Adaptive Tracking Control for Switched Nonlinear Systems Subject to Input Delay and Saturation Using Multi-Dimensional Taylor Network Approach

Wen-Jing He[1], Si-Min Liu[1], Shan-Liang Zhu[1,2], Yu-Qun Han[1,2,*]

1. School of Mathematics and Physics, Qingdao University of Science and Technology, Qingdao, 266061, China
E-mail: hewj928@163.com; xiongmaominmin@163.com; zhushanliang@qust.edu.cn; yuqunhan@163.com

2. The Research Institute for Mathematics and Interdisciplinary Sciences, Qingdao University of Science and Technology, Qingdao, 266061, China

Abstract: Aiming at switched nonlinear systems subject to input delay and saturation, a novel adaptive control strategy is proposed. Firstly, a compensation system is designed, which solves the problem caused by input delay and saturation. Then, multi-dimensional Taylor network (MTN) is used to approximate the unknown nonlinear function. Secondly, an adaptive MTN control strategy based on backstepping technology is proposed, which ensure that all signals in the closed-loop system are bounded and the tracking error remains within a small neighborhood of the origin. Finally, two simulation examples are given to verify the effectiveness of the control strategy proposed in this article.

Key Words: Adaptive control, MTN, Switched nonlinear systems, Input delay, Input saturation

1 INTRODUCTION

It is widely known that the actual systems are very complex, which have many characteristics, such as nonlinearity, multi-level, uncertainty and so on. Hybrid systems are the abstraction of numerous actual systems. As an important model to study hybrid systems from the perspective of system theory and cybernetics, switched systems are widely used in a multitude of practical systems, such as chemical reactor control systems [1], ship navigation control systems [2], robot control systems [3] and so on. Switched systems have quickly become a hot research direction in the field of control since it was proposed [4-6]. Many control methods for switched systems were reported, such as asynchronous control [7], H∞ control [8], adaptive control [9] and backstepping technique [10]. Among them, the combination of adaptive control and backstepping technology is most widely accepted method to cope with the control problem of switched systems [11-13]. However, it is difficult to realize the tracking control of the system with unknown and complex nonlinear structures only by using adaptive backtracking method.

In order to solve the nonlinear problems in the system, fuzzy logic systems (FLSs) and neural networks (NNs) are widely used in various nonlinear systems as two types of general approximators, such as large-scale systems [14, 15], stochastic systems [16, 17], switched systems [18, 19]. In recent years, multi-dimensional Taylor network (MTN), as a new type of NN, has been used to approximate complex nonlinear structures in the system. There is growing concern on MTN, which has the advantages of simple structure and less computational cost [20, 21]. Unfortunately, although MTN has strong approximation ability, there are still some extremely challenging problems that cannot be solved.

It should be emphasized that input delay often occurs in practical systems. For the control problem of nonlinear systems with input delay, many methods were reported, such as the method of introducing a new variable [22, 23], the method based on Lyapunov-Krasovskii functionals [24] and so on. However, input saturation is not considered by the above research. Input saturation limits the size of the actual control signal in the system, so it is inevitable in many practical systems. In order to deal with the input saturation problem in the system, many research results were published [25, 26]. But none of the above results can solve the problem caused by input delay and saturation. Authors of [27] designed a compensation system which provided a good solution to the problems of input delay and saturation. Therefore, it is of great practical significance to extend this method to switched nonlinear systems.

The tracking control problem of switched nonlinear systems subject to input delay and saturation is researched. A compensation system is designed, which counteracts the effects of input delay and saturation. Then, an adaptive backstepping control strategy based on MTN is proposed. The results show that the control strategy of this article is effective. The main contributions of this article are as follows: (i) For the problem of input delay, different with [28, 29], the method based on a compensation system is proposed, which is extended to switched nonlinear systems. (ii) Input delay and saturation are discussed for the first time in switched nonlinear systems. Although input delay and saturation were considered in [27, 30], the proposed controller cannot be applied to switched nonlinear systems. (iii) MTN technology is first applied to switched nonlinear systems subject to input delay and saturation. Authors in [23] extended MTN to switched nonlinear systems subject to input delay, but the proposed control strategy can not solve the problem caused by input saturation.

This work is supported by Shandong Provincial Natural Science Foundation, China (No. ZR2020QF055).

*Corresponding author: Yu-Qun Han.

