Local Stabilization of Input-Saturated Nonlinear Systems with Time-Delay via Fuzzy Control

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Abstract

In this paper, we present an analysis and design method for the control of input-saturated nonlinear systems with the time-delay. The target system is represented by Takagi-Sugeno (T-S) fuzzy model and the parallel distributed compensation (PDC) controller is designed to guarantee the local stability of the equilibrium point. We derive the sufficient condition for the local stability by applying Lyapunov-Krasovskii theorem and this condition is converted into the LMI problem.

Key Words : T-S fuzzy system, saturation, time-delay, LMI

1. Introduction

The model of practical plants shows many kinds of nonlinearities. The input saturation and the time-delay are the most famous nonlinearities among them. If we do not take the input saturation into consideration when we analyze or design the control systems, unexpected phenomena such as an integral wind up or limit cycle may occur [9], [6]. And, many researchers have revealed that the existence of the time-delay in state or input may induce complex behaviors such as oscillations, or the degradation of the performance. Even worse, a small delay can destabilize some kind of systems [1].

Therefore, both the input saturation and the time-delay should be taken into consideration in the controller design for the nonlinear system with the time-delay to guarantee the reliable performance. Recently, some papers proposed methods for the stabilization of the linear systems suffer from these input saturation and the time-delay [1],[2],[4],[5]. However, there are not, if any, much research results on the control of the nonlinear systems with the input saturation and the time-delay.

On the other hand, fuzzy logic has received much attention from the control theorists as a powerful tool for the nonlinear control. Among various kinds of fuzzy methods, Takagi-Sugeno (T-S) fuzzy system is widely accepted as a tool for design and analysis of fuzzy control systems [8]. The T-S fuzzy model can express a highly nonlinear functional relation with comparatively a small number of implications of rules [9].

The main contribution of this paper is to design of the fuzzy controller for the nonlinear systems with both of the nonlinearities mentioned above. By adopting an auxiliary matrix considering the characteristics of the saturation function and by applying the Lyapunov-Krasovskii theorem, the sufficient condition can be derived for the closed system to be locally stable. In the course of stability analysis, this sufficient condition is recast into linear matrix inequalities (LMI) problem [7].

This paper is organized as follows. In section 2, some preliminaries for the T-S model of the input-saturated nonlinear systems with the time-delay are given. The stability analysis of the whole closed-loop system with the proposed method is given in section 3. The validity and the effectiveness of the proposed method are examined through computer simulation in section 4. Finally, some concluding remarks are presented in section 5.

Notations The following general notations will be used throughout the paper. $\mathbf{R}$ denotes the set of real numbers, $\mathbf{R}^n$ denotes the n dimensional Euclidean space. The notation $X \geq Y$ (respectively, $X > Y$), where X and Y are symmetric matrices, means that the matrix $X - Y$ is positive semi-definite (respectively, positive definite).
$C_{n,\tau} = C([-\tau,0],\mathbf{R}^n)$ denotes the Banach space of continuous vector functions mapping the interval $[-\tau,0]$ into $\mathbf{R}^n$ with the topology of uniform convergence. The following norms will be used: $\|\cdot\|$ refers to either the Euclidean vector norm or the induced matrix 2-norm; $\|\phi\|_c = \sup_{-\tau\leq t\leq 0}\|\phi(t)\|$ stands for the norm of a function $\phi \in C_{n,\tau}$. Moreover, we denote by $C^v_{n,\tau}$ the set defined by $C^v_{n,\tau} = \{\phi \in C_{n,\tau} : \|\phi\|_c < v\}$, where v is a positive real number.

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2. Preliminaries

2.1 Problem formulation

Consider the input-saturated nonlinear MIMO system with the time-delay represented by T-S fuzzy system model as follows.

