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Reliable H_∞ Fuzzy Switching Control for Nonlinear Systems with Actuator Failures

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Abstract: This paper deals with the design problem of reliable H_∞ fuzzy switching controllers for continuous-time nonlinear systems with different actuator fault mode. First, the Takagi-Sugeno (T-S) fuzzy model is employed to represent a nonlinear system. Next, based on the fuzzy model, a faulty switched system is constructed to model various classes of faulty nonlinear systems. The objective is to design a state-feedback switching controller such that the switched system is asymptotically stable with H_∞ disturbance attenuation for arbitrary switching laws. Based on the linear matrix inequality (LMI) techniques, switching Lyapunov function method is adopted to establish sufficient conditions of existence and design method of reliable H_∞ switching fuzzy controller, which reduces the conservatism of the design. Finally, the validity and applicability of the proposed approaches are demonstrated by examples.

Key words: Fuzzy control; Switching control; H_∞ disturbance attenuation; Linear matrix inequality (LMI); Reliable control.

1. INTRODUCTION

The study of the reliable control design of nonlinear systems, which can tolerate the failure of the control components and maintain the desired system performance, has received considerable attention [1]-[4]. Yang and Liang employed the Halmiton-Jacobi inequality (HJI) approach to investigate the reliable control problem in [1] [3]. Yang studied the reliable H_∞ control and reliable guaranteed cost problem for nonlinear systems with sensor and/or actuator faults in [2]. Liang studied the reliable linear-quadratic regulator problems for nonlinear systems with actuator faults in [3]. Liu designed reliable controllers for uncertain nonlinear systems in terms of HJI [4]. It is known that the Hamliton-Jacobi inequality (HJI) is difficult to resolve.

In the past few years, there has been rapidly growing interest in fuzzy control of nonlinear systems, and there have been many successful applications. Recently, there have been some attempts to employ Takagi-Sugeno (T-S) fuzzy model for the design of nonlinear reliable control systems [5]-[6]. In [5] and [6], some improved LMI techniques were applied to the design of reliable LQ state-feedback fuzzy controller for nonlinear systems with actuator failures. Based on LMI, [7] proposed the design technique of reliable H_∞ fuzzy controllers for continuous-time nonlinear systems. Moreover, switching fuzzy model was employed for nonlinear systems [7]-[10]. We extend the idea to faulty switching for nonlinear systems.

In this study, we consider the reliable H_∞ control design for continuous-time nonlinear systems with actuator failures by employing the switching T-S fuzzy model. Firstly, the nonlinear system is represented or approximated by a T-S fuzzy model. Then, actuator failures are classified in terms of extent of failures. Switching fuzzy system is constructed respect to various classes of actuator failures. A switching sub-controller controls each class of faulty system. A state-feedback-switching controller is designed such that the closed-loop switched system is asymptotically stable with a prescribed H_∞ performance constraint for arbitrary switching law. Based

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on LMI technique, switching Lyapunov method is employed for the switching fuzzy system to obtain a reliable H_∞ switching fuzzy controller.

The main contribution of this paper is that a switching fuzzy model is constructed according to classes of actuator failures, and different reliable controller is designed respect to different class of actuator failures. Furthermore, the design technique is more flexible to deal with the reliable control problems for complex systems in the case of actuator failures. The rest of this paper is organized as follows. In section 2, we give system descriptions and the model of switching fuzzy system. In section 3, we use switching Lyapunov function to give sufficient conditions for the existence of reliable H_∞ controller under arbitrary switching law. Section 4 contains the simulation results, which show the feasibility and efficiency of the proposed method. In section 5, conclusions are presented.

