Neural Network-Based Event-triggered Adaptive Asymptotic Tracking Control for Switched Nonlinear Systems §

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Abstract

This paper addresses the event-triggered based adaptive asymptotic tracking control problem for switched nonlinear systems with unknown control directions based on neural network technique. A novel asymptotic tracking controller, in which Nussbaum functions are introduced to address the issue of unknown control directions, is designed by combining neural network control technology and event-triggered strategy. Different from the existing tracking control schemes, the proposed controller in this paper can guarantee that the tracking error ς_1 asymptotically converges to the origin and reduce the communication burden from the controller to the actuator. Finally, the effectiveness of the presented control design is proved by numerical examples.

Keywords: Event-triggered control, neural network technique, unknown control directions, switched nonlinear systems.

1 Introduction

Due to the uncertain parameters often exist in the actual systems, it is difficult to construct an accurate mathematical model to describe it. To solve the problem of controlling uncertain nonlinear systems, the adaptive backstepping design is proposed[1]. Then, after years of development, the adaptive backstepping design has become a powerful tool to handle with various kinds of nonlinear systems with uncertain parameters, such as uncertain stochastic nonlinear systems [2] and [3], nonlinear large-scale systems [4] and switched nonlinear systems [5] and [6] etc. However, when the uncertain nonlinear functions are completely unknown, these conclusions will fail. To solve this problem, the fuzzy logic system (FLS) [7]–[10] or neural network (NN) [11]–[16] is proposed. Specifically, in view of FLS and

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the adaptive backstepping design approach, an adaptive finite-time control issue for nonlinear systems with actuator faults has been studied in [8]. [14] studied the robust NN control issue for nonlinear time-delay systems by employing command filters based adaptive backstepping technique.

For general nonlinear systems, the signs of the control gain are usually unknown. At the same time, the unknown signs of the control gain also increase the complexity and difficulty of controlling such nonlinear systems. Thus, the aforementioned problem has attracted wide attention in the last decades. The Nussbaum gain technique proposed by [17] paved the way to handle the challenge of unknown control coefficients. Subsequently, the Nussbaum gain technique was widely used in the design process of controllers [18]–[23]. Especially, in [18], an adaptive tracking controller was presented for a kind of MIMO stochastic nonlinear systems with unknown control directions. In term of the Nusssbaum gains technique and backstepping design, [20] considered adaptive control issue for nonlinear systems with unknown control directions. An adaptive neural command filtered control strategy for nonlinear MIMO systems with unknown control directions was designed in [21].

It should be pointed out that the controller designed in the aforementioned papers [18]–[23] can only ensure that the tracking error is bounded as $t \to \infty$. However, the controller design scheme proposed in the above papers may fail in some cases where high precision tracking error is required. To address the aforementioned problem, the asymptotic tracking control approach is proposed. Then, a great deal of results in asymptotic tracking control have been obtained [25]–[30]. For example, in [25], an adaptive asymptotic tracking control approach was introduced for nonlinear systems subject to parameter uncertainty, unknown actuator nonlinearity and bounded external disturbance. In [28], the problem of asymptotic tracking control for switched nonlinear system was solved by designing a novel discontinuous controller.

On the other hand, in the aforementioned results, the control signals are continuously transmitted to the actuator regardless of whether the system needs it or not, which increases the communication burden and transmission costs. Therefore, to reduce communication burden and save resources, some scholars have presented event-triggered control (ETC). Different from the time-triggered control, the ETC takes the behavior of the system into consideration. Thus, considerable attention has been paid to ETC [31]–[39]. To list a few, the ETC problem for uncertain nonlinear systems was addressed in [33] by employing adaptive backstepping design and the triggering event. [36] considered the event-triggered tracking control problem of stochastic nonlinear systems by employing command filtered technique to solve the issue of complexity explosion. However, as far as we known, until now, there are few results about the event-triggered asymptotic tracking control for switched nonlinear systems with unknown control directions.

With the above observations, in this paper, a novel controller is proposed to handle the issue of NN based event-triggered adaptive asymptotic tracking control for switched nonlinear systems with unknown control directions. The contributions of the developed controller are highlighted as:

(1) For the first time, an NN based event-triggered adaptive asymptotic tracking control strategy for switched nonlinear systems with unknown control directions is proposed. Compared with [31]–[39],

a novel control law is proposed to address the problem of switched nonlinear systems with unknown control directions and event-triggered mechanism.

(2) Compared with the existing results in [33]–[37], the system output y can asymptotically track the desired signal y_d under our design controller.

The remainder of this paper is arranged as follows: The design method of event-triggered controller is presented in section 2. In section 3, simulation studies are given to prove the validity of the presented approach. Section 4 concludes this study.

2 Problem Statement

Consider the following system:

$$\begin{cases} \dot{\upsilon}_i = b_i g_{\sigma(t),i}(\bar{\upsilon}_i)\upsilon_{i+1} + f_{\sigma(t),i}(\bar{\upsilon}_i), 1 \le i \le n-1, \\ \dot{\upsilon}_n = b_n g_{\sigma(t),n}(\bar{\upsilon}_n)u + f_{\sigma(t),n}(\bar{\upsilon}_n), \\ \ y = \upsilon_1, \end{cases} \tag{1}$$

where $y \in R$, $u \in R$ and $\bar{\upsilon}_i = [\upsilon_1, \ldots, \upsilon_i]^T$ denote the system output, event-triggered input and states, respectively; $f_{\sigma(t),i}(\bar{\upsilon}_i)$ denotes unknown smooth nonlinear functions. $g_{\sigma(t),i}(\bar{\upsilon}_i)$ is known s-mooth nonlinear functions. $b_i = 1$ or $b_i = -1$ denotes the control directions, which are unknown. $\sigma(t) : [0, +\infty) \to \mathcal{W} = \{1, \cdots, w\}$ denotes the switching signal.

Our control aim is to devise an event-triggered controller to ensure that (1) the system output y can asymptotically track the desired trajectory y_d; (2) all signals of the controlled system are bounded.

To construct an event-triggered asymptotic tracking controller, the following Lemmas and Assumption are introduced.

Lemma 1 *[23] For any $(x, y) \in R^2$, the following inequality holds*

$$xy \le \frac{x^a}{a} + \frac{y^b}{b},$$

with $a > 1, b > 1, \frac{1}{a} + \frac{1}{b} = 1$.