$$\begin{aligned} PR_i &: \text{If } x_1(t) \text{ is } M_{i1} \text{ and } x_2(t) \text{ is } M_{i2}, \cdots, x_n(t) \text{ is } M_{in} \\ &\text{Then } \dot{x}(t) = A_i x(t) + A_{di} x(t-\tau) + B_i \sigma(u) \end{aligned} \tag{1}$$

with the initial condition

$$x(t_0+\theta) = \phi(\theta),\ \forall \theta \in [-\tau, 0],\ (t_0, \phi) \in \mathbf{R}^+ \times C_\tau^v$$

where, $x(t) = [x_1, x_2, \ldots, x_n] \in \mathbf{R}^n$ is the state vector, $u(t) \in \mathbf{R}^m$ is the input, $R_i\ (i = 1, 2, \ldots, r)$ is the i th fuzzy rule, r is the number of rule, $M_{i1}, M_{i2}, \ldots, M_{in}$ are fuzzy sets. Also, $A_i \in \mathbf{R}^{n \times n}$, $A_{di} \in \mathbf{R}^{n \times n}$ and $B_i = [b_{i1} \ \cdots \ b_{im}] \in \mathbf{R}^{n \times m}$. The saturation function $\sigma : \mathbf{R}^m \to \mathbf{R}^m$ is defined as

$$\sigma(u) = [\sigma(u_1) \ \cdots \ \sigma(u_m)]^T \tag{2}$$

where, $\sigma(u_i) = \mathrm{sgn}(u_i) \max\{1, |u_i|\}$. The time-delay $\tau(t) \le \tau_0$ is the unknown bounded time-varying delay in the state and it is assumed that

$$\dot{\tau}(t) \le \beta < 1 \tag{3}$$

that is, the derivative of the time-varying delay function is continuous and bounded. $\phi(t)$ represents a vector-valued initial continuous function. The output of the above fuzzy system is inferred as follows:

$$\dot{x}(t) = \sum_i^r h_i(x(t)) \{ A_i x(t) + A_{di} x(t-\tau) + B_i \sigma(u) \} \tag{4}$$

where,

$$w_i(x(t)) = \prod_{j=1}^n M_{ij}(x_j(t)),\ \sum_{i=1}^r w_i(x(t)) > 0,\ w_i(x(t)) > 0 \tag{5}$$

and

$$h_i(x(t)) = \frac{w_i(x(t))}{\sum_{i=1}^r w_i(x(t))},\ h_i(x(t)) \ge 0,\ \sum_{i=1}^r h_i(x(t)) = 1 \tag{6}$$

$h_i(x(t))$ is called a fuzzy basis function.

Our objective is to design the following PDC controller for the nonlinear systems described above.

$$\begin{aligned} CR_j &: \text{If } x_1(t) \text{ is } M_{j1} \text{ and } x_2(t) \text{ is } M_{j2}, \cdots, x_n(t) \text{ is } M_{jn} \\ &\text{Then } u_j(t) = F_j x(t) \end{aligned} \tag{7}$$

where, $F_j = [f_{j1}{}^T \ f_{j2}{}^T \ \cdots \ f_{jm}{}^T]^T$ is the controller gain matrices to be designed. The inferred control input is represented as

$$u(t) = \sum_{j=1}^r h_j(x(t)) F_j x(t) \tag{8}$$

With (4) and (8), the closed-loop system is represented as

$$\dot{x}(t) = \sum_{i=1}^r h_i(x(t)) \left\{ A_i x(t) + A_{di} x(t-\tau) + B_i \sigma\left(\sum_{j=1}^r h_j(x(t)) F_j x(t) \right) \right\} \tag{9}$$

2.2 Some definitions

Some useful definitions and concepts are given here for the further analysis.

For each matrices $F_j \in \mathbf{R}^{m \times n}$, define

$$L(F_j) := \{ x \in \mathbf{R}^n : |f_{jk} x| \le 1,\ k \in [1, m] \}. \tag{10}$$

Note that if F_j is the feedback matrix, then $L(F_j)$ is the region in the state space where the control is not saturated. Further, let $P \in \mathbf{R}^{n \times n}$ be a positive-definite matrix and denote

$$E(P, \rho) = \{ x \in \mathbf{R}^n : x^T P x \le \rho \} \tag{11}$$

which represents a ellipsoid. Let $V(x) = x^T P x$. The ellipsoid $E(P, \rho)$ is said to be *contractively invariant* if $\dot{V}(x) < 0$ for $\forall x \in E(P, \rho) \setminus \{0\}$. Clearly, if $E(P, \rho)$ is contractively invariant, then it is inside the domain of attraction.

3. Design of fuzzy controller

In this section, we design a fuzzy controller which stabilizes a input-saturated nonlinear system with the time-delay.