2. PRELIMINARIES AND SWITCHING FUZZY MODEL

Consider the continuous-time nonlinear system, which can be described by the following T-S fuzzy model:

Plant rule I: if $\theta_1(t)$ is M_1^i and …and $\theta_s(t)$ is M_s^i, then

$$\dot{x}(t) = A_i x(t) + B_{1i} w(t) + B_{2i} u(t), \tag{1}$$

$$z(t) = C_i x(t) + D_i w(t), i = 1, \cdots, r. \tag{2}$$

where $x(t) \in R^n$ is the state vector, $w(t) \in R^p$ is the exogenous disturbance vector which belongs to $L_2[0,\infty)$, $u(t) \in R^m$ is the control input vector, M_j^i is the fuzzy set, r is the number of if-then rules. $\theta_1(t) \sim \theta_s(t)$ are premise variables. A_i, B_{1i}, B_{2i}, C_i and D_i are known constant matrices with appropriate dimensions.

Given a pair of $(x(t), u(t))$, the final output of the fuzzy system is inferred as follows:

$$\begin{aligned}\dot{x}(t) &= \sum_{i=1}^{r} h_i(\theta(t))(A_i x(t) + B_{1i} w(t) + B_{2i} u(t)) \\ &= A(h)x(t) + B_1(h)w(t) + B_2(h)u(t),\end{aligned} \tag{3}$$

$$\begin{aligned}z(t) &= \sum_{i=1}^{r} h_i(\theta(t))(C_i x(t) + D_i w(t)) \\ &= C(h)x(t) + D(h)w(t).\end{aligned} \tag{4}$$

where $h_i(\theta(t)) = (\mu_i(\theta(t)) / \sum_{i=1}^{r} \mu_i(\theta(t))$, $\mu_i(\theta(t)) = \prod_{j=1}^{s} M_j^i(\theta_j(t))$,

$$A(h) = \sum_{i=1}^{r} h_i(\theta(t)) A_i,\ B_1(h) = \sum_{i=1}^{r} h_i(\theta(t)) B_{1i},\ B_2(h) = \sum_{i=1}^{r} h_i(\theta(t)) B_{2i},$$

$$C(h)=\sum_{i=1}^{r}h_i(\theta(t))C_i\ ,\ D(h)=\sum_{i=1}^{r}h_i(\theta(t))D_{1i}\ .$$

$M_j^i(\theta_j(t))$ is the grade of membership $\theta_j(t)$ of in M_j^i, and $\mu_i(\theta(t))$ represents the weight of the ith rule. It is easy to check that

$$h_i(\theta(t))\geq 0,\quad i=1,\cdots,r\,,$$

$$\text{and}\ \sum_{i=1}^{r}h_i(\theta(t))=1\,.$$

Suppose the number of possible actuator failures is N. Let $u_\tau^F(t)$ be the control input vector after failures have occurred. The following actuator failure model is adopted:

$$u_\tau^F(t)=\alpha_\tau u\,,\quad \tau=1,2,\cdots,N\,.$$

where $\alpha_\tau=diag\{\alpha_{\tau1},\alpha_{\tau2,}\cdots,\alpha_{\tau m}\}$, $0\leq\underline{\alpha_{\tau i}}\leq\alpha_{\tau i}\leq\overline{\alpha_{\tau i}}$, and $\underline{\alpha_{\tau i}}\leq 1,1\leq\overline{\alpha_{\tau i}}$,

$$\underline{\alpha_\tau}=\min_i\{\,\alpha_{\tau i}\},\overline{\alpha_\tau}=\max_i\{\alpha_{\tau i}\},\ i=1,2,\cdots,m\,.$$

Let $\beta_\tau=diag\{\beta_{\tau1},\beta_{\tau2},\cdots,\beta_{\tau m}\}$, $\beta_{\tau0}=diag\{\beta_{\tau01},\beta_{\tau02},\cdots\beta_{\tau0m}\}$,

$$\alpha_{\tau0}=diag\{\alpha_{\tau01},\alpha_{\tau02},\cdots,\alpha_{\tau0m}\}\,.$$

where $\beta_{\tau i}=\dfrac{\underline{\alpha_\tau}+\overline{\alpha_\tau}}{2}$, $\beta_{\tau0i}=\dfrac{\overline{\alpha_\tau}-\underline{\underline{\alpha_\tau}}}{\underline{\alpha_\tau}+\alpha_\tau}$, $\alpha_{\tau0i}=\dfrac{\alpha_{\tau i}-\beta_\tau}{\beta_\tau}$, $i=1,2,\cdots,m,\ \tau=1,2,\cdots,N$.