Definition 1 *[20] If the continuous function $\mathcal{N}(\chi)$ satisfies the following equalities:*

$$\lim_{\xi\to\infty} \sup \frac{1}{\xi}\int_0^{\xi} \mathcal{N}(\chi)d\chi = +\infty,$$
$$\lim_{\xi\to\infty} \inf \frac{1}{\xi}\int_0^{\xi} \mathcal{N}(\chi)d\chi = -\infty,$$

it is called Nussbaum functions. For example, $\chi^2\cos(\chi)$ and $e^{\chi^2}\cos(\pi/2\chi)$. In this paper, we choose $\mathcal{N}_i(\chi_i) = \frac{\alpha^2\beta^{2i}+1}{\beta^i\sqrt{\alpha^2\beta^{2i}+1}} e^{\alpha|\chi_i|}\sin(\frac{\chi_i}{\beta^i})$, where $i = 1, \cdots, l$, $\alpha > 0$ and $\beta = \frac{1}{\epsilon} > 0$ are design parameters.

Lemma 2 *[20] If a positive definite, radially unbounded function $V(t)$ satisfies the following inequality*

$$V(t) \leq c_1 + \sum_{i=1}^{l} \int_0^t (b_i \mathcal{N}_i(\zeta_i) - 1)\dot{\zeta}_i(s) ds,$$

where $c_1 > 0$ is a constant, then by choosing

$$\alpha > \max\left\{\sqrt{\frac{\epsilon^{2i}\cos(1/\epsilon)^2}{1-\cos(1/\epsilon)^2}}, \frac{\zeta}{\lambda}\ln(2l)\right\},$$

where $\lambda > 0$ is a constant, $\epsilon > 4$ is a positive integer. Then $V(t)$, $\zeta_i(t)$ and $\Sigma_{i=1}^{l} \int_0^t b_i \mathcal{N}_i(\zeta_i)\dot{\zeta}_i ds$ are bounded on $[0, \infty]$.

Lemma 3 *(Barbalat Lemma)[38] For $t > 0$, if ϕ is uniformly continuous function. Suppose $\lim_{t\to\infty} \int_0^t |\phi(\tau)| d\tau$ exists and is limited, we have*

$$\lim_{t\to\infty} \phi(t) = 0.$$

Assumption 1 *For $t > 0$, y_d and its time derivatives up to the $j-th$ order, $1 \leq j \leq n$ are known and bounded.*

To approximate the unknown nonlinear functions $h(Z)$, the following NN is employed.

$$\bar{h}(Z) = \psi^T S(Z),$$

where $\psi = [\psi_1, \psi_2, \ldots, \psi_q]^T \in R^q$ is the weight vector, the NN node number $q > 1$, and $S(Z) = [s_1(Z), s_2(Z), \ldots, s_q(Z)]^T \in R^q$ with $s_i(Z)$ being Gaussian function, which have the following form

$$s_i(Z) = \exp\left[\frac{-(Z-\nu_i)^T(Z-\nu_i)}{\xi_i^2}\right], \qquad i = 1, 2, \ldots, q,$$

where $\nu_i = [\nu_{i1}, \nu_{i2}, \ldots, \nu_{is}]^T$ is the center of the receptive field and ξ_i is the width of the Gaussian function. From [24], it can be concluded that with sufficiently large q, the NN can approximate any continuous function $h(Z)$ over a compact set Ω to arbitrary any accuracy $\varepsilon > 0$ as

$$h(Z) = \psi^{*T} S(Z) + \delta(Z),$$

where $\delta(Z)$ denotes the approximation error and satisfies $|\delta(Z)| \leq \varepsilon$, and $\psi^* = \arg\min\{\sup_{Z\in\Omega} |h(Z) - \psi^T S(Z)|\}$ is the unknown ideal constant weight vector.

3 Control Design Scheme

3.1 Virtual Controller Design

To develop a backstepping design process, the following coordinate transformations are defined as

$$\begin{cases} \varsigma_1 = \upsilon_1 - y_d, \\ \varsigma_i = \upsilon_i - \alpha_{i-1}, \qquad 2 \leq i \leq n, \end{cases} \tag{2}$$

where ς_i denotes the error signals, α_{i-1} refers to virtual control signals. Define $\tilde{\theta}_i = \theta_i - \hat{\theta}_i$, $\tilde{\rho}_i = \rho_i - \hat{\rho}_i$, $\hat{\theta}_i$ and $\hat{\rho}_i$ denote the estimation of θ_i and ρ_i, respectively. And $\theta_i = \|\psi_i\|$, $\rho_i = \tau_i$.

Step 1: From (1) and (2), it can be concluded that

$$\dot{\varsigma}_1 = b_1 g_{p,1}(\bar{\upsilon}_1)\upsilon_2 + f_{p,1}(\bar{\upsilon}_1) - \dot{y}_d. \tag{3}$$

Choose the Lyapunov function candidate as

$$V_1 = \frac{1}{2}\varsigma_1^2 + \frac{1}{2\gamma_1}\tilde{\theta}_1^2 + \frac{1}{2r_1}\tilde{\rho}_1^2,$$

where γ_1 and r_1 are positive design parameters. Its derivative along (3) yields

$$\dot{V}_1 \leq \varsigma_1(\bar{f}_{p,1}(Z_1) + b_1 g_{p,1}(\varsigma_2 + \alpha_1) - \frac{\varsigma_1 g_{p,1}^2}{2}) - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{r_1}\tilde{\rho}_1\dot{\hat{\rho}}_1, \tag{4}$$

let $\bar{f}_{p,1}(Z_1) = f_{p,1}(\bar{\upsilon}_1) - \dot{y}_d + \frac{\varsigma_1 g_{p,1}^2}{2}$. In view of the NN approximation property, there exists a NN $\psi_{p,1}^T S_1(Z_1)$ such that

$$\bar{f}_{p,1}(Z_1) = \psi_{p,1}^T S_1(Z_1) + \delta_1(Z_1), \tag{5}$$

where $|\delta_1(Z_1)| \leq \tau_1$ denotes the approximation error. By plugging (5) into (4), one has

$$\dot{V}_1 \leq \varsigma_1(\psi_{p,1}^T S_1(Z_1) + \delta_1(Z_1) + b_1 g_{p,1}(\varsigma_2 + \alpha_1) - \frac{\varsigma_1 g_{p,1}^2}{2}) - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 - \frac{1}{r_1}\tilde{\rho}_1\dot{\hat{\rho}}_1. \tag{6}$$

For any $\vartheta_1 > 0$, the following inequality holds

$$\varsigma_1\psi_{p,1}^T S_1(Z_1) \leq |\varsigma_1|\|\psi_1\|\|S_1\| = |\varsigma_1|\theta_1\|S_1\|, \tag{7}$$

$$|\varsigma_1|\|S_1\| \leq \frac{\varsigma_1^2 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1 + \vartheta_1^2}} + \vartheta_1. \tag{8}$$

