Received: 10 April 2021 | Revised: 15 July 2021 | Accepted: 12 September 2021

DOI: 10.1002/asjc.2720

RESEARCH ARTICLE

WILEY

Multi-dimensional Taylor network-based control for a class of nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint

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Funding information
Shandong Provincial Natural Science Foundation, China, Grant/Award Number: ZR2020QF055; Open Fund of the Key Laboratory of Ocean Circulation and Waves, Chinese Academy of Sciences, Grant/Award Number: KLOCW2003

Abstract

In this paper, the adaptive multi-dimensional Taylor network (MTN) control problem is investigated for nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint. By combining the MTN-based approximation method and the adaptive backstepping control method, a novel adaptive MTN control scheme is provided by constructing the time-varying barrier Lyapunov function (TVBLF). To implement the finite-time output constraint, the finite-time performance function (FTPF) is introduced in the control scheme. The proposed scheme can ensure that the tracking error finally converges to a small neighborhood of the origin in the finite-time and all signals in the closed-loop system are semi-globally uniformly ultimately bounded (SGUUB) in probability. Finally, two simulation examples are presented to show the effectiveness of the provided control scheme.

KEYWORDS

adaptive control, finite-time performance function, multi-dimensional Taylor network, nonlinear stochastic systems, time-varying barrier Lyapunov function

1 | INTRODUCTION

Stochastic disturbances exist widely in many practical systems, and they may reduce system performance or cause instability [1,2]. Driven by these problems and the practical engineering demand, the control problem for nonlinear stochastic systems has been paid an increasingly attention, and many significant methods have been proposed [3–12]. On the whole, the existing control methods for nonlinear stochastic systems can be mainly divided into two categories according to different stochastic Lyapunov functions. By using the quadratic Lyapunov function, Pan and Basar [3] proposed a backstepping-based control scheme for nonlinear stochastic systems via the risk-sensitive cost criterion. Afterwards, a lot of control problems of nonlinear stochastic systems have been further investigated based on the above functions [5–7]. As another alternative, the quartic Lyapunov function was introduced to handle some special terms in the Lyapunov analysis which arise due to the differentiation rule in the process of designing controllers for nonlinear stochastic systems [8]. At present, this method is widely applied to several different problems, such as tracking control [4], decentralized control [10,11], and control of high-order systems [9,12]. However, it is difficult to solve the problems such as unknown functions and uncertainties only by the aforementioned control methods.

In consideration of the above problems, many approximation methods, such as fuzzy logic systems (FLSs) methods [13,14], neural network (NN) methods [15–19], and multi-dimensional Taylor network (MTN) methods [20,21], have been widely used in the control problems of

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nonlinear stochastic systems. Compared with NN or FLSs, the MTN has the advantages of the simple structure, the good real-time performance, and the low computational cost. Therefore, the MTN control method has received increasing attention, and many achievements have been reported [22–30]. For example, by using the MTN-based control methods, the asymptotically tracking problem and the optimal control problem were considered for nonlinear systems [22,23], respectively. At the moment, this control method has been naturally extended to nonlinear stochastic systems, such as the stochastic system with input dead-zone [24], the uncertain nonlinear stochastic system [25,26], and the large-scale nonlinear stochastic system [27]. Although many important MTN-based results have been obtained in the study of nonlinear stochastic systems, the research results on full state constraints systems are still insufficient.

As we know, full state constraints problems are ubiquitous in many practical control areas, and violating constraints may cause poor performance of the control systems [31,32]. Therefore, the full state constraints problem cannot be ignored in the controller design process. To resolve this problem, the barrier Lyapunov function (BLF) has been proposed in [33]. At the moment, several different styles of BLFs have been widely used to solve control problems of full state constraints systems, such as log-type [34], integral-type [35], and tan-type [36]. Especially, Zhu et al. [37] recently proposed a tracking control scheme based on the time-varying barrier Lyapunov function (TVBLF) for state constraints systems. However, it is worth noting that the stochastic disturbances have not been taken into account in [32]. On the other hand, practical systems often require that the tracking error converges to a small neighborhood of the origin in the finite-time [38–40]. Therefore, many finite-time control schemes have been obtained for several different systems [41–48], such as nonlinear stochastic systems [41], and full state constraints stochastic systems [44], non-triangular stochastic systems [47], and high-order stochastic systems [48]. However, there are few results on finite-time output constraint of nonlinear stochastic systems with full state constraints, which motivate our research.

Based on the above observations, this paper investigates the adaptive control problem for nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint. An adaptive MTN control scheme is developed by constructing the proper TVBLF. In this scheme, the MTNs are employed to approximate the unknown functions in the process of the controller design, and a finite-time performance function (FTPF) is introduced to implement the finite-time output constraint. The proposed control scheme can guarantee that the tracking error finally converges to a small neighborhood of the origin in the finite-time and all the signals in the closed-loop system are bounded in probability. Finally, the simulation results illustrate the effectiveness of the provided control scheme. Compared with the existing works, the main contributions of this paper are as follows:

i. A novel adaptive MTN scheme is first presented for nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint. In the current MTN-based research results [20–30], the existing MTN control schemes cannot be directly utilized to dispose of the control problem of the systems considered in this paper. The MTN method is successfully extended to the stochastic system in this paper.
ii. In this paper, the stochastic disturbances, the full state constraints and the finite-time output constraint of stochastic systems are considered at the same time. Compared with the research results of state constraints systems [32–36] and the existing finite-time control results [42–45], the proposed scheme can guarantee that the state variables of stochastic systems satisfy time-varying constraints and the tracking error converges to a small neighborhood of the origin at a settling time.
iii. The online computation burden of the proposed control scheme has greatly alleviated thanks to the simple structure of the MTN. Therefore, we can draw a conclusion that the proposed MTN-based control scheme has excellent practical value.