2 FORMULATION AND PRELIMINARIES

2.1 System description

A class of switched nonlinear systems subject to input delay and saturation are considered as follows

$$\begin{cases} \dot{x}_i = x_{i+1} + f_{i,\sigma(t)}(\bar{x}_i) + \Delta_{i,\sigma(t)}(t,\bar{x}_i), i = 1,\cdots,n-1 \\ \dot{x}_n = sat(u(t-\tau)) + f_{n,\sigma(t)}(\bar{x}_n) + \Delta_{n,\sigma(t)}(t,\bar{x}_n) \\ y = x_1 \end{cases} \quad (1)$$

where $\boldsymbol{x} = [x_1, x_2, \cdots, x_n]^{\mathrm{T}} \in \mathbb{R}^n$ is the state vector with $\bar{\boldsymbol{x}}_i = [x_1, x_2, \cdots, x_i]^{\mathrm{T}} \in \mathbb{R}^i$. $sat(u(t-\tau))$ represents the control input with time delay and saturation. τ is a known time delay. $y \in \mathbb{R}$ is the system output. $\sigma(t)$: $R_+ \to M = \{1,\cdots,m\}$ defines the switching signal with m is the number of subsystem. For $k \in M$, $i = 1,2,\cdots,n$, $f_{i,k}(\cdot)$ is an unknown smooth nonlinear function and $\Delta_{i,k}(\cdot)$ is an uncertain external disturbance.

The *control objectives* is to design an adaptive controller, such that the system output can track the given reference signal in a small error and all signals in the closed-loop system remain bounded.

Assumption 1 [23]: For $i = 1,2,\cdots,n, k \in M$, the external disturbance satisfies $|\Delta_{i,k}(t,\bar{x}_i)| \le \Lambda_{i,k}$, with $\Lambda_{i,k}$ is a constant.

Assumption 2 [23]: The reference signal y_d and its up to the n-th order time derivative are known and bounded.

Assumption 3 [27]: In the time interval $0 \le t \le \tau_0$, the time delay τ of system (1) does not escape to infinity and $\tau \le \tau_0$.

2.2 Multi-dimensional Taylor Network

Lemma 1 [21]: On a compact set Ω , for a continuous function $F(Z)$: $^n \to$ and $\forall \varepsilon > 0$, the following MTN exists

$$F(Z) = \boldsymbol{\theta}^{*\mathrm{T}} P_{m_n}(Z) + \delta(Z) \quad (2)$$

with $Z \triangleq [z_1, z_2, \cdots, z_n]^{\mathrm{T}} \in \mathbb{R}^n$ is the input vector of MTN. $P_{m_n}(Z) \triangleq [z_1, \cdots, z_n, \cdots, z_1^m, \cdots, z_n^m]^{\mathrm{T}} \in \mathbb{R}^l$ defines the middle layer vector of MTN. $\delta(Z)$ is the approximate error satisfies $|\delta(Z)| < \varepsilon$. $\boldsymbol{\theta}$ is the weight vector of MTN.

3 ADAPTIVE MTN CONTROLER DESIGN

First of all, for $i = 1,2,\cdots,n$, define unknown constant $\theta_i = max\left\{\|\boldsymbol{\theta}_{i,k}\|^2 : k \in M\right\}$, with $\boldsymbol{\theta}_{i,k}$ is the weight vector of MTN. $\hat{\theta}_i$ is the estimated value of θ_i and satisfies $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$.

In order to eliminate the influence of input delay and saturation, the compensation system is designed.

$$\begin{aligned} \dot{\gamma}_i &= \gamma_{i+1} - q_i \gamma_i, i = 1,2,\cdots,n-1 \\ \dot{\gamma}_n &= sat(u(t-\tau)) - u(t) - q_n \gamma_n \end{aligned} \quad (3)$$

with $q_1 > \frac{1}{2}, q_i > 1(i = 2,\cdots,n)$ are known design parameters, and the initial condition of the system (3) is $\gamma(0) = 0$.

The input with delay and saturation can be written as

$$sat(u(t-\tau)) = \begin{cases} u_M, & u(t-\tau) \ge u_M \\ u(t-\tau), & -u_m \le u(t-\tau) \le u_M \\ u_m, & u(t-\tau) \le -u_m \end{cases} \quad (4)$$

with $u_m, u_M > 0$ are constants.