Combining (6)-(7) with (8) results in

$$\dot{V}_1 \leq \varsigma_1(b_1 g_{p,1}(\varsigma_2 + \alpha_1) + \frac{\varsigma_1\theta_1 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1 + \vartheta_1^2}} - \frac{\varsigma_1 g_{p,1}^2}{2}) - \frac{1}{\gamma_1}\tilde{\theta}_1\dot{\hat{\theta}}_1 + \theta_1\vartheta_1 + |\varsigma_1|\tau_1 - \frac{1}{r_1}\tilde{\rho}_1\dot{\hat{\rho}}_1. \tag{9}$$

Based on Lemma 1, we get

$$\varsigma_1 b_1 g_{p,1}\varsigma_2 \leq \frac{\varsigma_1^2 g_{p,1}^2}{2} + \frac{\varsigma_2^2}{2}. \tag{10}$$

It follows from (9) and (10) that

$$\begin{aligned}\dot{V}_1 \leq{}& \varsigma_1(b_1 g_{p,1}\alpha_1 + \frac{\varsigma_1\hat{\theta}_1 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1 + \vartheta_1^2}}) + \frac{\varsigma_2^2}{2} + \frac{1}{\gamma_1}\tilde{\theta}_1(\frac{\gamma_1\varsigma_1^2 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1 + \vartheta_1^2}} - \dot{\hat{\theta}}_1) + \theta_1\vartheta_1 \\ &+ \frac{1}{r_1}\tilde{\rho}_1(r_1|\varsigma_1| - \dot{\hat{\rho}}_1) + \frac{\varsigma_1^2\hat{\rho}_1^2}{\sqrt{\varsigma_1^2\hat{\rho}_1^2 + \vartheta_1^2}} + \vartheta_1.\end{aligned} \tag{11}$$

Choose the virtual controller α_1 as

$$\begin{cases} \alpha_1 = \mathcal{N}_1(\nu_1)\eta_1, \\ \dot{\nu}_1 = \varsigma_1 g_{p,1}\eta_1, \\ \eta_1 = \frac{1}{g_{p,1}}(-c_1\varsigma_1 - \frac{\varsigma_1\hat{\theta}_1 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1+\vartheta_1^2}} - \frac{\varsigma_1\hat{\rho}_1^2}{\sqrt{\varsigma_1^2\hat{\rho}_1^2+\vartheta_1^2}}), \end{cases} \tag{12}$$

and the adaptive laws as

$$\dot{\hat{\theta}}_1 = \frac{\gamma_1\varsigma_1^2 S_1^T S_1}{\sqrt{\varsigma_1^2 S_1^T S_1 + \vartheta_1^2}} - \gamma_1\vartheta_1\hat{\theta}_1, \tag{13}$$

$$\dot{\hat{\rho}}_1 = r_1|\varsigma_1| - r_1\vartheta_1\hat{\rho}_1. \tag{14}$$

Replacing (12)-(14) into (11) yields

$$\dot{V}_1 \leq -c_1\varsigma_1^2 + b_1\mathcal{N}_1(\nu_1)\dot{\nu}_1 - \dot{\nu}_1 + \frac{\varsigma_2^2}{2} + \vartheta_1\tilde{\theta}_1\hat{\theta}_1 + \vartheta_1\tilde{\rho}_1\hat{\rho}_1 + \vartheta_1(1+\theta_1).$$

Remark 1 *As we all know, the approximation error will occur when the NN is utilized to approximate the unknown nonlinear function. However, when we study the asymptotic tracking of uncertain switched nonlinear systems, it is necessary to solve this approximation error. In this paper, an adaptive law is presented to solve this approximation error.*

Step i**.** $2 \leq i \leq n-1$: By (1) and (2), there holds

$$\dot{\varsigma}_i = b_i g_{p,i}(\bar{\upsilon}_i)\upsilon_{i+1} + f_{p,i}(\bar{\upsilon}_i) - \dot{\alpha}_{i-1}. \tag{15}$$

where $\dot{\alpha}_{i-1} = \sum_{k=1}^{i-1}(\frac{\partial\alpha_{i-1}}{\partial\upsilon_k}(b_k g_{p,k}(\bar{\upsilon}_k)\upsilon_{k+1} + f_{p,k}(\bar{\upsilon}_k)) + \frac{\partial\alpha_{i-1}}{\partial\hat{\theta}_k}\dot{\hat{\theta}}_k + \frac{\partial\alpha_{i-1}}{\partial\hat{\rho}_k}\dot{\hat{\rho}}_k) + \sum_{k=0}^{i-1}\frac{\partial\alpha_{i-1}}{\partial y_d^{(k)}}y_d^{(k+1)}$. Choose the Lyapunov function candidate as

$$V_i = V_{i-1} + \frac{1}{2}\varsigma_i^2 + \frac{1}{2\gamma_i}\tilde{\theta}_i^2 + \frac{1}{2r_i}\tilde{\rho}_i^2.$$

Its derivative is

$$\dot{V}_i \leq \dot{V}_{i-1} + \varsigma_i(b_i g_{p,i}(\varsigma_{i+1}+\alpha_i) + \bar{f}_{p,i}(Z_i) - \frac{\varsigma_i g_{p,i}^2}{2}) - \frac{1}{\gamma_i}\tilde{\theta}_i\dot{\hat{\theta}}_i - \frac{1}{r_i}\tilde{\rho}_i\dot{\hat{\rho}}_i - \frac{\varsigma_i^2}{2}, \tag{16}$$

where $\bar{f}_{p,i}(Z_i) = f_{p,i}(\bar{\upsilon}_i) - \dot{\alpha}_{i-1} + \frac{\varsigma_i g_{p,i}^2}{2} + \frac{\varsigma_i}{2}$. As is the same case of (5), the following equality can be obtained

$$\bar{f}_{p,i}(Z_i) = \psi_{p,i}^T S_i(Z_i) + \delta_i(Z_i), \tag{17}$$

where $|\delta_i(Z_i)| \leq \tau_i$ denotes the approximation error. By (16) and (17) one has

$$\dot{V}_i \leq \dot{V}_{i-1} + \varsigma_i(\psi_{p,i}^T S_i(Z_i) + \delta_i(Z_i) + b_i g_{p,i}(\varsigma_{i+1}+\alpha_i) - \frac{\varsigma_i g_{p,i}^2}{2}) - \frac{1}{\gamma_i}\tilde{\theta}_i\dot{\hat{\theta}}_i - \frac{1}{r_i}\tilde{\rho}_i\dot{\hat{\rho}}_i - \frac{\varsigma_i^2}{2}. \tag{18}$$