Then

$$\alpha_\tau=(I+\alpha_{\tau0})\beta_\tau\stackrel{\wedge}{=}(I+\Delta)\beta_\tau\,,\ |\,\Delta\,|\leq\beta_{\tau0}\leq 1\,. \tag{5}$$

Remark 1: The failure model implies nominal case without actuator failure. When $\alpha_{\tau i}=1,i=1,2\cdots,m$, the system is nominal without failure.

Then the system with actuator failures can be represented by means of the following faulty switched system:

$$\dot{x}(t)=A(h)x(t)+B_1(h)w(t)+B_2(h)u_{\sigma(t)}^F(t)\,, \tag{6}$$

$$z(t)=C(h)x(t)+D(h)w(t)\,. \tag{7}$$

where

$\sigma(t): \quad R_+ \to M = \arg\{i \mid \beta_i \neq \beta_j, j = i+1, i+2, \cdots, N, i = 1,2\cdots, N\} \hat{=} \{1,2,\cdots,T\}, T < N$ is a piecewise constant function, called a switching signal, $u^F_{\sigma(t)}(t)$ be the control input vector after some class of failure have occurred.

Remark 2: The actuator failures are classified into T classes, where T is the number of classes for failures. Each switched subsystem represents a corresponding class of faulty model in the above switched system (6)-(7).

The following switching fuzzy controller is proposed to deal with the above switched system:

Control rule q_j:

If $\theta_1(t)$ is M_1^i, and … ,and $\theta_s(t)$ is M_s^i,

Then $u_{qj}(t) = K_{qj}x(t), \quad j = 1,2\cdots, r, q = 1,2\cdots, T$.

where $K_{qj} \in R^{m\times n}, j = 1,2\cdots, r, q = 1,2\cdots, T$ are constant matrices to be determined.

The switching controller is represented by

$$u_q(t) = \sum_{i=1}^{r} h_i(z(t))K_{qj}x(t) = K_q(h)x(t). \tag{8}$$

where $K_q(h) = \sum_{i=1}^{r} h_i(z(t))K_{qj}, \quad q = 1,2\cdots, T$.

By (5) and (6) (7) we derive the following closed-loop faulty switching model:

$$\dot{x}(t) = (A(h) + B_2(h)(I+\Delta)\beta_\sigma K_\sigma(h))x(t) + B_1(h)w(t), \tag{9}$$

$$z(t) = C(h)x(t) + D(h)w(t). \tag{10}$$

Definition 1: The unforced fuzzy system (3)-(4) is said to be stable with γ–disturbance attenuation, if the disturbance-free fuzzy system is asymptotically stable and the output $z(t)$ of the system under the zero initial condition ($x_0 = 0$) satisfies

$$\int_0^\infty z^T(t)z(t)dt < \gamma^2 \int_0^\infty w^T(t)w(t)dt$$

for any nonzero $w(t) \in L_2[0,\infty)$, where $\gamma > 0$ is a prescribed level of disturbance attenuation.

Definition 2: A switched controller of the form (8) is said to be a reliable switching fuzzy controller for the system (6)-(7) if the switching fuzzy system (9)-(10) is stable with γ–disturbance attenuation.

The problem under consideration is to design a state-feedback fuzzy switching controller of the form (8) such that it is a reliable H_∞ controller for the switching fuzzy system (6)-(7).