Before designing an adaptive controller based on MTN by backstepping method, the following coordinate transformations are defined

$$\begin{aligned} z_1 &= x_1 - y_d - \gamma_1 \\ z_i &= x_i - \alpha_{i-1} - y_d^{(i-1)} - \gamma_i, i = 2,3,\cdots,n \end{aligned} \quad (5)$$

with $\alpha_i\,(i = 1,2,\cdots,n-1)$ is the virtual control signal.

The virtual control signal and the actual control law in the adaptive MTN control strategy backstepping-based are constructed as

$$\begin{aligned} \alpha_i &= -r_i z_i - \frac{1}{2\ell_i^2} z_i \hat{\theta}_i P_{m_i}^{\mathrm{T}} P_{m_i}, i = 1,2,\cdots,n-1 \\ u &= -r_n z_n - \frac{1}{2\ell_n^2} z_n \hat{\theta}_n P_{m_n}^{\mathrm{T}} P_{m_n} \end{aligned} \quad (6)$$

with $r_i, \ell_i > 0\,(i = 1,2,\cdots,n)$ are constants.

Step 1: The following candidate Lyapunov function is considered

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} \tilde{\theta}_1^2 \quad (7)$$

The time derivative of V_1 can be written as

$$\dot{V}_1 = z_1 (z_2 + \alpha_1 + F_{1,k} + \Delta_{1,k}) - \frac{3}{2} z_1^2 - \tilde{\theta}_1 \dot{\hat{\theta}}_1 \quad (8)$$

with $F_{1,k} = f_{1,k} + q_1 \gamma_1 + \frac{3}{2} z_1$.

From Lemma 1, for $\forall \varepsilon_{1,k} > 0$, a MTN that can be used to approximate $F_{1,k}$, such as

$$F_{1,k} = \boldsymbol{\theta}_{1,k}^{\mathrm{T}} P_{m_1}(\boldsymbol{z}_1) + \delta_{1,k}(\boldsymbol{z}_1) \quad (9)$$

with $\boldsymbol{z}_1 = [z_1]^{\mathrm{T}}$ is the input vector. $\delta_{1,k}(\boldsymbol{z}_1)$ is the approximation error and satisfies $|\delta_{1,k}(\boldsymbol{z}_1)| < \varepsilon_{1,k}$.

According to Young's inequality and Assumption 1, one has

$$z_1 F_{1,k} \le \frac{1}{2\ell_1^2} z_1^2 \theta_1 P_{m_1}^{\mathrm{T}} P_{m_1} + \frac{1}{2}\ell_1^2 + \frac{1}{2} z_1^2 + \frac{1}{2}\varepsilon_{1,k}^2 \quad (10)$$

$$z_1 (z_2 + \Delta_{1,k}) \le z_1^2 + \frac{1}{2} z_2^2 + \frac{1}{2}\Lambda_{1,k}^2 \quad (11)$$

Substituting (6), (10) and (11) into (8), one has

$$\dot{V}_1 \le -r_1 z_1^2 + \tilde{\theta}_1 \left(\frac{1}{2\ell_1^2} z_1^2 P_{m_1}^{\mathrm{T}} P_{m_1} - \dot{\hat{\theta}}_1 \right) + \frac{1}{2} z_2^2 + \frac{1}{2}\left(\Lambda_{1,k}^2 + \ell_1^2 + \varepsilon_{1,k}^2 \right) \tag{12}$$

Step $i(2 \le i \le n-1)$ ***:*** The following candidate Lyapunov function is considered

$$V_i = V_{i-1} + \frac{1}{2} z_i^2 + \frac{1}{2}\tilde{\theta}_i^2 \tag{13}$$

The time derivative of V_i can be written as

$$\dot{V}_i = \dot{V}_{i-1} + z_i\left(z_{i+1} + \alpha_i + F_{i,k} + \Delta_{i,k} \right) - 2z_i^2 - \tilde{\theta}_i \dot{\hat{\theta}}_i \tag{14}$$

with $F_{i,k} = 2z_i + f_{i,k} + q_i \gamma_i - \dot{\alpha}_{i-1}$.