2 | SYSTEM DESCRIPTION AND PRELIMINARIES

2.1 | Problem description

In this paper, consider the nonlinear stochastic system as follows:

$$\begin{cases} dx_i(t)=[f_i(\bar{\mathbf{x}}_i(t))+h_i(\bar{\mathbf{x}}_i(t))x_{i+1}(t)]dt+g_i^{\mathrm{T}}(\bar{\mathbf{x}}_i(t))d\boldsymbol{\omega} \\ \qquad 1\le i\le n-1 \\ dx_n(t)=[f_n(\bar{\mathbf{x}}_n(t))+h_n(\bar{\mathbf{x}}_n(t))u]dt+g_n^{\mathrm{T}}(\bar{\mathbf{x}}_n(t))d\boldsymbol{\omega} \\ \qquad y=x_1(t) \end{cases} \tag{1}$$

where $\bar{\mathbf{x}}_n(t)=[x_1,x_2,\cdots,x_n]^{\mathrm{T}}\in \mathrm{R}^n$ denotes state vectors of the system and $\bar{\mathbf{x}}_i(t)=[x_1,x_2,\cdots,x_i]^{\mathrm{T}}\in \mathrm{R}^i$. $f_i(\cdot):R^i\to R$ and $h_i(\cdot):R^i\to R$ are the unknown nonlinear

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functions with $f_i(\mathbf{0})=\mathbf{0}$. $u \in R$ and $y \in R$ are the input and output of the system, respectively. $g_i(\cdot): R^i \rightarrow R^r$ are the unknown functions and satisfy $g_i(\mathbf{0})=\mathbf{0}$. $\boldsymbol{\omega}$ is an independent r-dimensional standard Wiener process. For the system (1), all states x_i are restricted in the sets $\Omega_{x_i}=\{x_i \in R \| x_i| < k_{c_i}(t)\}$, where $k_{c_i}(t)$ are time-varying continuous functions.

The control objective of this paper is to design a novel adaptive MTN control scheme for the stochastic system (1), which shall meet the following requirements: (i) the system output y can track the given reference signal y_d and the tracking error finally converges to a small neighborhood of the origin in the finite-time; (ii) all the signals in the closed-loop system are semi-globally uniformly ultimately bounded (SGUUB) in probability and the system states satisfy the given limited conditions.

2.2 | Preliminaries

In order to introduce the definitions and theorems of the nonlinear stochastic system, consider the following system

$$d\mathbf{x}(t)=f(\mathbf{x}(t))dt+g(\mathbf{x}(t))d\boldsymbol{\omega} \tag{2}$$

where $\mathbf{x} \in R^n$ is the system state, $\boldsymbol{\omega}$ is an independent r-dimensional standard Wiener process, and $f: R^n \rightarrow R^n$, $g: R^n \rightarrow R^{n\times r}$ stand for unknown smooth nonlinear functions and satisfy $f(\mathbf{0})=\mathbf{0}$, $g(\mathbf{0})=\mathbf{0}$.

Definition 1. [37]: Consider the nonlinear stochastic system (2), for any function $V(\mathbf{x},t) \in C^2$, the differential operator $\mathcal{L}$ is defined as follows:

$$\mathcal{L}V(\mathbf{x},t)=\frac{\partial V}{\partial t}+\frac{\partial V}{\partial \mathbf{x}}f+\frac{1}{2}\mathrm{Tr}\left\{g^{\mathrm{T}}\frac{\partial^2 V}{\partial \mathbf{x}^2}g\right\} \tag{3}$$

where C^2 denotes the set of all functions with twice continuous partial derivative.

Lemma 1. [33]: For the nonlinear stochastic system (2), there exists a Lyapunov function $V(\mathbf{x})$, for constants $a>0$ and $b>0$, such that

$$\begin{cases} \phi_1(|\mathbf{x}|) \leq V(\mathbf{x}) \leq \phi_2(|\mathbf{x}|) \\ \mathcal{L}V(\mathbf{x}) \leq -aV(\mathbf{x})+b \end{cases}$$

where ϕ_1 and ϕ_2 are K_∞-functions, then, the system (2) has a unique strong solution and the following inequality holds

$$E(V(t)) \leq V(0)e^{-at}+\frac{b}{a}$$

2.3 | Finite-time output constraint

To achieve the control objective (i), the following definition is introduced.

Definition 2. [49]: A continuous function $v(t)$ is named as the finite-time performance function (FTPF), if it satisfies the following properties:

1. $v(0)>0$;
2. $\dot{v}(t) \leq 0$;
3. $\lim_{t\rightarrow T_f} v(t)=v_{T_f}>0$ and $v(t)=v_{T_f}$ for any $t \geq T_f$ where v_{T_f} and T_f are the arbitrarily small constant and settling time, respectively.