3. RELIABLE H_∞ SWITCHING FUZZY CONTROLLER DESIGN

It is known that single Lyapunov method is conservative since a single Lyapunov function must work for all classes of actuator failure. In order to reduce the conservatism, here, we will use switching Lyapunov method for the design of reliable switching fuzzy controller.

Theorem 1: Consider the switching fuzzy system (9)-(10). For some given $\gamma > 0$, if there exist symmetric positive definite matrices $P_q = P_q^T > 0$, $q = 1,2\cdots,T$ such that

$$\begin{bmatrix} \begin{matrix}(A(h)+B_2(h)\beta_q K_q(h))P_q + \\ P_q(A(h)+B_2(h)\beta_q K_q(h))^T\end{matrix} & * & * & * & * \\ B_1^T(h)P_q & -\gamma^2 I & * & * & * \\ C(h) & D(h) & -I & * & * \\ B_2^T(h) & 0 & 0 & -I & * \\ \beta_q K_q(h) & 0 & 0 & 0 & -\beta_{q0}^{-2} I \end{bmatrix} < 0 \tag{11}$$

where '*' denotes the transposed elements in the symmetric positions, then the system (8)-(9) is stable with γ–disturbance attenuation.

Proof: Consider switching Lyapunov functions $V = x^T P_q x,\ q = 1,2\cdots,N$, and the time derivative of the function along the state trajectory (9) is

$$\begin{aligned}\dot{V} &= x^T((A(h)-B_2(h)(I+\Delta)\beta_q K_q(h))P_q + P_q(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h))^T)x \\ &+ w^T B_1^T(h)P_q x + x^T P_q B_1(h)w.\end{aligned} \tag{12}$$

From (12) and recalling (10), use the Schur complement, it can be verified that

$$\dot{V} + z^T z - \gamma^2 w^T w$$

$$\begin{aligned}&= x^T((A(h)+B_2(h)(I+\Delta)\beta_q K_q(h))^T P_q + P_q(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h)) \\ &\quad + C^T(h)C(h))x + w^T B_1^T(h)P_q x + x^T P_q B_1(h)w + w^T D^T(h)C(h)x + \\ &\quad x^T C^T(h)D(h)w + w^T D^T(h)D(h)w - \gamma^2 w^T w\end{aligned}$$

$$= \begin{bmatrix} x^T & w^T \end{bmatrix} \begin{bmatrix} \begin{matrix}(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h)) \\ + C^T(h)C(h)\end{matrix} & * \\ B_1^T(h)P_q + D^T(h)C(h) & -\gamma^2 I \end{bmatrix} \begin{bmatrix} x \\ w \end{bmatrix} < 0 .$$

Thus

$$\begin{bmatrix} (A(h)+B_2(h)(I+\Delta)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h)) & * & * \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix} < 0 .$$

Use the inequality $2a^T b \le a^T a + b^T b$, it follows that

$$\begin{bmatrix} (A(h)+B_2(h)(I+\Delta)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)(I+\Delta)\beta_q K_q(h)) & * & * \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix} =$$

$$\begin{bmatrix} (A(h)+B_2(h)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)\beta_q K_q(h)) & * & * \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix} + \begin{bmatrix} B_2(h) \\ 0 \\ 0 \end{bmatrix} \Delta \begin{bmatrix} \beta_q K_q(h) & 0 & 0 \end{bmatrix}$$

$$+ \left(\begin{bmatrix} B_2(h) \\ 0 \\ 0 \end{bmatrix} \Delta \begin{bmatrix} \beta_q K_q(h) & 0 & 0 \end{bmatrix} \right)^T$$

$$\le \begin{bmatrix} (A(h)+B_2(h)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)\beta_q K_q(h)) & * & * \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix} + \begin{bmatrix} B_2(h) \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} B_2(h) \\ 0 \\ 0 \end{bmatrix}^T$$

$$+ \begin{bmatrix} \beta_q K_q(h) \\ 0 \\ 0 \end{bmatrix} \beta_{q0}^2 \begin{bmatrix} \beta_q K_q(h) \\ 0 \\ 0 \end{bmatrix}^T$$

$$
= \begin{bmatrix} (A(h)+B_2(h)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)\beta_q K_q(h)) + B_2(h)B_2^T(h) & * & * \\ +\beta_q K_q(h)\beta_{q0}^2(\beta_q K_q(h))^T & & \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix}.
$$