Similar to (7) and (8), we can obtain

$$\varsigma_i \psi_{p,i}^T S_i(Z_i) \le |\varsigma_i| \|\psi_i\| \|S_i\| = |\varsigma_i| \theta_i \|S_i\|, \tag{19}$$

$$|\varsigma_i| \|S_i\| \le \frac{\varsigma_i^2 S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}} + \vartheta_i. \tag{20}$$

It follows from (18), (19) and (20) that

$$\begin{aligned} \dot{V}_i \le \dot{V}_{i-1} + \varsigma_i (b_i g_{p,i} (\varsigma_{i+1} + \alpha_i) + \frac{\varsigma_i \theta_i S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}} \\ - \frac{\varsigma_i g_{p,i}^2}{2}) + \theta_i \vartheta_i + |\varsigma_i| \tau_i - \frac{1}{\gamma_i} \tilde{\theta}_i \dot{\hat{\theta}}_i - \frac{1}{r_i} \tilde{\rho}_i \dot{\hat{\rho}}_i - \frac{\varsigma_i^2}{2}. \end{aligned} \tag{21}$$

In view of Lemma 1, we have

$$\varsigma_i b_i g_{p,i} \varsigma_{i+1} \le \frac{\varsigma_i^2 g_{p,i}^2}{2} + \frac{\varsigma_{i+1}^2}{2}. \tag{22}$$

By (21) and (22), there holds

$$\begin{aligned} \dot{V}_i \le \dot{V}_{i-1} + \varsigma_i (b_i g_{p,i} \alpha_i + \frac{\varsigma_i \hat{\theta}_i S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}}) + \frac{\varsigma_{i+1}^2}{2} + \frac{\varsigma_i^2 \hat{\rho}_i^2}{\sqrt{\varsigma_i^2 \hat{\rho}_i^2 + \vartheta_i^2}} + \theta_i \vartheta_i + \frac{1}{r_i} \tilde{\rho}_i (r_i |\varsigma_i| - \dot{\hat{\rho}}_i) \\ + \frac{1}{\gamma_i} \tilde{\theta}_i (\frac{\gamma_i \varsigma_i^2 S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}} - \dot{\hat{\theta}}_i) + \vartheta_i - \frac{\varsigma_i^2}{2}. \end{aligned} \tag{23}$$

Now, construct the virtual controller α_i as

$$\begin{cases} \alpha_i = \mathcal{N}_i(\nu_i) \eta_i, \\ \dot{\nu}_i = \varsigma_i g_{p,i} \eta_i, \\ \eta_i = \frac{1}{g_{p,i}} (-c_i \varsigma_i - \frac{\varsigma_i \hat{\theta}_i S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}} - \frac{\varsigma_i \hat{\rho}_i^2}{\sqrt{\varsigma_i^2 \hat{\rho}_i^2 + \vartheta_i^2}}), \end{cases} \tag{24}$$

and the adaptive laws as

$$\dot{\hat{\theta}}_i = \frac{\gamma_i \varsigma_i^2 S_i^T S_i}{\sqrt{\varsigma_i^2 S_i^T S_i + \vartheta_i^2}} - \gamma_i \vartheta_i \hat{\theta}_i, \tag{25}$$

$$\dot{\hat{\rho}}_i = r_i |\varsigma_i| - r_i \vartheta_i \hat{\rho}_i. \tag{26}$$

Based on (23)-(26), it yields

$$\dot{V}_i \le \sum_{j=1}^{i} (-c_j \varsigma_j^2 + b_j \mathcal{N}_j(\nu_j) \dot{\nu}_j - \dot{\nu}_j + \vartheta_j \tilde{\theta}_j \hat{\theta}_j + \vartheta_j \tilde{\rho}_j \hat{\rho}_j + \vartheta_j (1 + \theta_j)) + \frac{\varsigma_{i+1}^2}{2}.$$

3.2 Event-triggered Controller Design

Step n. The actual controller and the triggering event are given as

$$\tau(t) = \mathcal{N}_n(\nu_n)w(t), \tag{27}$$

$$\dot{\nu}_n = \varsigma_n g_{p,n} w(t), \tag{28}$$

$$w(t) = \alpha_n - \bar{\mathrm{m}}_1 \tanh \frac{\varsigma_n g_{p,n} \bar{\mathrm{m}}_1}{\vartheta_n}, \tag{29}$$

$$u(t) = \tau(t_k), \qquad \forall t \in [t_k, t_{k+1}), \tag{30}$$

$$t_{k+1} = \inf\{t > t_k \| \Upsilon(t)| \geq h_1\}, \tag{31}$$

where $\Upsilon(t) = \tau(t) - u(t)$ is the measurement error, $\vartheta_n > 0, h_1 > 0$, and $\bar{\mathrm{m}}_1 > h_1$ are design parameters.

Remark 2 *This paper focus on an event-triggered asymptotic tracking control for switched nonlinear systems with unknown control directions. However, it is difficult to handle with the tracking control issue of switched nonlinear system with unknown control directions under the condition of event-triggered input. To address this difficulty, an improved control law (27) is proposed.*

Theorem 1 *If the switched system (1) satisfies Assumption 1 and Lemmas 1-3, then the proposed controller can guarantee that all signals of the closed-loop system are bounded and the tracking error ς_1 will converge to zero as $t \to \infty$. Meanwhile the Zeno phenomena can be avoided.*

Proof: It follows from (1) and (2) that

$$\dot{\varsigma}_n = b_n g_{p,n}(\bar{\upsilon}_n)u + f_{p,n}(\bar{\upsilon}_n) - \dot{\alpha}_{n-1}. \tag{32}$$

where $\dot{\alpha}_{n-1} = \sum_{k=1}^{n-1}(\frac{\partial \alpha_{n-1}}{\partial \upsilon_k}(b_k g_{p,k}(\bar{\upsilon}_k)\upsilon_{k+1} + f_{p,k}(\bar{\upsilon}_k)) + \frac{\partial \alpha_{n-1}}{\partial \hat{\theta}_k}\dot{\hat{\theta}}_k + \frac{\partial \alpha_{n-1}}{\partial \hat{\rho}_k}\dot{\hat{\rho}}_k) + \sum_{k=0}^{n-1} \frac{\partial \alpha_{n-1}}{\partial y_d^{(k)}} y_d^{(k+1)}$. Choose the Lyapunov function candidate as follows

$$V_n = V_{n-1} + \frac{1}{2}\varsigma_n^2 + \frac{1}{2\gamma_n}\tilde{\theta}_n^2 + \frac{1}{2r_n}\tilde{\rho}_n^2.$$