With the consideration of the properties in Definition 2, a FTPF is defined as

$$v(t)=\begin{cases} \left(v_0-\frac{t}{T_f}\right)e^{1-\frac{T_f}{T_f-t}}+v_{T_f}, & t \in [0,T_f) \\ v_{T_f}, & t \in [T_f,+\infty) \end{cases} \tag{4}$$

where $v_0>1$ and $v_{T_f}>0$ are parameters to be designed.

Remark 1. The function $v(t)$ satisfies all the properties in Definition 2, and the initial condition of $v(t)$ is $v(0)=v_0+v_{T_f}$. Apparently, $v(t)$ is a continuous function.

2.4 | Relative lemmas and assumptions

For the controller design, the following lemmas and assumptions is presented.

Lemma 2. [37]: For any $|z|<k_b(t)$, the following inequality holds

$$\log\frac{k_b^4(t)}{k_b^4(t)-z^4} \leq \frac{z^4}{k_b^4(t)-z^4}$$

where $z \in R$, $k_b(t)>0$ is a time-varying function.

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In this paper, the MTNs are used to estimate unknown smooth nonlinear functions in the system. The MTN is composed by polynomials, which includes the input, middle and output layers. The more details of the MTN are available at research results [18–25]. We only introduce the approximation theory of the MTN as follows:

Lemma 3. [24]: On a compact set $\Omega_Z \subset R^n$, for any continuous smooth nonlinear function $f(\mathbf{Z})$, there exists a MTN $\boldsymbol{\varphi}^{*\mathrm{T}} S_{m_n}(\mathbf{Z})$, for $\forall \varepsilon > 0$, such that

$$f(\mathbf{Z}) = \boldsymbol{\varphi}^{*\mathrm{T}} S_{m_n}(\mathbf{Z}) + \delta(\mathbf{Z}), \quad |\delta(\mathbf{Z})| \le \varepsilon \tag{5}$$

where $\mathbf{Z} = [z_1, z_1, \ldots, z_n]^{\mathrm{T}}$, $S_{m_n}(\mathbf{Z}) = \left[\underbrace{z_1, z_2, \ldots, z_n}_{1 \text{ term}}, \underbrace{z_1^2, z_2^2, \ldots, z_n^2}_{2 \text{ term}}, \ldots, \underbrace{z_1^m, z_2^m, \ldots, z_n^m}_{m \text{ term}}\right]^{\mathrm{T}}$, and $\delta(\mathbf{Z})$ is the approximation error. $\boldsymbol{\varphi}^* = [\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \ldots, \boldsymbol{\varphi}_n]^{\mathrm{T}}$ is the optimal weight vector and defined by

$$\boldsymbol{\varphi}^* := \arg \min_{\boldsymbol{\varphi} \in R^N} \left\{ \sup_{Z \in \Omega_Z} \left| f(\mathbf{Z}) - \boldsymbol{\varphi}^{\mathrm{T}} S(\mathbf{Z}) \right| \right\} \tag{6}$$

Remark 2. Even though the MTN and NN are all three-layer network structure in form, their principles are different. The NN introduce basic function such as exponential functions, partial fractions and step to achieve nonlinear transformation, which have shortcomings of the long training time and high computational complexity. However, the MTN approximates the nonlinear functions by making full use of orthogonal polynomials. Compared with the NN, the MTN has a simpler structure and better real-time performance. Therefore, the MTN has better approximation capability.

Assumption 1. [49]: The signs of $h_i(\overline{\mathbf{x}}_i)$ are constant, and there exist constants $h_{i0} > 0$ and $h_{i1} > 0$, $1 \le i \le n$, such that $0 < h_{i0} \le |h_i(\overline{\mathbf{x}}_i)| \le h_{i1}$. Without loss of generality, we can assume that $h_{i0} \le h_i(\overline{\mathbf{x}}_i) \le h_{i1}$.

Assumption 2. [33]: The desired signal $y_d(t)$ satisfies $|y_d(t)| \le A_1(t) < k_{c_1}(t)$ and its ith time derivative $y_d^{(i)}(t)$ satisfy $\left| y_d^{(i)}(t) \right| \le C_i(t)$, $i = 1, \ldots, n$, where $A_1(t)$ and $C_i(t) > 0$ are continuous functions.

3 | CONTROLLER DESIGN

In this chapter, an adaptive MTN controller will be designed by using the backstepping technology.

Firstly, a change of coordinates is introduced as follows:

$$z_i = x_i - \alpha_{i-1} \quad (i = 1, 2, \cdots, n) \tag{7}$$

where α_{i-1} are the intermediate virtual control signals, which will be designed later, and $\alpha_0 = y_d$.