Similar to the work of (9)-(12), we can get

$$\dot{V}_i \le -\sum_{j=1}^{i} r_j z_j^2 + \frac{1}{2} z_{i+1}^2 + \sum_{j=1}^{i} \tilde{\theta}_j \left(\frac{1}{2\ell_j^2} z_j^2 P_{m_j}^{\mathrm{T}} P_{m_j} - \dot{\hat{\theta}}_j \right) + \frac{1}{2}\sum_{j=1}^{i}\left(\Lambda_{j,k}^2 + \ell_j^2 + \varepsilon_{j,k}^2 \right) \tag{15}$$

Step n ***:*** The following candidate Lyapunov function is considered

$$V_n = V_{n-1} + \frac{1}{2} z_n^2 + \frac{1}{2}\tilde{\theta}_n^2 \tag{16}$$

The time derivative of V_n can be written as

$$\dot{V}_n = \dot{V}_{n-1} + z_n\left(u + F_{n,k} + \Delta_{n,k} \right) - \frac{3}{2} z_n^2 - \tilde{\theta}_n \dot{\hat{\theta}}_n \tag{17}$$

with $F_{n,k} = \frac{3}{2} z_n + f_{n,k} - \dot{\alpha}_{n-1} - y_d^{(n)} + q_n \gamma_n$.

Similar to the work of (9)-(12), we can get

$$\dot{V}_n \le -\sum_{j=1}^{n} r_j z_j^2 + \sum_{j=1}^{n} \tilde{\theta}_j \left(\frac{1}{2\ell_j^2} z_j^2 P_{m_j}^{\mathrm{T}} P_{m_j} - \dot{\hat{\theta}}_j \right) + \frac{1}{2}\sum_{j=1}^{n}\left(\Lambda_{j,k}^2 + \ell_j^2 + \varepsilon_{j,k}^2 \right) \tag{18}$$

4 STABILITY ANALYSIS

Theorem 1: Consider a class of switched nonlinear systems (1) subject to input delay and saturation, if the virtual control signal and the actual control are selected as (6), the adaptive control law is designed as

$$\dot{\hat{\theta}}_j = -\eta_j \hat{\theta}_j + \frac{1}{2\ell_j^2} z_j^2 P_{m_j}^{\mathrm{T}} P_{m_j} \tag{19}$$

with $j = 1,2,\cdots,n$, $\eta_j > 0$ is a constant. For any bounded initial conditions, one has

(1) All signals in the closed-loop system remain bounded.

(2) The tracking error will converge to a small region of the origin.

Proof: Select the Lyapunov function as follows

$$V = V_n = \frac{1}{2}\sum_{j=1}^{n} z_j^2 + \frac{1}{2}\sum_{j=1}^{n} \tilde{\theta}_j^2 \tag{20}$$

According to (18) and (19), one has

$$\begin{aligned} \dot{V} &\le -\frac{1}{2}\bar{\eta}\sum_{j=1}^{n}\tilde{\theta}_j^2 + \frac{1}{2}\sum_{j=1}^{n}\eta_j\theta_j^2 - \sum_{j=1}^{n} r_j z_j^2 + \frac{1}{2}\sum_{j=1}^{n}\left(\Lambda_{j,\max}^2 + \ell_j^2 + \varepsilon_{j,\max}^2 \right) \\ &\le -aV + b \end{aligned} \tag{21}$$

with $\bar{\eta} = \min\left\{ \eta_j \,|\, j = 1,2,\cdots,n \right\}$, $a = \min\left\{ 2r_j, \bar{\eta} \,|\, j = 1,\cdots,n \right\}$, $b = \frac{1}{2}\sum_{j=1}^{n}\eta_j\theta_j^2 + \frac{1}{2}\sum_{j=1}^{n}\left(\Lambda_{j,\max}^2 + \ell_j^2 + \varepsilon_{j,\max}^2 \right)$.

For the compensation system (3), the Lyapunov function is selected as follows

$$V_\gamma = \frac{1}{2}\sum_{j=1}^{n}\gamma_j^2 \tag{22}$$

The time derivative of V_γ can be written as

$$\dot{V}_\gamma = -qV_\gamma + c \tag{23}$$

with $\left| sat\left(u(t-\tau) \right) - u \right| \le c_u$, $c = \frac{c_u}{\lambda}$. For $j = 1,\cdots,n$, $q = \min\left\{ \bar{q}_j \right\}$, $\bar{q}_1 = q_1 - \frac{1}{2}$, $\bar{q}_i = q_i - 1$, $i = 2,\cdots,n-1$, $\bar{q}_n = q_n - \frac{1}{2} - \frac{\lambda}{4}$ and λ is a known positive constant.