Similarly, differentiating V_n yields

$$\dot{V}_n \leq \dot{V}_{n-1} + \varsigma_n(b_n g_{p,n} u + \bar{f}_{p,n}(Z_n)) - \frac{1}{\gamma_n}\tilde{\theta}_n\dot{\hat{\theta}}_n - \frac{1}{r_n}\tilde{\rho}_n\dot{\hat{\rho}}_n - \frac{\varsigma_n^2}{2}, \tag{33}$$

where $\bar{f}_{p,n}(Z_n) = f_{p,n}(\bar{\upsilon}_n) - \dot{\alpha}_{n-1} + \frac{\varsigma_n}{2}$. Using (31) gets $\tau(t) = u(t) + \zeta(t)h_1$, $t_k \leq t < t_{k+1}$, where $|\zeta(t)| \leq 1$ is timevarying parameter. Then, (33) can be rewritten as

$$\dot{V}_n \leq \dot{V}_{n-1} + \varsigma_n(b_n g_{p,n}(\tau(t) - \zeta(t)h_1) + \bar{f}_{p,n}(Z_n)) - \frac{1}{\gamma_n}\tilde{\theta}_n\dot{\hat{\theta}}_n - \frac{1}{r_n}\tilde{\rho}_n\dot{\hat{\rho}}_n - \frac{\varsigma_n^2}{2}. \tag{34}$$

Putting (27)-(29) into (34) yields

$$\dot{V}_n \leq \dot{V}_{n-1} + \varsigma_n(g_{p,n}(\alpha_n - \bar{\mathrm{m}}_1 \tanh \frac{\varsigma_n g_{p,n}\bar{\mathrm{m}}_1}{\vartheta_n}) + \bar{f}_{p,n}(Z_n)) + b_n\mathcal{N}_n(\nu_n)\dot{\nu}_n$$
$$-\dot{\nu}_n - \varsigma_n b_n g_{p,n}\zeta(t)h_1 - \frac{1}{\gamma_n}\tilde{\theta}_n\dot{\hat{\theta}}_n - \frac{1}{r_n}\tilde{\rho}_n\dot{\hat{\rho}}_n - \frac{\varsigma_n^2}{2}. \tag{35}$$

The virtual controller can be designed as

$$\alpha_n = \frac{1}{g_{p,n}}(-c_n\varsigma_n - \frac{\varsigma_n\hat{\theta}_n S_n^T S_n}{\sqrt{\varsigma_n^2 S_n^T S_n + \vartheta_n^2}} - \frac{\varsigma_n\hat{\rho}_n^2}{\sqrt{\varsigma_n^2\hat{\rho}_n^2 + \vartheta_n^2}}), \tag{36}$$

and the adaptive laws as

$$\dot{\hat{\theta}}_n = \frac{\gamma_n\varsigma_n^2 S_n^T S_n}{\sqrt{\varsigma_n^2 S_n^T S_n + \vartheta_n^2}} - \gamma_n\vartheta_n\hat{\theta}_n, \tag{37}$$

$$\dot{\hat{\rho}}_n = r_n|\varsigma_n| - r_n\vartheta_n\hat{\rho}_n. \tag{38}$$

From (35)-(38), one can obtained that

$$\begin{aligned}\dot{V}_n \leq & \sum_{i=1}^{n}(-c_i\varsigma_i^2 + b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i + \vartheta_i\tilde{\theta}_i\hat{\theta}_i - \dot{\nu}_i + \vartheta_i\tilde{\rho}_i\hat{\rho}_i + \vartheta_i(1+\theta_i)) \\ & -\varsigma_n g_{p,n}\bar{\mathrm{m}}_1 \tanh\frac{\varsigma_n g_{p,n}\bar{\mathrm{m}}_1}{\vartheta_n} - \varsigma_n b_n g_{p,n}\zeta(t)h_1.\end{aligned} \tag{39}$$

According to [33], it yields

$$0 \leq |\eta| - \eta\tanh(\frac{\eta}{\iota}) \leq 0.2785\iota, \tag{40}$$

where $\iota > 0$ and $\eta \in R$. From (40), one has

$$\begin{aligned}\dot{V}_n \leq & \sum_{i=1}^{n}(-c_i\varsigma_i^2 + b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i + \vartheta_i\tilde{\theta}_i\hat{\theta}_i + \vartheta_i\tilde{\rho}_i\hat{\rho}_i + \vartheta_i(1+\theta_i)) \\ & -|\varsigma_n g_{p,n}\bar{\mathrm{m}}_1| - \varsigma_n b_n g_{p,n}\zeta(t)h_1 + 0.2785\vartheta_n.\end{aligned}$$

Then, by using $\bar{\mathrm{m}}_1 > h_1$, we can obtain

$$\dot{V}_n \leq \sum_{i=1}^{n}(-c_i\varsigma_i^2 + b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i + \vartheta_i\tilde{\theta}_i\hat{\theta}_i + \vartheta_i\tilde{\rho}_i\hat{\rho}_i + \vartheta_i(1+\theta_i)) + 0.2785\vartheta_n. \tag{41}$$

Notice that

$$\tilde{\theta}_i\hat{\theta}_i = -\tilde{\theta}_i^2 + \tilde{\theta}_i\theta_i \leq \frac{\theta_i^2}{4}, \tag{42}$$

$$\tilde{\rho}_i\hat{\rho}_i = -\tilde{\rho}_i^2 + \tilde{\rho}_i\rho_i \leq \frac{\rho_i^2}{4}. \tag{43}$$

Inserting (42) and (43) into (41) yields

$$\dot{V}_n \leq \sum_{i=1}^{n}(-c_i\varsigma_i^2 + b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i + \vartheta_i\Delta_i), \tag{44}$$

where $\Delta_i = \frac{\theta_i^2}{4} + \frac{\rho_i^2}{4} + (1+\theta_i)$ and $\Delta_n = \frac{\theta_n^2}{4} + \frac{\rho_n^2}{4} + (1+\theta_n) + 0.2785$.

Integrating (44) from 0 to t

$$\begin{aligned}V_n(t) \leq & V_n(0) + \sum_{i=1}^{n}(-c_i\int_0^t \varsigma_i^2 ds + \Delta_i\int_0^t \vartheta_i ds + \int_0^t (b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i)ds) \\ \leq & C + \sum_{i=1}^{n}\int_0^t (b_i\mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i)ds,\end{aligned} \tag{45}$$

where $C = V_n(0) + \sum_{i=1}^{n} \Delta_i \bar{\vartheta}_i$, $\lim_{t\to\infty} \int_0^t \vartheta_i(s)ds \leq \bar{\vartheta}_i < \infty$ with $\bar{\vartheta}_i$ being a positive constant. Applying Lemma 2, it can be concluded that $V_n(t)$, ν_i and $\sum_{i=1}^{n} \int_0^t b_i \mathcal{N}_i(\nu_i)\dot{\nu}_i ds$ are bounded. Thus, the boundedness of ς_i, $\hat{\theta}_i$ and $\hat{\rho}_i$ can be deduced.