According (1) and (7), we have

$$\begin{cases} dz_1 = [f_1(\mathbf{x}_1) + h_1(\mathbf{x}_1) x_2 - \dot{y}_d] dt + g_1^{\mathrm{T}}(\mathbf{x}_1) d\omega \\ dz_i = [f_i(\overline{\mathbf{x}}_i) + h_i(\overline{\mathbf{x}}_i) x_{i+1} - \Delta\alpha_{i-1}] dt + \left(g_i - \sum_{j=1}^{i-1} \frac{\partial \alpha_{i-1}}{\partial x_j} g_j \right)^{\mathrm{T}} d\omega \\ \qquad i = 2, \cdots, n-1 \\ dz_n = [f_n(\overline{\mathbf{x}}_n) + h_n(\overline{\mathbf{x}}_n) u - \Delta\alpha_{n-1}] dt + \left(g_n - \sum_{j=1}^{n-1} \frac{\partial \alpha_{i-1}}{\partial x_j} g_j \right)^{\mathrm{T}} d\omega \end{cases} \tag{8}$$

with $\Delta\alpha_{i-1} = \sum_{j=1}^{i-1} \frac{\partial \alpha_{i-1}}{\partial x_j} \left(f_j + h_j x_{j+1} \right) + \sum_{j=0}^{i-1} \frac{\partial \alpha_{i-1}}{\partial y_d^{(j)}} y_d^{(j+1)} + \sum_{j=1}^{i-1} \frac{\partial \alpha_{i-1}}{\partial \widehat{\boldsymbol{\varphi}}_j} \dot{\widehat{\boldsymbol{\varphi}}}_j + \frac{1}{2} \sum_{j,k=1}^{i-1} \frac{\partial^2 \alpha_{i-1}}{\partial x_j \partial x_k} g_j^{\mathrm{T}} g_k + \sum_{p=1}^{i-1} \sum_{q=0}^{i-1-p} \frac{\partial \alpha_{i-1}}{\partial k_{b_p}^{(q)}} k_{b_p}^{(q+1)}$, where $\widehat{\boldsymbol{\varphi}}_j$ are the MTN parameters and $\dot{\widehat{\boldsymbol{\varphi}}}_j$ are the adaptive laws, which will be determined later.

Step 1: Consider the stochastic Lyapunov function candidate as

$$V_1 = \frac{1}{4} \log \frac{k_{b_1}^4(t)}{k_{b_1}^4(t) - z_1^4} + \frac{1}{2} h_{10} \widetilde{\boldsymbol{\varphi}}_1^{\mathrm{T}} \boldsymbol{\Gamma}_1^{-1} \widetilde{\boldsymbol{\varphi}}_1 \tag{9}$$

where $k_{b_1}(t) = v(t) > z_1$, $\boldsymbol{\Gamma}_1 = \boldsymbol{\Gamma}_1^{\mathrm{T}} > 0$ is a symmetric positive definite matrix, $\widetilde{\boldsymbol{\varphi}}_1 = \boldsymbol{\varphi}_1 - \widehat{\boldsymbol{\varphi}}_1$ is the parameter error vector.

According to Definition 1 and (9), we have

$$\begin{aligned} \mathcal{L}V_1 = & -\frac{z_1^4}{(v^4(t) - z_1^4)} \frac{\dot{v}(t)}{v(t)} + \frac{z_1^3}{v^4(t) - z_1^4} [f_1 + h_1 x_2 - \dot{y}_d] \\ & + \frac{z_1^2 \left(3v^4(t) + z_1^4\right)}{2\left(v^4(t) - z_1^4\right)^2} g_1^{\mathrm{T}} g_1 - h_{10} \widetilde{\boldsymbol{\varphi}}_1^{\mathrm{T}} \boldsymbol{\Gamma}_1^{-1} \dot{\widehat{\boldsymbol{\varphi}}}_1 \end{aligned} \tag{10}$$

By using Young's Inequality, we obtain

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$$\frac{z_1^2\left(3v^4(t)+z_1^4\right)}{2(v^4(t)-z_1^4)^2}g_1^{\mathrm{T}}g_1 \le \frac{z_1^4\left(3v^4(t)+z_1^4\right)^2}{8(v^4(t)-z_1^4)^4}\|g_1\|^4+\frac{1}{2} \tag{11}$$

Substituting (11) into (10), we have

$$\begin{aligned}\mathcal{L}V_1 \le & -\frac{z_1^4}{(v^4(t)-z_1^4)}\frac{\dot{v}(t)}{v(t)}+\frac{z_1^3}{v^4(t)-z_1^4}\left[\overline{f}_1+h_1x_2\right]+\frac{1}{2} \\ & -h_{10}\widetilde{\boldsymbol{\varphi}}_1^{\mathrm{T}}\boldsymbol{\Gamma}_1^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_1-\frac{h_{10}}{2}\frac{z_1^6}{(v^4(t)-z_1^4)^2}-\frac{3z_1^4h_1}{4(v^4(t)-z_1^4)^{4/3}}\end{aligned} \tag{12}$$

where $\overline{f}_1=f_1-\dot{y}_d+\frac{z_1\left(3v^4(t)+z_1^4\right)^2}{8\left(v^4(t)-z_1^4\right)^3}\|g_1\|^4+\frac{z_1^3}{2\left(v^4(t)-z_1^4\right)}+\frac{3z_1}{4\left(v^4(t)-z_1^4\right)^{1/3}}$.