Based on (21) and (23), using the similar analysis method in [27], the conclusions of Theorem 1 are correct.

5 SIMULATION

A numerical example and a practical example are presented to verify the effectiveness of the proposed control strategy.

Example 1: The following third-order switched nonlinear systems subject to input delay and saturation is considered.

$$\begin{cases} \dot{x}_1 = x_2 + f_{1,\sigma(t)} + \Delta_{1,\sigma(t)} \\ \dot{x}_2 = x_3 + f_{2,\sigma(t)} + \Delta_{2,\sigma(t)} \\ \dot{x}_3 = sat\left(u(t-\tau) \right) + f_{3,\sigma(t)} + \Delta_{3,\sigma(t)} \\ y = x_1 \end{cases} \tag{24}$$

with $x_1(0) = x_2(0) = x_3(0) = 0$, input delay $\tau = 0.1$ and $\sigma(t): [0,\infty] \to M = \{1,2\}$. $f_{1,1} = -0.1x_1$, $f_{2,1} = -0.1x_1x_2$, $f_{3,1} = -0.1x_2x_3$, $f_{1,2} = -0.2x_1$, $f_{2,2} = -0.2x_1x_2$, $f_{3,2} = -0.2x_1x_3$, $\Delta_{1,1} = 0.1\sin t$, $\Delta_{2,1} = 0.2\sin t$, $\Delta_{3,1} = 0.3\sin t$, $\Delta_{1,2} = 0.1\cos t$, $\Delta_{2,2} = 0.2\cos t$, $\Delta_{3,2} = 0.3\cos t$, $u_M = u_m = 50$. The desired trajectory is $y_d = 0.5\sin t$.

The parameters in the controller are selected as $\eta_1 = 6$, $\eta_2 = 1$, $\eta_3 = 0.2$, $r_1 = r_2 = 10$, $r_3 = 2$ and $\ell_1 = \ell_2 = \ell_3 = 1$. The simulation results are shown in Figs 1-5.

Fig 1 describes the trajectory of system output and desired signal. Fig 2 shows the trajectory of the tracking error. Fig 3 displays the actual control input with input delay and saturation. Fig 4 depicts the trajectory of the state variables. Fig 5 represents the trajectory of switching signal. It can be seen that the control objective has been achieved, satisfactory results have been obtained.

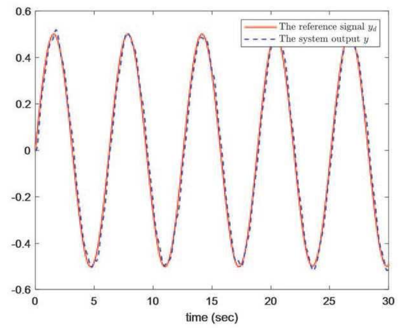

Fig 1. System output y and desired trajectory y_d of Example 1.

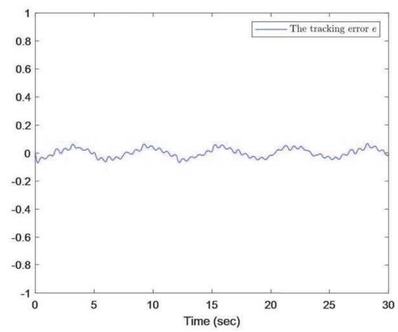

Fig 2. The tracking error $y - y_d$ of Example 1.

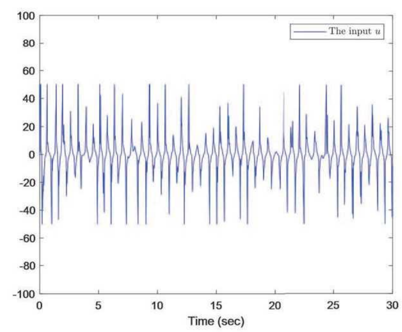

Fig 3. System input $sat\left(u\left(t-\tau\right)\right)$ of Example 1.

