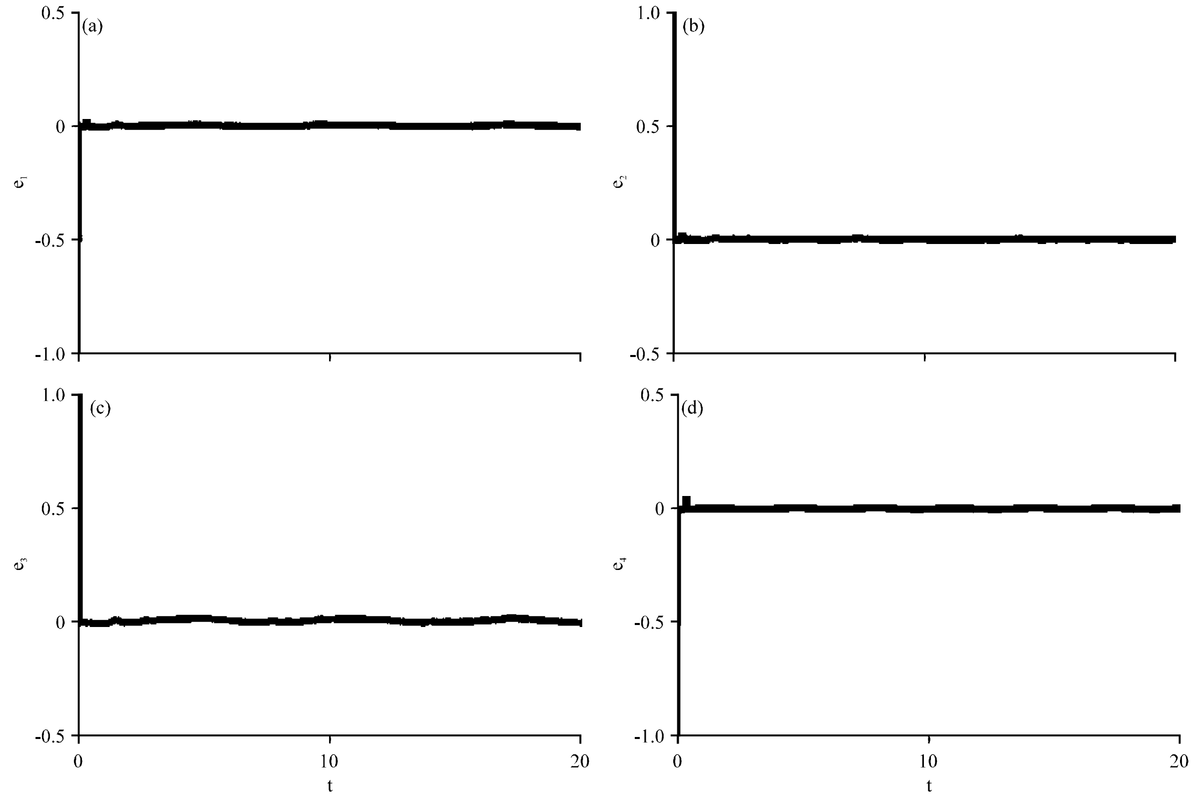

Fig. 3(a-d): The response of the errors (a) e_1, (b) e_2, (c) e_3 and (d) e_4

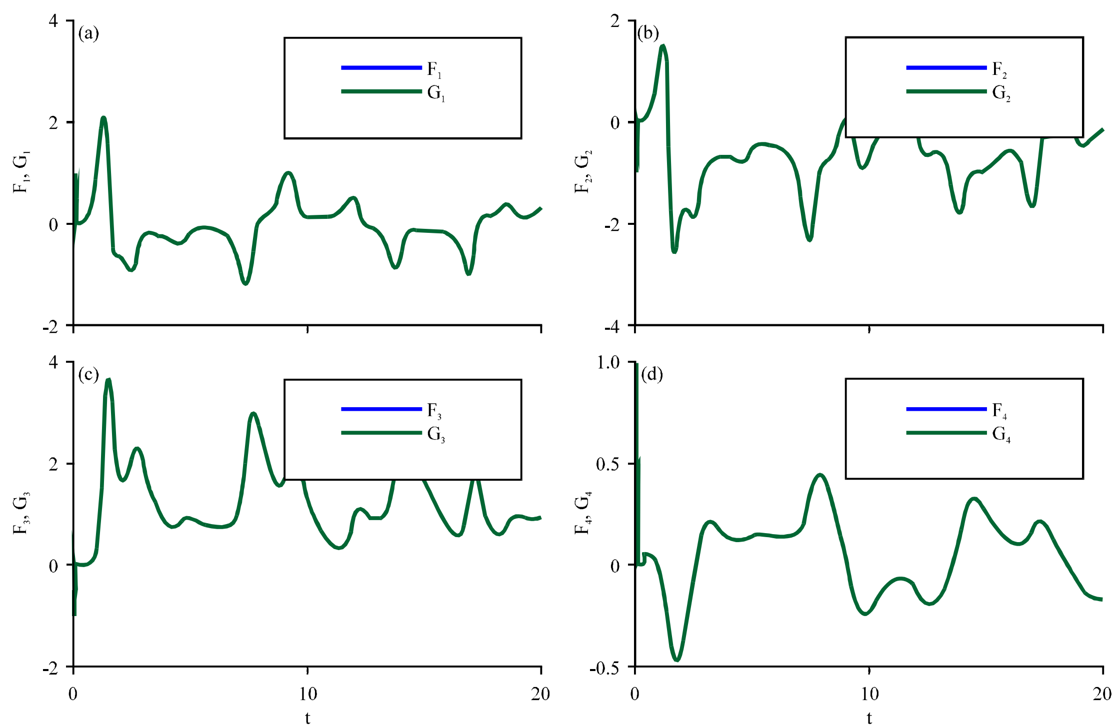

Fig. 4(a-d): The response of function vectors (a) F_1, G_1, (b) F_2, G_2, (c) F_3, G_3 and (d) F_4, G_4

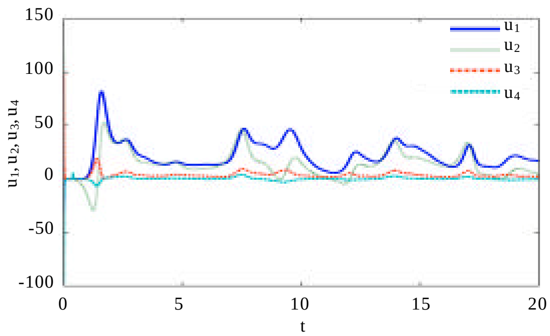

Fig. 5: The response of the control inputs u_1, u_2, u_3 and u_4

G_1 (y,t), G_2 (y,t), G_3 (y,t) and G_4 (y,t) are synchronized with the F_1 (x, t), F_2 (x, t), F_3 (x, t) and F_4 (x, t) well after small interval. Figure 5 shows the response of the inputs u_1, u_2, u_3 and u_4. The simulation results demonstrate the effectiveness of the proposed method.

CONCLUSION

In this study, the problem of robust generalized lag synchronization for two non-identical chaotic systems with varying parameters and disturbance had been addressed. By using fuzzy logic rules approximating nonlinearity then tedious calculations could be avoided. Unknown constants were estimated by the adaptive law. Utilizing proposed adaptive fuzzy controller, the dynamics of error system could achieve asymptotical stability. In comparison with the traditional method, selectivity was much great for the system state function vectors. By using state function vectors instead of state vectors, it was much difficult for the signal to be cracked. Simulation results were given to demonstrate the effectiveness of the proposed scheme.

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