As we all know, $\overline{f}_1$ is a unknown function. By Lemma 3, we can use a MTN $\boldsymbol{\varphi}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)$ to estimate $\overline{f}_1$. In other words, for $\forall\overline{\delta}_1>0$, a MTN $\boldsymbol{\varphi}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)$ is applied to approach $\overline{f}_1$, such that

$$\overline{f}_1=\boldsymbol{\varphi}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)+\delta_1(\mathbf{z}_1),|\delta_1(\mathbf{z}_1)|\le\overline{\delta}_1 \tag{13}$$

where $\mathbf{z}_1=[z_1]^{\mathrm{T}}$ is the input of the MTN and $\delta_1(\mathbf{z}_1)$ is the approximation error.

By Young's Inequality, we obtain

$$\frac{z_1^3}{v^4(t)-z_1^4}\delta_1(\mathbf{z}_1)\le\frac{h_{10}}{2}\frac{z_1^6}{(v^4(t)-z_1^4)^2}+\frac{1}{2h_{10}}\overline{\delta}_1^2 \tag{14}$$

$$\frac{z_1^3h_1z_2}{v^4(t)-z_1^4}\le\frac{3z_1^4h_1}{4(v^4(t)-z_1^4)^{4/3}}+\frac{1}{4}z_2^4h_1 \tag{15}$$

Substituting (7), (13), (14) and (15) into (12), we have

$$\begin{aligned}\mathcal{L}V_1 \le & -\frac{z_1^4}{(v^4(t)-z_1^4)}\frac{\dot{v}(t)}{v(t)}+\frac{z_1^3}{v^4(t)-z_1^4}\left[\boldsymbol{\varphi}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)+h_1\alpha_1\right]+\frac{1}{2} \\ & -h_{10}\widetilde{\boldsymbol{\varphi}}_1^{\mathrm{T}}\boldsymbol{\Gamma}_1^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_1+\frac{1}{2h_{10}}\overline{\delta}_1^2+\frac{1}{4}z_2^4h_1\end{aligned} \tag{16}$$

Based on (16), taking the intermediate control signal α_1 as

$$\alpha_1=-k_1z_1-\frac{1}{h_{10}}\overline{k}_1z_1-\widehat{\boldsymbol{\varphi}}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1) \tag{17}$$

where $\overline{k}_1=\sqrt{(\dot{v}(t)/v(t))^2+\sigma_1}$, $k_1>0$ and $\sigma_1>0$ are design parameters.

By the definition of $\overline{k}_1$, we have

$$\overline{k}_1+\frac{\dot{v}(t)}{v(t)}>0 \tag{18}$$

According to Assumption 1 and (17), we obtain

$$\begin{aligned}\frac{z_1^3h_1\alpha_1}{v^4(t)-z_1^4}\le & -k_1h_{10}\frac{z_1^4}{v^4(t)-z_1^4}-\overline{k}_1\frac{z_1^4}{v^4(t)-z_1^4} \\ & -\frac{z_1^3h_{10}\widehat{\boldsymbol{\varphi}}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)}{v^4(t)-z_1^4}\end{aligned} \tag{19}$$

Substituting (17), (18) and (19) into (16), we have

$$\begin{aligned}\mathcal{L}V_1 \le & -k_1h_{10}\frac{z_1^4}{v^4(t)-z_1^4}+\frac{1}{4}z_2^4h_1+\frac{\overline{\delta}_1^2}{2h_{10}} \\ & +\frac{1}{2}+\widetilde{\boldsymbol{\varphi}}_1^{\mathrm{T}}h_{10}\left[\frac{z_1^3S_{m_1}(\mathbf{z}_1)}{(v^4(t)-z_1^4)^2}-\boldsymbol{\Gamma}_1^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_1\right]\end{aligned} \tag{20}$$

Step i: Consider the stochastic Lyapunov function candidate as

$$V_i=V_{i-1}+\frac{1}{4}\log\frac{k_{b_i}^4(t)}{k_{b_i}^4(t)-z_i^4}+\frac{1}{2}h_{i0}\widetilde{\boldsymbol{\varphi}}_i^{\mathrm{T}}\boldsymbol{\Gamma}_i^{-1}\widetilde{\boldsymbol{\varphi}}_i \tag{21}$$

where $\widetilde{\boldsymbol{\varphi}}_i=\boldsymbol{\varphi}_i-\widehat{\boldsymbol{\varphi}}_i$ is the parameter error vector, $\boldsymbol{\Gamma}_i=\boldsymbol{\Gamma}_i^{\mathrm{T}}>0$ is a symmetric positive definite matrix.

According to Definition 1 and (21), we have

$$\begin{aligned}\mathcal{L}V_i= & \mathcal{L}V_{i-1}-\frac{z_i^4}{\left(k_{b_i}^4(t)-z_i^4\right)}\frac{\dot{k}_{b_i}}{k_{b_i}} \\ & +\frac{z_i^3}{k_{b_i}^4(t)-z_i^4}[f_i+h_ix_{i+1}-\Delta\alpha_{i-1}] \\ & +\frac{z_i^2\left(3k_{b_i}^4(t)+z_i^4\right)}{2\left(k_{b_i}^4(t)-z_i^4\right)^2}\widetilde{g}_i^{\mathrm{T}}\widetilde{g}_i+h_{i0}\widetilde{\boldsymbol{\varphi}}_i^{\mathrm{T}}\boldsymbol{\Gamma}_i^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_i\end{aligned} \tag{22}$$

where $\widetilde{g}_i=g_i-\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}g_j$.