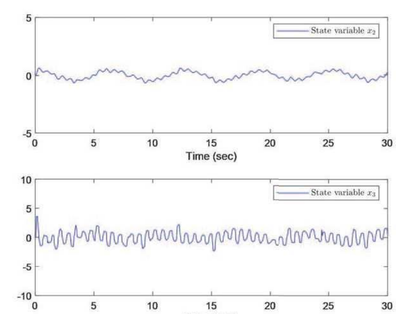

Fig 4. State variables x_2, x_3 of Example 1.

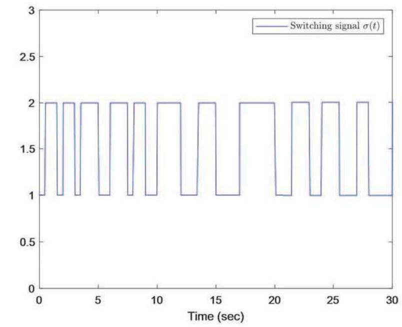

Fig 5. Switching signal of Example 1.

Example 2: The continuous stirred tank reactor (CSTR) with two modes feed stream can be modelled as switched nonlinear systems with input delay and saturation as follows

$$\begin{cases} \dot{x}_1 = x_2 + f_{1,\sigma(t)} \\ \dot{x}_2 = g_{\sigma(t)} sat\left(u\left(t-\tau\right)\right) \\ y = x_1 \end{cases} \tag{25}$$

with initial state and switching signal are the same as those in Example 1. $f_{1,1} = 0.1x_1$, $f_{1,2} = x_1$, $g_1 = g_2 = [1, 1]$, $u_M = u_m = 5$, $y_d = 0.5\left(\sin t + \sin\left(0.5t\right)\right)$.

The parameters in the controller are selected as $r_1 = 15$, $r_2 = 5$, $\eta_1 = \eta_2 = 0.1$, and $\ell_1 = \ell_2 = 1$. The simulation results are shown in Figs 6-10.

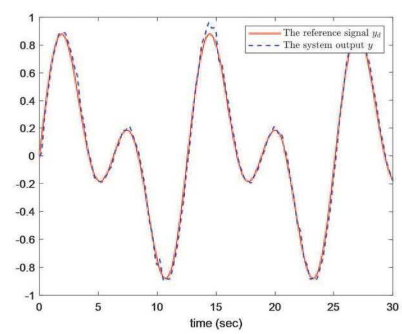

Fig 6. System output y and desired trajectory y_d of Example 2.

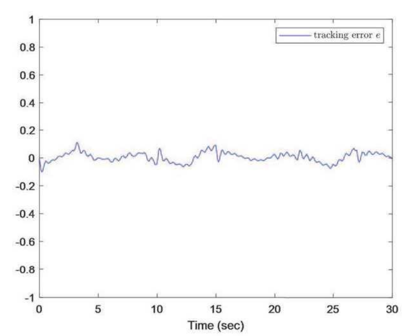

Fig 7. The tracking error $y - y_d$ of Example 2.

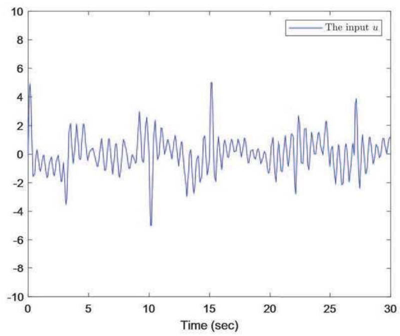

Fig 8. System input $sat\left(u\left(t-\tau\right)\right)$ of Example 2.

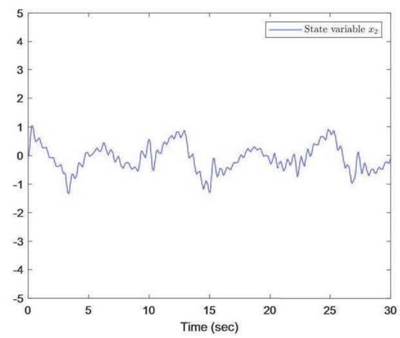

Fig 9. State variables x_2 of Example 2.

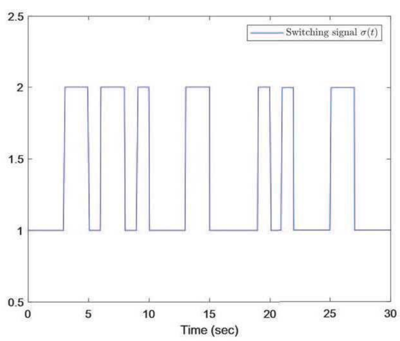

Fig 10. Switching signal of Example 2.