3.1 Sufficient condition for local stability

Let $G = [g_1{}^T \ \cdots \ g_m{}^T]^T \in \mathbf{R}^{m \times n}$ denote the auxiliary feedback matrix. For two matrices F, G and a vector $v \in \mathbf{R}^m$, denote

$$M(v, F, G) = \begin{bmatrix} v_1 f_1 + (1 - v_1) g_1 \\ \vdots \\ v_m f_m + (1 - v_m) g_m \end{bmatrix} \tag{12}$$

Let $N = \{ v \in \mathbf{R}^m : v_k = 1 \ or \ 0 \}$. There are 2^r elements in N. We will use a $v \in N$ to choose from F and G for a new matrix $M(v, F, G)$: if $v_k = 1$, then the k th row of $M(v, F, G)$ is f_k and if $v_k = 0$, then the k th row of $M(v, F, G)$ is g_k.

The following theorem provides the local stability condition of the systems composed of the plant (4) and the controller (8).

Theorem 1 : Given an ellipsoid $E(P, \rho)$, if there exists a common $P > 0$, $\Gamma > 0$, and $F_j, G_j \in \mathbf{R}^{m \times n}$ such that

$$\begin{aligned} &(A_i + B_i M(v^j, F_j, G_j))^T P + P(A_i + B_i M(v^j, F_j, G_j)) \\ &+ P A_{di} \Gamma^{-1} A_{di}{}^T P + (1 - \beta)^{-1} \Gamma < 0 \end{aligned} \tag{13}$$

for $\forall\, i, j \in [1, r]$, $\forall v^j \in N$ and $E(P, \rho) \subset L(G_j)$, then $E(P, \rho)$ is a contractively invariant set.

Proof :
Let

$$V(x)=x^T(t)Px(t)+\frac{1}{1-\beta}\left\{\int_{t-\tau}^{t}x^T(\sigma)\Gamma x(\sigma)d\sigma\right\} \quad (14)$$

Obviously, there exist σ_1 and σ_2 such that

$$\sigma_1\|x(t)\|^2\le V(x(t))\le\sigma_2\|x(t)\|^2 \quad (15)$$

The time-derivative of $V(x)$ along the trajectory of (9) is

$$\begin{aligned}\dot V(x)=&\sum_{i=1}^{r}h_i(x(t))\left[x^T(t)\left\{A_i^TP+PA_i\right\}x(t)\right]\\&+\sum_{i=1}^{r}h_i(x)\left[x^T(t-\tau)A_{di}^TPx(t)+x^T(t)PA_{di}x(t-\tau)\right]\\&+2x^T(t)P\sum_{i=1}^{r}h_i(x(t))\left[\sum_{k=1}^{m}b_{ik}\sigma\left(\sum_{j=1}^{r}h_jf_{jk}x(t)\right)\right]\\&+\frac{1}{1-\beta}\left\{x^T(t)\Gamma x(t)-(1-\dot\tau)x^T(t-\tau)\Gamma x(t-\tau)\right\}\end{aligned} \quad (16)$$

For each term, $2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x\right)$

(i) if $x^T(t)Pb_{ik}\ge 0$ and $\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\le -1$, then,

$$\begin{aligned}&2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right)\\&=-2h_i(x(t))x^T(t)Pb_{ik}\le 2h_i(x(t))x^T(t)Pb_{ik}g_{jk}x(t)\end{aligned}$$

Here we note that $-1\le g_{jk}x(t)$, $\forall x(t)\in E(P,\rho)$.

(ii) if $x^T(t)Pb_{ik}\ge 0$ and $\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\ge -1$, then

$$\sigma\left(\sum_{j=1}^{r}h_j(x(t))F_{jk}x(t)\right)\le\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t) \text{ and}$$

$$\begin{aligned}&2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right)\\&\le 2h_ix^T(t)Pb_{ik}\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\end{aligned}$$

(iii) if $x^T(t)Pb_{ik}\le 0$ and $\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\ge 1$, then,

$$\begin{aligned}&2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right)\\&=2h_i(x(t))x^T(t)Pb_{ik}\le 2h_i(x(t))x^T(t)Pb_{ik}g_{jk}x(t)\end{aligned}$$

Here we note that $1\ge g_{jk}x(t)$, $\forall x\in E(P,\rho)$.