Use the Schur complement again, the inequality (11) is true if the following inequality

$$
\begin{bmatrix} (A(h)+B_2(h)\beta_q K_q(h))^T P_q + \\ P_q(A(h)+B_2(h)\beta_q K_q(h)) + B_2(h)B_2^T(h) & * & * \\ +\beta_q K_q(h)\beta_{q0}^2(\beta_q K_q(h))^T & & \\ B_1^T(h)P_q & -\gamma^2 I & * \\ C(h) & D(h) & -I \end{bmatrix} < 0
$$

holds.

It is readily seen that the system (9)-(10) is stable with γ –disturbance attenuation.

Theorem 2: Consider the switched system (6)-(7). For some given scalar γ, if there exist matrices $X_q = X_q^T > 0$, and $Y_{qj}, q = 1,2\cdots,T, j = 1,2\cdots,r$ satisfying the following LMIs:

$$
\Xi_{qii} < 0, \quad i = 1,2\cdots,r, \tag{13}
$$

$$
\frac{1}{r-1}\Xi_{qii} + \frac{1}{2}(\Xi_{qij} + \Xi_{qji}) < 0, \quad 1 \le i \ne j \le r, \tag{14}
$$

then there exist switched controller of the form (8) such that it is a reliable H_∞ controller. Furthermore, the state feedback matrices are given by

$$
X_q = P_q^{-1}, K_{qj} = Y_{qj}X_q^{-1}, \quad q = 1,2\cdots,T, j = 1,2\cdots,r. \tag{15}
$$

where

$$\Xi_{qij}=\begin{bmatrix} A_iX_q+X_qA_i^T+B_{2i}\beta_qY_{qj}+(B_{2i}\beta_qY_{qj})^T & * & * & * & * \\ B_{1i}^T & -\gamma^2 I & * & * & * \\ C_iX_q & D_i & -I & * & * \\ B_{2i}^TX_q & 0 & 0 & -I & * \\ \beta_qY_{qj} & 0 & 0 & 0 & -\beta_{q0}^{-2}I \end{bmatrix}. \tag{16}$$

The symbol '*' denotes the transposed elements for symmetric positions.

Proof: From theorem 1, Pre- and post—multiplying the left-hand side matrix in (11) by the matrix $diag\{P_q^{-1},I,I,I,I\}$**,** respectively, it follows that the matrix inequality (11) is equivalent to

$$\begin{bmatrix} \begin{matrix}P_q^{-1}(A(h)+B_2(h)\beta_qK_q(h))^T+\\(A(h)+B_2(h)\beta_qK_q(h))P_q^{-1}\end{matrix} & * & * & * & * \\ B_1^T(h) & -\gamma^2 I & * & * & * \\ C(h)P_q^{-1} & D(h) & -I & * & * \\ B_2^T(h)P_q^{-1} & 0 & 0 & -I & * \\ (\beta_qK_q(h))P_q^{-1} & 0 & 0 & 0 & -\beta_{q0}^{-2}I \end{bmatrix}<0 . \tag{17}$$

Defining

$$X_q=P_q^{-1}\quad ,K_{qj}=Y_{qj}P_q,\quad q=1,2\cdots,T,\, j=1,2\cdots,r,$$

we conclude that the inequality (11) can be written as

$$\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(z(t))h_j(z(t))\Xi_{qij}<0 . \tag{18}$$

By using [11,Th.2.2], we have that if the conditions (13) and (14) hold, then (18) is fulfilled.