Figs 6-10 further verify the effectiveness of the strategy proposed in this article.

6 CONCLUSION

An adaptive control strategy based on MTN is proposed for tracking control of switched nonlinear systems with input delay and saturation. Firstly, a compensation system is introduced to counteract the influence of input delay and saturation. Secondly, the combination of unknown nonlinear functions in the backstepping process is approximated by a MTN. Then, a novel adaptive controller based on MTN is proposed. The results show that all signals in the closed-loop system are bounded, and the tracking error can converge to a small neighborhood of the origin. Finally, two examples are presented, which verify that the control strategy proposed in this article is satisfactory.

REFERENCES

[1] S. M. Tabatabaei, S. Kamali, M. M. Arefi, and J. D. Cao, "Prescribed performance adaptive DSC for a class of time-delayed switched nonlinear systems in nonstrict-feedback form: Application to a two-stage chemical reactor," *Journal of Process Control,* vol. 89, pp. 85-94, 2020.

[2] Z. H. Deng, L. Shi, T. Liu, and B. Wang, "Switching method for long-term inertial navigation system based on switched control," *The Journal of Navigation,* vol. 72, no. 5, pp. 1315-1330, 2019.

[3] X. Wang and J. Zhao, "Switched adaptive tracking control of robot manipulators with friction and changing loads," *International Journal of Systems Science,* vol. 46, no. 6, pp. 955-965, 2015.

[4] D. Yang, G. D. Zong, S. K. Nguang, and X. D. Zhao, "Bumpless transfer H∞ anti-disturbance control of switching Markovian LPV systems under the hybrid switching," *IEEE Transactions on Cybernetics,* 2020. DOI: 10.1109/TCYB.2020.3024988.

[5] G. D. Zong, D. Yang, J. Lam, and X. Q. Song, "Fault-tolerant control of switched LPV systems: a bumpless transfer approach," *IEEE/ASME Transactions on Mechatronics,* 2021. DOI: 10.1109/TMECH.2021.3096375.

[6] Z. Y. Wang, L. J. Gao and H. Y. Liu, "Stability and stabilization of impulsive switched system with inappropriate impulsive switching signals under asynchronous switching," *Nonlinear Analysis: Hybrid Systems,* vol. 39, pp. 100976, 2021.

[7] M. Li, Y. Chen, L. Y. Xu, and Z. Y. Chen, "Asynchronous control strategy for semi-Markov switched system and its application," *Information Sciences,* vol. 532, pp. 125-138, 2020.

[8] W. A. Zhang, L. Yu and S. Yin, "A switched system approach to H∞ control of networked control systems with time-varying delays," *Journal of the Franklin Institute,* vol. 348, no. 2, pp. 165-178, 2011.

[9] L. J. Long, Z. Wang and J. Zhao, "Switched adaptive control of switched nonlinearly parameterized systems with unstable subsystems," *Automatica,* vol. 54, pp. 217-228, 2015.

[10] R. C. Ma and J. Zhao, "Backstepping design for global stabilization of switched nonlinear systems in lower triangular form under arbitrary switchings," *Automatica,* vol. 46, no. 11, pp. 1819-1823, 2010.

[11] M. L. Chiang and L. C. Fu, "Adaptive stabilization of a class of uncertain switched nonlinear systems with backstepping control," *Automatica,* vol. 50, no. 8, pp. 2128-2135, 2014.

[12] G. Y. Lai, Z. Liu, Y. Zhang, C. L. Philip Chen, and S. L. Xie, "Adaptive backstepping-based tracking control of a class of uncertain switched nonlinear systems," *Automatica,* vol. 91, pp. 301-310, 2018.

[13] F. Wang, B. Chen, Z. Y. Zhang, and C. Lin, "Adaptive tracking control of uncertain switched stochastic nonlinear systems," *Nonlinear Dynamics,* vol. 84, no. 4, pp. 2099-2109, 2016.

[14] S. C. Tong, Y. M. Li and H. G. Zhang, "Adaptive neural network decentralized backstepping output-feedback control for nonlinear large-scale systems with time delays," *IEEE Transactions on Neural Networks,* vol. 22, no. 7, pp. 1073-1086, 2011.