By Young's Inequality, we obtain

$$\frac{z_i^2\left(3k_{b_i}^4(t)+z_i^4\right)}{2\left(k_{b_i}^4(t)-z_i^4\right)^2}\widetilde{g}_i^{\mathrm{T}}\widetilde{g}_i\le\frac{z_i^4\left(3k_{b_i}^4(t)+z_i^4\right)^2}{8\left(k_{b_i}^4(t)-z_i^4\right)^4}\|\widetilde{g}_i\|^4+\frac{1}{2} \tag{23}$$

Substituting (23) into (22), we have

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$$\mathcal{L}V_i \le \mathcal{L}V_{i-1} - \frac{z_i^4 \dot{k}_{b_i}}{\left(k_{b_i}^4(t) - z_i^4\right) k_{b_i}} + \frac{z_i^3}{k_{b_i}^4(t) - z_i^4}\left[\overline{f}_i + h_i x_{i+1}\right] - \frac{h_{i0} z_i^6}{2\left(k_{b_i}^4(t) - z_i^4\right)^2} - \frac{3 z_i^4 h_i}{4\left(k_{b_i}^4(t) - z_i^4\right)^{4/3}} - h_{i0}\widetilde{\boldsymbol{\varphi}}_i^{\mathrm{T}} \boldsymbol{\Gamma}_i^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_i - \frac{z_i^4 h_{i-1}}{4} + \frac{1}{2} \tag{24}$$

where $\overline{f}_i = f_i - \Delta\alpha_{i-1} + \frac{\left(k_{b_i}^4(t)-z_i^4\right)}{4} z_i h_{i-1} + \frac{z_i\left(3k_{b_i}^4(t)+z_i^4\right)^2}{8\left(k_{b_i}^4(t)-z_i^4\right)^3}\|\widetilde{g}_i\|^4 + \frac{z_i^3}{2\left(k_{b_i}^4(t)-z_i^4\right)} + \frac{3z_i}{4\left(k_{b_i}^4(t)-z_i^4\right)^{1/3}}$.

$\overline{f}_i$ is also a unknown function, and we can use a MTN $\boldsymbol{\varphi}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i)$ to estimate $\overline{f}_i$. In other words, for $\forall \overline{\delta}_i > 0$, a MTN $\boldsymbol{\varphi}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i)$ is applied to approach $\overline{f}_i$, such that

$$\overline{f}_i = \boldsymbol{\varphi}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i) + \delta_i(\mathbf{z}_i), |\delta_i(\mathbf{z}_i)| \le \overline{\delta}_i \tag{25}$$

where $\mathbf{z}_i = [z_1, \cdots, z_i]^{\mathrm{T}}$ is the input of the MTN and $\delta_i(\mathbf{z}_i)$ is the approximation error.

According to Young's Inequality, we obtain

$$\frac{z_i^3}{k_{b_i}^4(t) - z_i^4}\delta_i(\mathbf{z}_i) \le \frac{h_{i0}}{2}\frac{z_i^6}{\left(k_{b_i}^4(t) - z_i^4\right)^2} + \frac{1}{2h_{i0}}\overline{\delta}_i^2 \tag{26}$$

$$\frac{z_i^3 h_i z_{i+1}}{k_{b_i}^4(t) - z_i^4} \le \frac{3 z_i^4 h_i}{4\left(k_{b_i}^4(t) - z_i^4\right)^{4/3}} + \frac{1}{4} z_{i+1}^4 h_i \tag{27}$$

Substituting (7), (25), (26) and (27) into (24), we have

$$\mathcal{L}V_i \le \mathcal{L}V_{i-1} - \frac{z_i^4}{\left(k_{b_i}^4(t) - z_i^4\right)}\frac{\dot{k}_{b_i}}{k_{b_i}} + \frac{z_i^3}{k_{b_i}^4(t) - z_i^4}\left[h_i\alpha_i + \boldsymbol{\varphi}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i)\right] + \frac{1}{2} - h_{i0}\widetilde{\boldsymbol{\varphi}}_i^{\mathrm{T}}\boldsymbol{\Gamma}_i^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_i + \frac{1}{2h_{i0}}\overline{\delta}_i^2 - \frac{z_i^4 h_{i-1}}{4} + \frac{1}{4} z_{i+1}^4 h_i \tag{28}$$

Based on (28), taking the intermediate control signal α_i as

$$\alpha_i = -k_i z_i - \frac{1}{h_{i0}}\overline{k}_i z_i - \widehat{\boldsymbol{\varphi}}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i) \tag{29}$$

where $\overline{k}_i = \sqrt{\left(\dot{k}_{b_i}/k_{b_i}\right)^2 + \sigma_i}$, $k_i > 0$ and $\sigma_i > 0$ are design parameters.