It follows from theorem 1 that (8) is the reliable H_∞ switching controller for the switched system (6)-(7).

4. ILLUSTRATIVE EXAMPLE

In this section, a numerical example is presented to verify the proposed design method. Consider the following fuzzy system:

Rule I: if $x_1(t)$ is M_i, then

$$\dot{x}(t)=A_1x(t)+B_{1i}w(t)+B_{2i}u(t),$$

$$z(t)=C_ix(t)+D_iw(t)\ \ ,i=1,2 .$$

where $x(t)=\begin{bmatrix}x_1(t) & x_2(t) & x_3(t)\end{bmatrix}^T$, $u(t)=\begin{bmatrix}u_1(t) & u_2(t)\end{bmatrix}^T$, and

$$A_1=\begin{bmatrix}-1 & 0.5 & -0.8\\ 1 & -2 & 0.8\\ 0.2 & -1 & -2\end{bmatrix},\ A_2=\begin{bmatrix}-1 & 0.5 & -0.8\\ -1 & -2 & -0.8\\ 0.2 & 1 & -2\end{bmatrix},\ B_{11}=B_{12}=\begin{bmatrix}0.5\\ 0\\ 0.1\end{bmatrix},$$

$$B_{21}=B_{22}=\begin{bmatrix}0.05 & 0\\ 0 & 0.1\\ 0 & 0\end{bmatrix},\ C_1=C_2=\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},\ D_1=D_2=\begin{bmatrix}0\\ 0.1\\ 0\end{bmatrix},$$

The faulty switching model is constructed as

$$\dot{x}(t)=A(h)x(t)+B_1(h)w(t)+B_2(h)\alpha_\sigma u(t),$$
$$z(t)=C(h)x(t)+D(h)w(t).$$

where $\sigma(t):\ R_+\to M=\{1,2\}$.

Assume the parameters of two classes of actuator faults are as follows:

$$\beta_1=\{0.1,0.1,0.1\},\beta_{10}=\{0.5,0.5,0.5\},$$

and $$\beta_2=\{0.175,0.175,0.175\},\beta_{20}=\{0.1429,0.1429,0.1429\}.$$

Let $\gamma=0.6$, by solving LMI (17), the state feedback gain matrices can be obtained as

$$K_{11}=\begin{bmatrix}-0.8583 & -0.8890 & 0.0749\\ -2.0445 & 2.6230 & 0.3162\end{bmatrix},K_{12}=\begin{bmatrix}-0.9740 & 0.8115 & 0.3762\\ -0.1110 & 4.4909 & -0.0846\end{bmatrix},$$

$$K_{21}=\begin{bmatrix}-19.7900 & 2.5463 & -0.6703\\ 5.0293 & -88.9676 & 18.0392\end{bmatrix},K_{22}=\begin{bmatrix}-16.9152 & 3.7760 & -0.7271\\ 5.0677 & -51.7965 & 10.4148\end{bmatrix}.$$

Assume that the initial condition is $x_0(t)=\begin{bmatrix}-0.8 & 0.6 & 1\end{bmatrix}$. Figs.1 and 2 show the control results for the nominal case and the first class of actuator failure case respectively.