(iv) if $x^T(t)Pb_{ik}\le 0$ and $\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\le 1$, then

$$\sigma\left(\sum_{j=1}^{r}h_j(x(t))F_{jk}x(t)\right)\ge\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t) \text{ and}$$

$$\begin{aligned}&2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right)\\&\le 2h_i(x(t))x^T(t)Pb_{ik}\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\end{aligned}$$

Combining all the four cases lead us to get

$$\begin{aligned}&2h_i(x(t))x^T(t)Pb_{ik}\sigma\left(\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right)\\&\le\max\left\{2h_i(x(t))x^T(t)Pb_{ik}\sum_{j=1}^{r}h_j(x(t))g_{jk}x(t),\right.\\&\qquad\left.2h_i(x(t))x^T(t)Pb_{ik}\sum_{j=1}^{r}h_j(x(t))f_{jk}x(t)\right\}\\&\qquad\forall\, i\in[1,r],\ \forall k\in[1,m],\ \forall x\in E(P,\rho)\end{aligned} \quad (17)$$

Therefore, we have, $\forall x\in E(P,\rho)$
By definition (12) with appropriate selection of the vector v_k^j, it follows that for $\forall x\in E(P,\rho)$,

$$\begin{aligned}\dot V(x)\le&\sum_{i=1}^{r}h_i(x(t))\left[x^T(t)\left\{A_i^TP+PA_i\right\}x(t)\right]\\&+\sum_{i=1}^{r}h_i(x(t))\left[x^T(t-\tau)A_{di}^TPx(t)+x^T(t)PA_{di}x(t-\tau)\right]\\&+\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(x(t))h_j(x(t))\left[2x^T(t)PB_iM(v^j,F_j,G_j)x(t)\right]\\&+\frac{1}{1-\beta}\left\{x^T(t)\Gamma x(t)-(1-\dot\tau)x^T(t-\tau)\Gamma x(t-\tau)\right\}\end{aligned} \quad (18)$$

Therefore, we get

$$\begin{aligned}\dot V(x)\le&\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(x(t))h_j(x(t))\Big[x^T(t)\Big\{\left(A_i+B_iM(v^j,F_j,G_j)\right)^TP\\&+P\left(A_i+B_iM(v^j,F_j,G_j)\right)\\&+PA_{di}\Gamma^{-1}A_{di}^TP+(1-\beta)^{-1}\Gamma\Big\}x(t)\Big]\end{aligned} \quad (19)$$

If (13) is satisfied, $\dot V(x)<0$ for all $x(t)\in E(P,\rho)\setminus\{0\}$. From this fact and the Lyapunov-Krasovskii theorem, the equilibrium point of the whole closed-loop system is asymptotically stable for all $x(t)\in E(P,\rho)\setminus\{0\}$. ■

3.2 Maximization of the domain of attraction via LMI and controller design

Theorem 1 gives a sufficient condition for stability of the equilibrium point and it also can be used for determining the feedback control gain. The optimization problem satisfying condition (13) that maximizes the domain of attraction can be arranged as [3]. Let $X_R=E(R,1)\subset\mathbf{R}^n$ with $R>0$ be a prescribed bounded convex set which is assumed to be ellipsoid type in this paper. The problem of finding maximal region is the same problem of finding of a maximum scalar value α such that $\alpha X_R \subset E(P,\rho)$ for given X_R and an ellipsoid $E(P,\rho)$.

Therefore, the optimization problem can be summarized as

$$\sup_{P>0,\rho,G_j} \alpha \qquad \text{s.t.}$$

$$\text{C1: (15) for } \forall v^j \in \mathrm{N},\ \forall i \in [1,r],\ \forall j \in [1,r] \qquad (20)$$

$$\text{C2: } E(P,\rho) \subset L(G_j) \qquad (21)$$

$$\text{C3: } \alpha X_R \subset E(P,\rho) \qquad (22)$$

Here, without loss of generality, ρ is just set to 1. These conditions can be reformulated into LMI problems which can be solvable via numerical computation. Let $Q = P^{-1}$, $\gamma = \alpha^{-1}$, $\overline{\Gamma} = \Gamma^{-1}$ and $S^j = M(v^j, F_j, G_j)Q$. s_i^j denotes the i th row of S^j and $s_i^{G_j}$ denotes the i th row of G_jQ.