By the definition of $\overline{k}_i$, we have

$$\overline{k}_i + \frac{\dot{k}_{b_i}}{k_{b_i}} > 0 \tag{30}$$

According to Assumption 1 and (29), we obtain

$$\frac{z_i^3 h_i \alpha_i}{k_{b_i}^4(t) - z_i^4} \le -k_i h_{i0}\frac{z_i^4}{k_{b_i}^4(t) - z_i^4} - \overline{k}_i\frac{z_i^4}{k_{b_i}^4(t) - z_i^4} - \frac{z_i^3 h_i \widehat{\theta}_i^{\mathrm{T}} S_{m_i}(\mathbf{z}_i)}{k_{b_i}^4(t) - z_i^4} \tag{31}$$

Substituting (20), (29), (30) and (31) into (28), we have

$$\mathcal{L}V_i \le -\sum_{j=1}^{i} k_i h_{i0}\frac{z_i^4}{k_{b_i}^4(t) - z_i^4} + \frac{1}{4} z_{i+1}^4 h_i + \frac{i}{2} + \sum_{j=1}^{i}\frac{\overline{\delta}_j^2}{2h_{j0}} - \sum_{j=1}^{i}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}} h_{j0}\left[\frac{z_j^3 S_{m_j}(\mathbf{z}_j)}{\left(k_{b_j}^4(t) - z_j^4\right)^2} - \boldsymbol{\Gamma}_j^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_j\right] \tag{32}$$

Step n: Consider the stochastic Lyapunov function candidate as

$$V_n = V_{n-1} + \frac{1}{4}\log\frac{k_{b_n}^4(t)}{k_{b_n}^4(t) - z_n^4} + \frac{1}{2} h_{n0}\widetilde{\boldsymbol{\varphi}}_n^{\mathrm{T}}\boldsymbol{\Gamma}_n^{-1}\widetilde{\boldsymbol{\varphi}}_n \tag{33}$$

where $\widetilde{\boldsymbol{\varphi}}_n = \boldsymbol{\varphi}_n - \widehat{\boldsymbol{\varphi}}_n$ is the parameter error vector, $\boldsymbol{\Gamma}_n = \boldsymbol{\Gamma}_n^{\mathrm{T}} > 0$ is a symmetric positive definite matrix.

According to Definition 1 and (33), we have

$$\mathcal{L}V_n = \mathcal{L}V_{n-1} - \frac{z_n^4}{\left(k_{b_n}^4(t) - z_n^4\right)}\frac{\dot{k}_{b_n}}{k_{b_n}} + \frac{z_n^3}{k_{b_n}^4(t) - z_n^4}\left[f_n + h_n u - \Delta\alpha_{n-1}\right] + \frac{z_n^2\left(3k_{b_n}^4(t) + z_n^4\right)}{2\left(k_{b_n}^4(t) - z_n^4\right)^2}\widetilde{g}_n^{\mathrm{T}}\widetilde{g}_n - h_{n0}\widetilde{\boldsymbol{\varphi}}_n^{\mathrm{T}}\boldsymbol{\Gamma}_n^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_n \tag{34}$$

where $\widetilde{g}_n = g_n - \sum_{j=1}^{n-1}\frac{\partial\alpha_{i-1}}{\partial x_j} g_j$.

By Young's Inequality, we obtain

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$$\frac{z_n^2\left(3k_{b_n}^4(t)+z_n^4\right)}{2\left(k_{b_n}^4(t)-z_n^4\right)^2}\widetilde{g}_n^{\mathrm{T}} \le \frac{z_n^4\left(3k_{b_n}^4(t)+z_n^4\right)^2}{8\left(k_{b_n}^4(t)-z_n^4\right)^4}\|\widetilde{g}_n\|^4+\frac{1}{2} \tag{35}$$

Substituting (35) into (34), we have

$$\begin{aligned}\mathcal{L}V_n \le \mathcal{L}V_{n-1} &- \frac{z_n^4}{\left(k_{b_n}^4(t)-z_n^4\right)}\frac{\dot{k}_{b_n}}{k_{b_n}} \\ &+ \frac{z_n^3}{k_{b_n}^4(t)-z_n^4}\left[\overline{f}_n+h_n u\right]+\frac{1}{2}-h_{n0}\widetilde{\boldsymbol{\varphi}}_n^{\mathrm{T}}\boldsymbol{\Gamma}_n^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_n \\ &- \frac{h_{n0}}{2}\frac{z_n^6}{\left(k_{b_n}^4(t)-z_n^4\right)^2}-\frac{z_n^4 h_{n-1}}{4}\end{aligned} \tag{36}$$

where $\overline{f}_n = f_n - \Delta\alpha_{n-1} + \frac{\left(k_{b_n}^4(t)-z_n^4\right)}{4}z_n h_{n-1} + \frac{z_n^3}{2\left(k_{b_n}^4(t)-z_n^4\right)} + \frac{z_n\left(3k_{b_n}^4(t)+z_n^4\right)^2}{8\left(k_{b_n}^4(t)-z_n^4\right)^3}\|\widetilde{g}_n\|^4$.