[15] L. Cao, H. Y. Li, N. Wang, and Q. Zhou, "Observer-based event-triggered adaptive decentralized fuzzy control for nonlinear large-scale systems," *IEEE Transactions on Fuzzy Systems,* vol. 27, no. 6, pp. 1201-1214, 2019.

[16] S. C. Tong, Y. Li, Y. M. Li, and Y. J. Liu, "Observer-based adaptive fuzzy backstepping control for a class of stochastic nonlinear strict-feedback systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics),* vol. 41, no. 6, pp. 1693-1704, 2011.

[17] S. C. Tong, T. Wang, Y. M. Li, and H. G. Zhang, "Adaptive neural network output feedback control for stochastic nonlinear systems with unknown dead-zone and unmodeled dynamics," *IEEE Transactions on Cybernetics,* vol. 44, no. 6, pp. 910-921, 2014.

[18] C. C. Hua, G. P. Liu, Y. F. Li, and X. P. Guan, "Adaptive neural tracking control for interconnected switched systems with non-ISS unmodeled dynamics," *IEEE Transactions on Cybernetics,* vol. 49, no. 5, pp. 1669-1679, 2019.

[19] S. C. Tong, S. Sui and Y. M. Li, "Observed-based adaptive fuzzy tracking control for switched nonlinear systems with dead-zone," *IEEE Transactions on Cybernetics,* vol. 45, no. 12, pp. 2816-2826, 2015.

[20] H. S. Yan and Z. Y. Duan, "Tube-based model predictive control using multidimensional Taylor network for nonlinear time-delay systems," *IEEE Transactions on Automatic Control,* vol. 66, no. 5, pp. 2099-2114, 2021.

[21] Y. Q. Han, "Design of decentralized adaptive control approach for large-scale nonlinear systems subjected to input delays under prescribed performance," *Nonlinear Dynamics,* vol. 106, no. 1, pp. 565-582, 2021.

[22] Y. Q. Han, W. J. He, N. Li, and S. L. Zhu, "Adaptive tracking control of a class of nonlinear systems with input delay and dynamic uncertainties using multi-dimensional Taylor network," *International Journal of Control, Automation and Systems,* vol. 19, no. 12, pp. 4078-4089, 2021.

[23] W. J. He, Y. Q. Han, N. Li, and S. L. Zhu, "Novel adaptive controller design for a class of switched nonlinear systems subject to input delay using multi-dimensional Taylor network," *International Journal of Adaptive Control and Signal Processing,* vol. 36, no. 3, pp. 607-624, 2022.

[24] Y. E. Wang, X. M. Sun and B. W. Wu, "Lyapunov-Krasovskii functionals for switched nonlinear input delay systems under asynchronous switching," *Automatica,* vol. 61, pp. 126-133, 2015.

[25] Y. Q. Han, N. Li, W. J. He, and S. L. Zhu, "Adaptive multi-dimensional Taylor network funnel control of a class of nonlinear systems with asymmetric input saturation," *International Journal of Adaptive Control and Signal Processing,* vol. 35, no. 5, pp. 713-726, 2021.

[26] C. Y. Wen, J. Zhou, Z. T. Liu, and H. Y. Su, "Robust adaptive control of uncertain nonlinear systems in the presence of input saturation and external disturbance," *IEEE Transactions on Automatic Control,* vol. 56, no. 7, pp. 1672-1678, 2011.

[27] J. L. Ma, S. Y. Xu, G. M. Zhuang, Y. L. Wei, and Z. Q. Zhang, "Adaptive neural network tracking control for uncertain nonlinear systems with input delay and saturation," *International Journal of Robust and Nonlinear Control,* vol. 30, no. 7, pp. 2593-2610, 2020.

[28] N. Li, Y. Q. Han, W. J. He, and S. L. Zhu, "Control design for stochastic nonlinear systems with full-state constraints and input delay: a new adaptive approximation method," *International Journal of Control, Automation and Systems,* 2021.(Accepted)

[29] D. Yue and Q. L. Han, "Delayed feedback control of uncertain systems with time-varying input delay," *Automatica,* vol. 41, no. 2, pp. 233-240, 2005.

[30] B. Zhou, H. J. Gao, Z. L. Lin, and G. R. Duan, "Stabilization of linear systems with distributed input delay and input saturation," *Automatica,* vol. 48, no. 5, pp. 712-724, 2012.