From (45), we get

$$\sum_{i=1}^{n} c_i \int_0^t \varsigma_i^2 ds \leq C + \sum_{i=1}^{n} \int_0^t (b_i \mathcal{N}_i(\nu_i)\dot{\nu}_i - \dot{\nu}_i)ds, \tag{46}$$

by using of the continuity and the boundedness of ς_1, we prove that ς_1 is uniformly continuous. Therefore, in view of Lemma 3, we get $\lim_{t\to\infty} \varsigma_1 = 0$.

By using $\Upsilon(t) = \tau(t) - u(t)$, one has

$$\frac{d}{dt}|\Upsilon| = \frac{d}{dt}\sqrt{\Upsilon * \Upsilon} = \text{sign}(\Upsilon)\dot{\Upsilon} \leq |\dot{\tau}|.$$

It can be seen from (27) and (29) that τ is differentiable and $\dot{\tau}$ is a function of all the bounded signals. Thus, there exists a positive constant ϱ satisfying $|\dot{\tau}| \leq \varrho$. From $\Upsilon(t_k) = 0$ and $\lim_{t\to t_{k+1}} \Upsilon(t) = h_1$, the Zeno phenomenon is avoided when $\{t_{k+1} - t_k\} \geq h_1/\varrho$.

4 Simulation Example

In this part, a continuous stirred tank reactor [28] is proposed to prove the feasibility of the designed controller. Consider the following switched nonlinear systems

$$\begin{cases} \dot{D}_A = \frac{q_\sigma}{V}(D_{Af_\sigma} - D_A) - b_0 e^{-\frac{E}{RT}} D_A, \\ \dot{T} = \frac{q_\sigma}{V}(T_{f_\sigma} - T) - b_1 e^{-\frac{E}{RT}} D_A + \frac{UA}{V\rho D_P}(T_c - T), \end{cases} \tag{47}$$

where D_A denotes the concentration of species A in the reactor, T and T_c are the reactor temperature and variable temperature of coolant stream, respectively. The physical meanings can be founded in [28].

Select $\upsilon_1 = D_A - D_A^*$ and $\upsilon_2 = \frac{q_\sigma}{V}(D_{Af_\sigma} - D_A) - b_0 e^{-\frac{E}{RT}} D_A$, the system (47) can be transformed into

$$\begin{cases} \dot{\upsilon}_1 = f_{\sigma,1}(\upsilon_1) + \upsilon_2, \\ \dot{\upsilon}_2 = u, \\ y = \upsilon_1, \end{cases}$$

where $\sigma(t) = 1, 2,\ f_{1,1} = 0.5\upsilon_1,\ f_{2,1} = 2\upsilon_1$.

The virtual controllers, the event-triggered controller and event-triggered mechanism are designed as

$$\begin{cases} \alpha_1 = \mathcal{N}_1(\nu_1)\frac{1}{g_{p,1}}(-c_1\varsigma_1 - \frac{\varsigma_1\hat{\theta}_1 S_1^T(Z_1)S_1(Z_1)}{\sqrt{\varsigma_1^2 S_1^T(Z_1)S_1(Z_1)+\vartheta_1^2}} - \frac{\varsigma_1\hat{\rho}_1^2}{\sqrt{\varsigma_1^2\hat{\rho}_1^2+\vartheta_1^2}}), \\ \alpha_2 = \frac{1}{g_{p,2}}(-c_2\varsigma_2 - \frac{\varsigma_2\hat{\theta}_2 S_2^T(Z_2)S_2(Z_2)}{\sqrt{\varsigma_2^2 S_2^T(Z_2)S_2(Z_2)+\vartheta_2^2}} - \frac{\varsigma_2\hat{\rho}_2^2}{\sqrt{\varsigma_2^2\hat{\rho}_2^2+\vartheta_2^2}}), \\ \tau(t) = \mathcal{N}_2(\nu_2)(\alpha_2 - \bar{\mathrm{m}}_1 \tanh\frac{\varsigma_2\bar{\mathrm{m}}_1}{\vartheta_2}), \\ u = \tau(t_k), \quad k \in z^+, \\ t_{k+1} = \inf\{t > t_k \| \Upsilon(t)| \geq h_1\}, \end{cases}$$

then, the adaptive laws are designed as

$$\begin{aligned} \dot{\hat{\theta}}_1 &= \frac{\gamma_1\varsigma_1^2 S_1^T(Z_1)S_1(Z_1)}{\sqrt{\varsigma_1^2 S_1^T(Z_1)S_1(Z_1)+\vartheta_1^2}} - \gamma_1\vartheta_1\hat{\theta}_1, \\ \dot{\hat{\theta}}_2 &= \frac{\gamma_2\varsigma_2^2 S_2^T(Z_2)S_2(Z_2)}{\sqrt{\varsigma_2^2 S_2^T(Z_2)S_2(Z_2)+\vartheta_2^2}} - \gamma_2\vartheta_2\hat{\theta}_2, \\ \dot{\hat{\rho}}_1 &= r_1|\varsigma_1| - r_1\vartheta_1\hat{\rho}_1, \\ \dot{\hat{\rho}}_2 &= r_2|\varsigma_2| - r_2\vartheta_2\hat{\rho}_2, \end{aligned}$$

where $Z_1 = z_1$ and $Z_2 = [z_1, z_2, \hat{\theta}_1, \hat{\rho}_1]^T$. The desired signal is given by $y_d(t) = 0.5\sin t$. Choose the initial values as $\upsilon_1(0) = 0.01, \upsilon_2(0) = 1, \hat{\theta}_1(0) = 2, \hat{\theta}_2(0) = 2, \hat{\rho}_1(0) = 2, \hat{\rho}_2(0) = 2$. The design parameters are selected as $c_1 = 2, c_2 = 2, r_1 = 30, r_2 = 30, \gamma_1 = 10, \gamma_2 = 10, \bar{\mathrm{m}}_1 = 12, h_1 = 11.5, \alpha = 1, \beta = \frac{1}{5}, \vartheta_1 = 10e^{-0.7t}, \vartheta_2 = 10e^{-0.1t}$.

Figs.1-6 show the simulation results of designed control scheme. Figs.1 shows the tracking signals and tracking error signal. The trajectories of υ_1 and υ_2 are shown in Fig.2. Figs.3 depicts the trajectories of the adaptive laws $\hat{\theta}_1, \hat{\theta}_2, \hat{\rho}_1$ and $\hat{\rho}_2$. The trajectories of the control input u and trigger time interval are illustrated in Fig.4. Fig.5 describes the trajectories of $\mathcal{N}_1(\nu_1)$ and $\mathcal{N}_2(\nu_2)$. Finally, Fig.6 shows the trajectory of switching signal $\sigma(t)$.