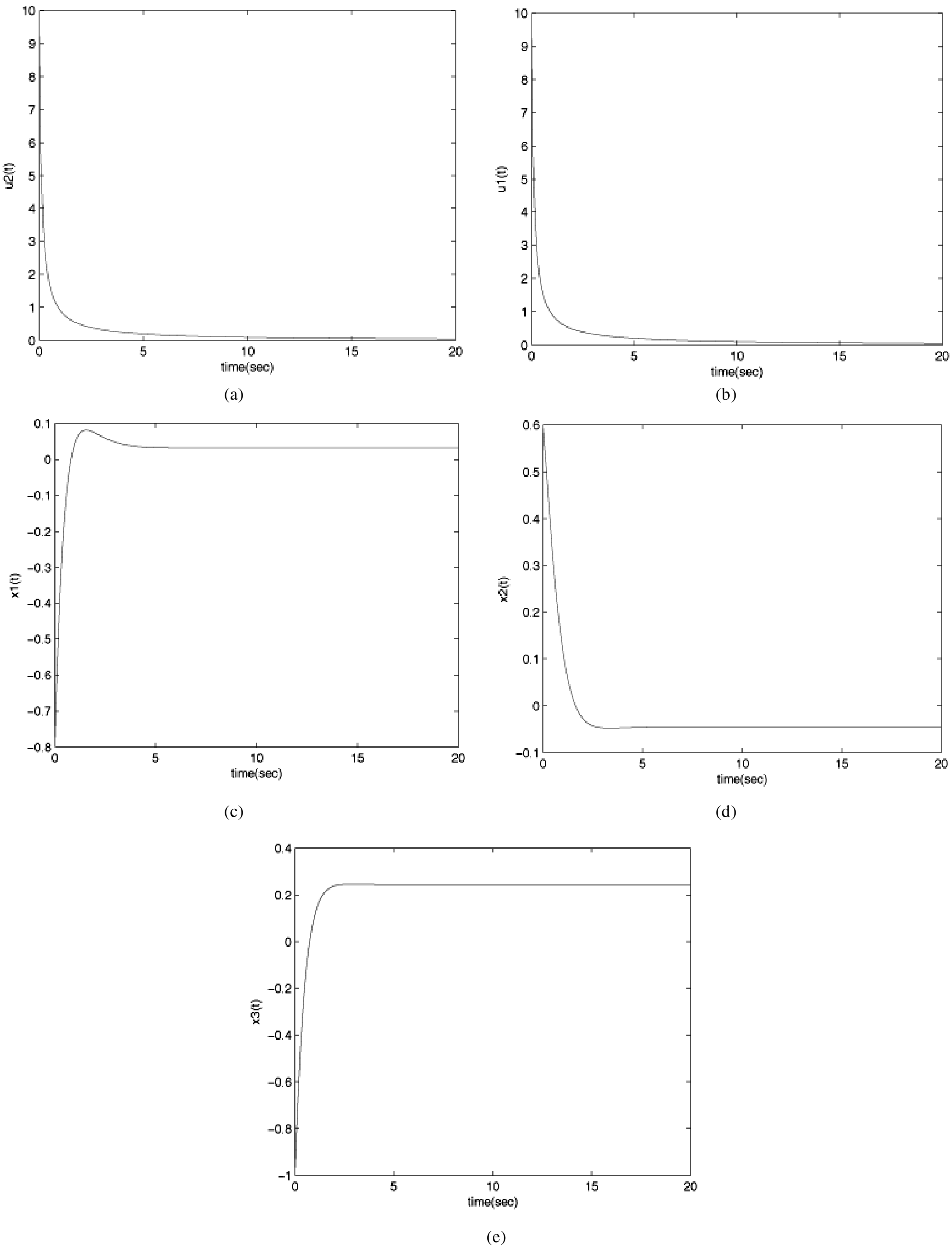

Fig. 1: Control Results for the Nominal Case. (a) $u_1(t)$. (b) $u_2(t)$. (c) $x_1(t)$. (d) $x_2(t)$.