Then, the above conditions are arranged as the following LMI' s by using Schur complement and by method from [6] when R is given.

$$\inf_{Q>0,\gamma,S^j} \gamma \qquad \text{s.t.}$$

C1′ :

$$\begin{bmatrix} QA_i^T + A_iQ + S^{j^T}B_i^T + B_iS^j + A_{di}\overline{\Gamma}A_{di}^T & Q \\ Q & -(1-\beta)\overline{\Gamma} \end{bmatrix} < 0$$

$$, \forall v^j \in \mathrm{N},\ \forall i \in [1,r],\ \forall j \in [1,r] \qquad (23)$$

$$\text{C2}':\quad \begin{bmatrix} 1 & s_i^{G_j} \\ s_i^{G_j} & Q \end{bmatrix} \geq 0,\ \forall i \in [1,m],\ \forall j \in [1,r] \qquad (24)$$

$$\text{C3}':\quad \begin{bmatrix} \gamma R & I \\ I & Q \end{bmatrix} \geq 0 \qquad (25)$$

4. Example and simulation

In this section, an illustrative computer simulation example is provided to demonstrate the validity of the suggested method for uncertain nonlinear systems subjected to input saturation.

Plant Rule i:

PR_i : If $x_1(t)$ is M_{i1} and $x_2(t)$ is M_{i2}

Then $\dot{x}(t) = A_i x(t) + A_{di}(t-\tau) + B_i\sigma(u)$

where

$$A_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},\quad A_2 = \begin{bmatrix} 1 & 1.5 \\ 0.3 & -2 \end{bmatrix},\quad A_{d1} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},$$

$$A_{d2} = \begin{bmatrix} 1 & 1.5 \\ 0.3 & -2 \end{bmatrix},\quad B_1 = B_2 = \begin{bmatrix} 0 \\ 5 \end{bmatrix}.$$

Note that the given plant is unstable.

By the proposed design procedure, we get

$$Q = \begin{bmatrix} 7.32504352084994 & -11.26572027051286 \\ -11.26572027051286 & 21.59633118676618 \end{bmatrix},$$

$$F_1 = [-52.24989595520085 \quad -33.72395933402391],$$

$$F_2 = [-52.04591626420655 \quad -33.29057682533222],$$

and $\alpha = 1.10657259311132$.

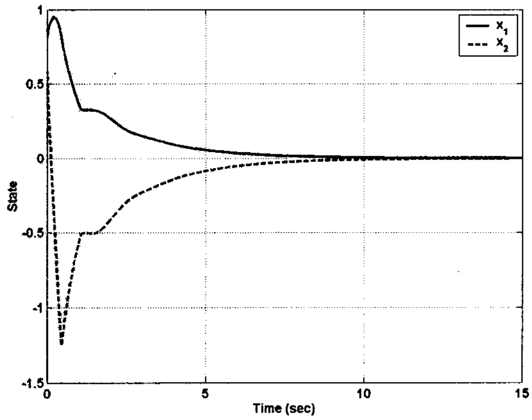

Fig. 1 x_1 **and** x_2

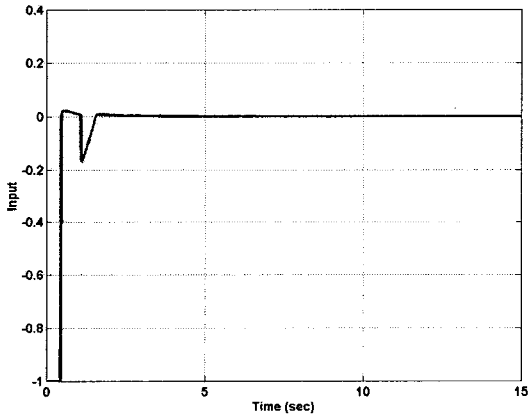

Fig. 2 input u

Figs. 1 and 2 show the response of the plant when the obtained gains are used in the fuzzy controller and the control input. The initial values of the states are chosen to be (0.8, 0.6). The solid line denotes x_1 and the dotted line denotes x_2. It can be seen that x_1, x_2 converge to zero in spite of the time-delay and input saturation.

5. Conclusion

In this paper, fuzzy control approach for the control of the input-saturated nonlinear systems with the time-delay has been presented. With the proposed method, the closed-loop system can be stabilized in spite of the saturated input and the time-delay effect. The sufficient condition for the stability is derived and the analysis and design procedures are reformulated as LMI problems.

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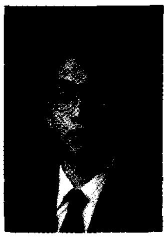

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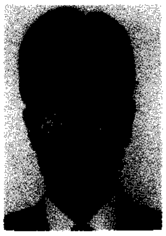

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