5 Conclusions

In this article, a novel event-triggered asymptotic tracking controller is proposed for switched nonlinear systems with unknown control directions. The Nussbaum functions are exploited to handle with the issue of nonlinear systems with unknown control directions. The NN is utilized to approximate the unknown nonlinear functions. It is proven that under our presented control scheme, the system output y can asymptotically track the desired signal y_d, and closed-loop systems are stability.

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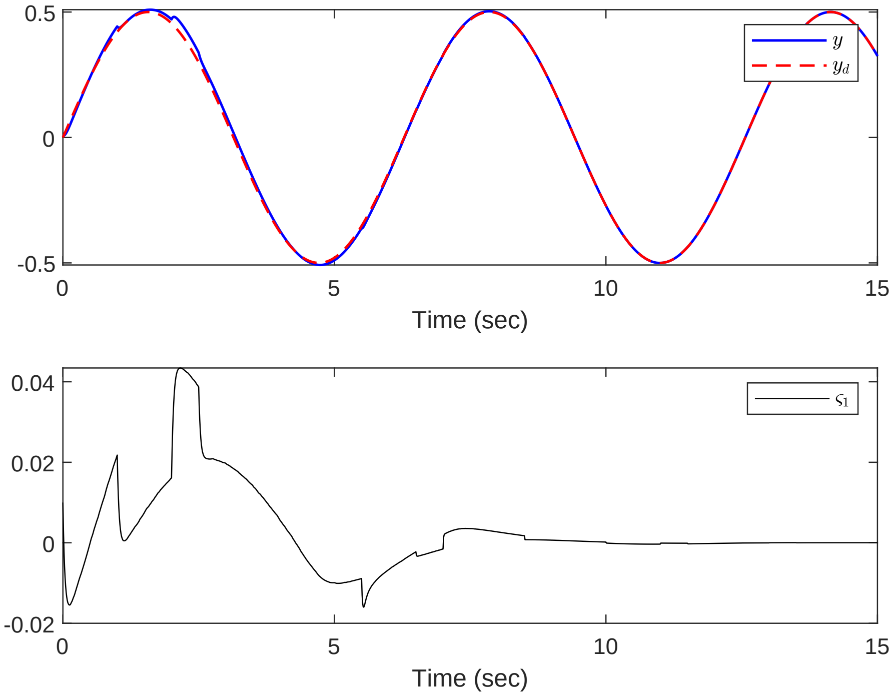

Fig. 1: The trajectories of y, y_d and ς_1.

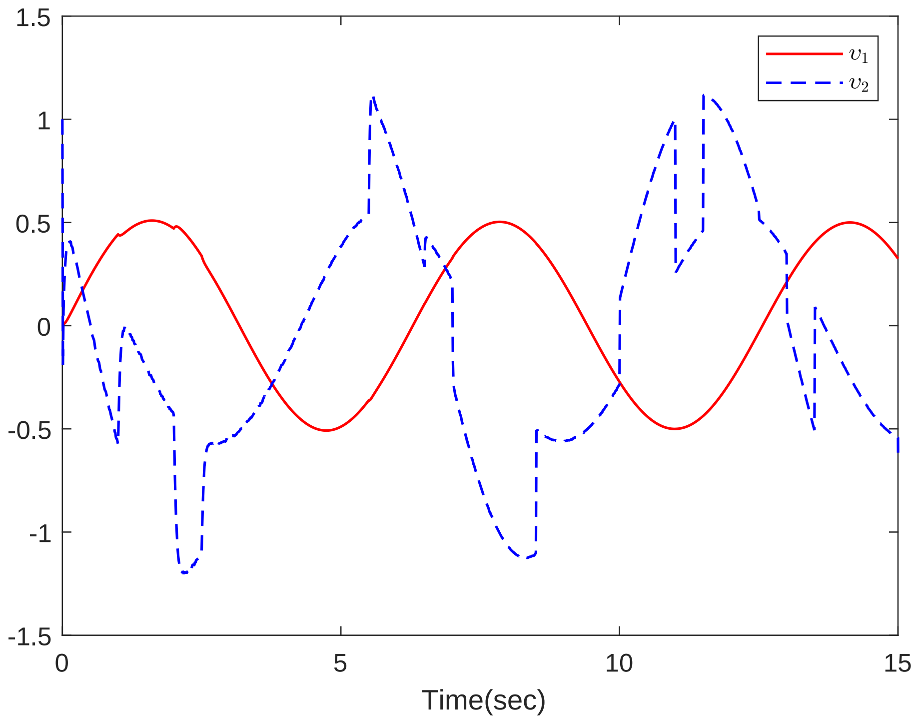

Fig. 2: The trajectories of system states υ_1 and υ_2.

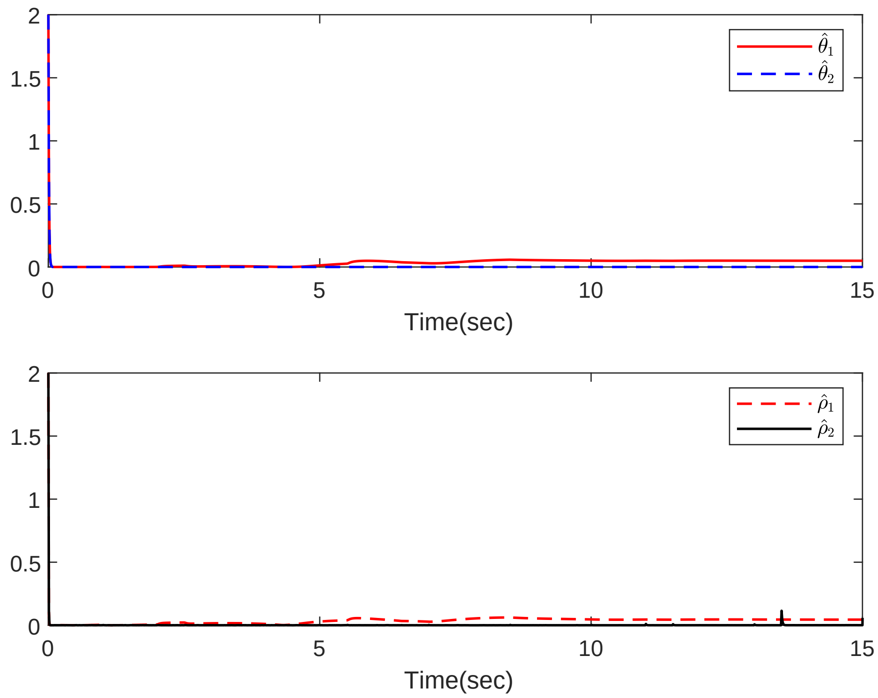

Fig. 3: The trajectories of adaptive laws $\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{\rho}_1$ and $\hat{\rho}_2$.