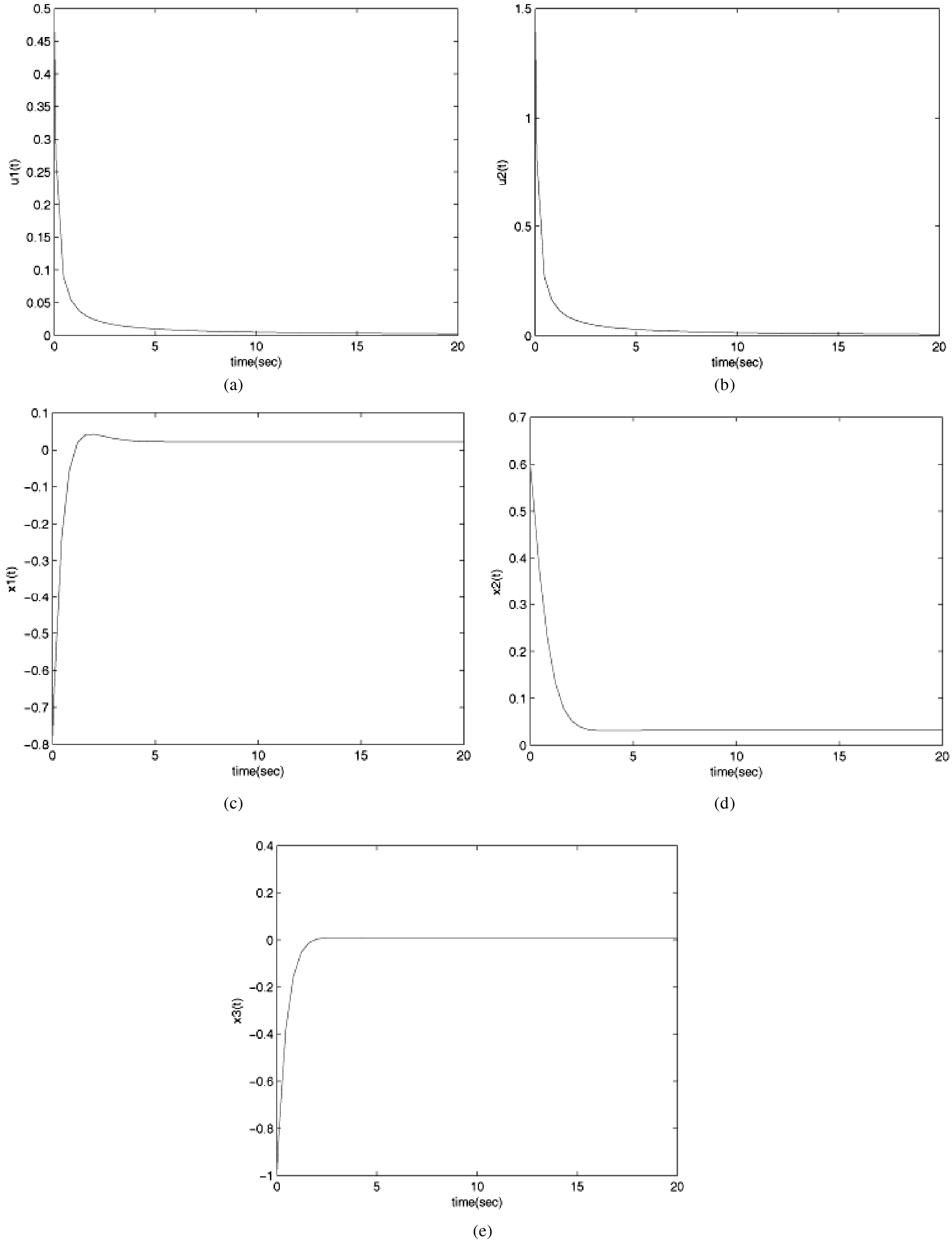

Fig. 2: Control Results for the First Class of Actuator Failure Case. (a) $u_1(t)$. (b) $u_2(t)$. (c) $x_1(t)$. (d) $x_2(t)$. (e) $x_3(t)$

5. CONCLUSION

In this paper, the reliable H_∞ switching fuzzy control problem has been studied for continuous-time nonlinear systems with different actuator failures. A faulty switching system is constructed, which covers the cases of various faults and nominal case. Based on LMI technique, switching Lyapunov function method is adopted to obtain a reliable switching fuzzy controller. The resulting controller satisfies a prescribed H_∞ performance constraint. Finally, the simulation results illustrate that the proposed method is effective.

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