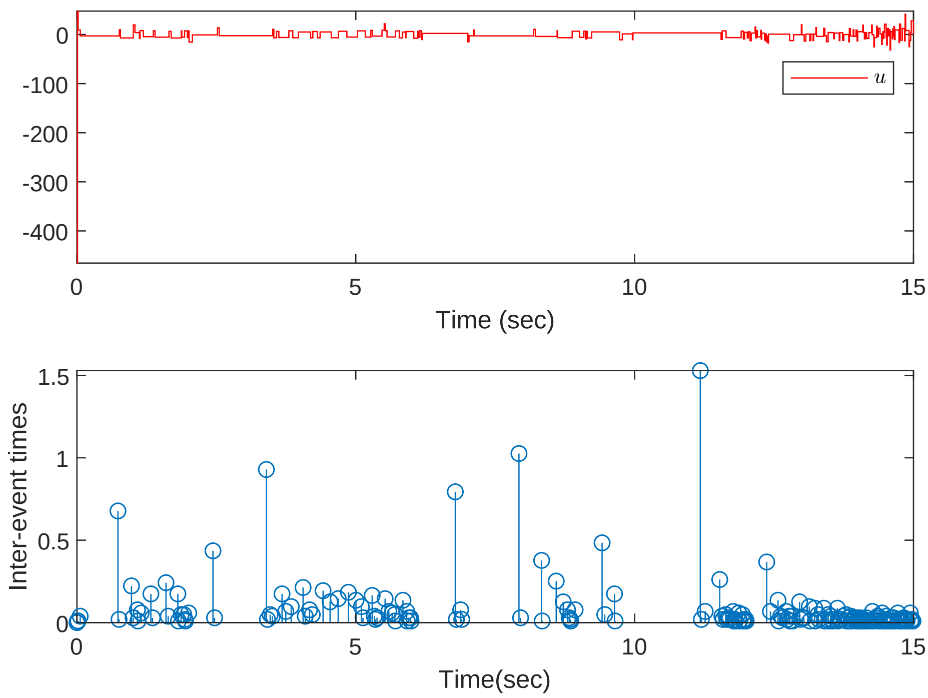

Fig. 4: The trajectory of control input u and trigger time interval.

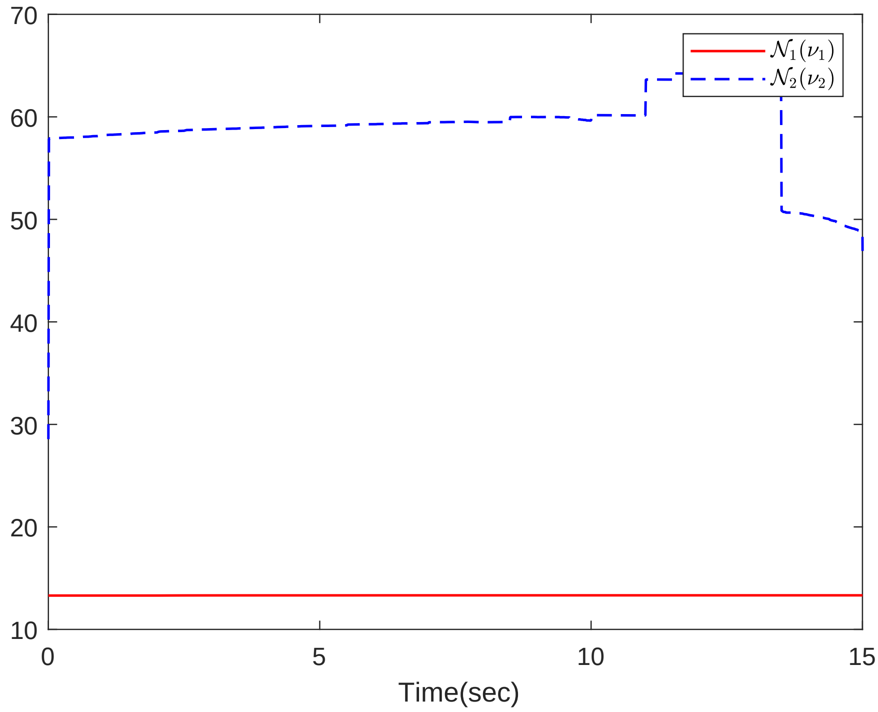

Fig. 5: The trajectories of $\mathcal{N}_1(\nu_1)$ and $\mathcal{N}_2(\nu_2)$.

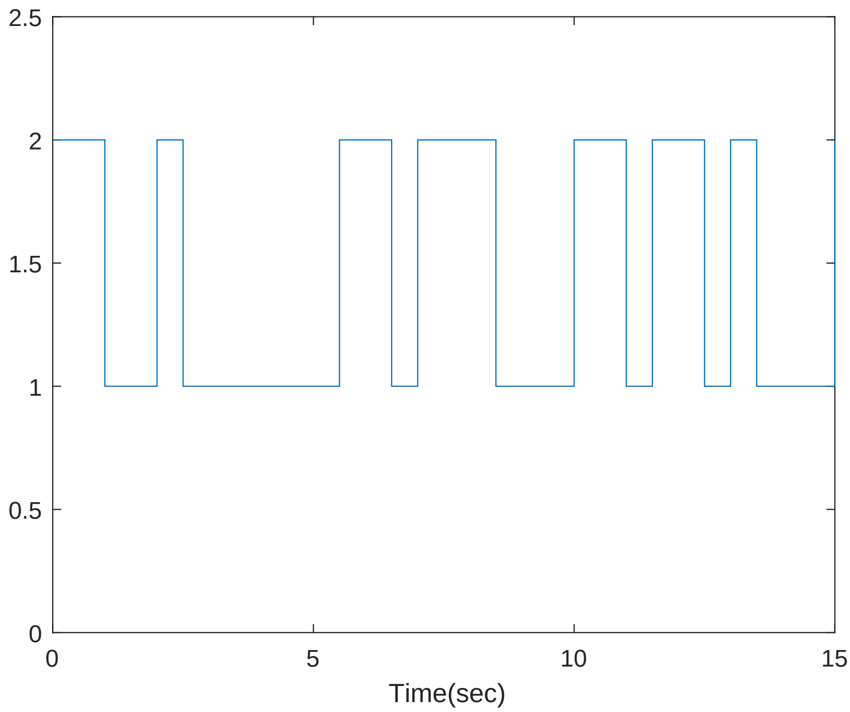

Fig. 6: The trajectory of switching signal.

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