In view of $\overline{f}_n$ is a unknown function. By Lemma 3, for $\forall\overline{\delta}_n>0$, a MTN $\boldsymbol{\varphi}_n^{\mathrm{T}}S_{m_n}(\mathbf{z}_n)$ can be applied to estimate $\overline{f}_n$, such that

$$\overline{f}_n = \boldsymbol{\varphi}_n^{\mathrm{T}}S_{m_n}(\mathbf{z}_n)+\delta_n(\mathbf{z}_n), |\delta_n(\mathbf{z}_n)| \le \overline{\delta}_n \tag{37}$$

where $\mathbf{z}_n = [z_1,\cdots,z_n]^{\mathrm{T}}$ is the input of the MTN and $\delta_n(\mathbf{z}_n)$ is the approximation error.

According to Young's Inequality and (35), we obtain

$$\frac{z_n^3}{k_{b_n}^4(t)-z_n^4}\delta_n(\mathbf{z}_n) \le \frac{h_{n0}}{2}\frac{z_n^6}{\left(k_{b_n}^4(t)-z_n^4\right)^2}+\frac{1}{2h_{n0}}\overline{\delta}_n^2 \tag{38}$$

Substituting (7), (37) and (38) into (36), we have

$$\begin{aligned}\mathcal{L}V_n \le \mathcal{L}V_{n-1} &- \frac{z_n^4}{\left(k_{b_n}^4(t)-z_n^4\right)}\frac{\dot{k}_{b_n}}{k_{b_n}}+\frac{z_n^3}{k_{b_n}^4(t)-z_n^4}\left[h_n u+\boldsymbol{\varphi}_n^{\mathrm{T}}S_{m_n}(\mathbf{z}_n)\right] \\ &+\frac{1}{2}-h_{n0}\widetilde{\boldsymbol{\varphi}}_n^{\mathrm{T}}\boldsymbol{\Gamma}_n^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_n+\frac{1}{2h_{n0}}\overline{\delta}_n^2-\frac{z_n^4 h_{n-1}}{4}\end{aligned} \tag{39}$$

Taking the control input u as

$$u = -k_n z_n - \frac{1}{h_{n0}}\overline{k}_n z_n - \widehat{\boldsymbol{\varphi}}_n^{\mathrm{T}}S_{m_n}(\mathbf{z}_n) \tag{40}$$

where $\overline{k}_n = \sqrt{\left(\dot{k}_{b_n}/k_{b_n}\right)^2+\sigma_n}$, $k_n>0$ and $\sigma_n>0$ are design parameters.

By definition of $\overline{k}_n$, we have

$$\overline{k}_n + \frac{\dot{k}_{b_n}}{k_{b_n}} > 0 \tag{41}$$

According to Assumption 1 and (40), we have

$$\begin{aligned}\frac{z_n^3 h_n u}{k_{b_n}^4(t)-z_n^4} \le &-k_n h_{n0}\frac{z_n^4}{k_{b_n}^4(t)-z_n^4}-\overline{k}_n\frac{z_n^4}{k_{b_n}^4(t)-z_n^4} \\ &-\frac{z_n^3 h_n\widehat{\boldsymbol{\varphi}}_n^{\mathrm{T}}S_{m_n}(\mathbf{z}_n)}{k_{b_n}^4(t)-z_n^4}\end{aligned} \tag{42}$$

Substituting (32), (40), (41) and (42) into (39), we have

$$\begin{aligned}\mathcal{L}V_n \le &-\sum_{j=1}^{n}k_j h_{j0}\frac{z_j^4}{k_{b_j}^4(t)-z_j^4}+\frac{n}{2}+\sum_{j=1}^{n}\frac{\overline{\delta}_j^2}{2h_{j0}} \\ &-\sum_{j=1}^{n}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}h_{j0}\left[\frac{z_j^3 S_{m_j}(\mathbf{z}_j)}{\left(k_{b_j}^4(t)-z_j^4\right)^2}-\boldsymbol{\Gamma}_j^{-1}\dot{\widehat{\boldsymbol{\varphi}}}_j\right]\end{aligned} \tag{43}$$

Select the adaptation laws $\dot{\widehat{\boldsymbol{\varphi}}}_j$ as

$$\dot{\widehat{\boldsymbol{\varphi}}}_j = \boldsymbol{\Gamma}_j\frac{z_j^3 S_{m_j}(\mathbf{z}_j)}{\left(k_{b_j}^4(t)-z_j^4\right)^2}-\boldsymbol{\Gamma}_j\eta_j\widehat{\boldsymbol{\varphi}}_j,\quad j=1,2,\ldots,n \tag{44}$$

where $\eta_j>0$ are designed parameters.

Substituting (44) into (43), we have

$$\mathcal{L}V_n \le -\sum_{j=1}^{n}k_j h_{j0}\frac{z_j^4}{k_{b_j}^4(t)-z_j^4}-\sum_{j=1}^{n}h_{j0}\eta_j\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\widehat{\boldsymbol{\varphi}}_j+\frac{n}{2}+\sum_{j=1}^{n}\frac{\overline{\delta}_j^2}{2h_{j0}} \tag{45}$$

By Young's Inequality, we obtain

$$h_{j0}\eta_j\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\widehat{\boldsymbol{\varphi}}_j \le -\frac{h_{j0}\eta_j}{2}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\widetilde{\boldsymbol{\varphi}}_j+\frac{h_{j0}\eta_j}{2}\|\boldsymbol{\varphi}_j\|^2 \tag{46}$$

with

$$-\frac{h_{j0}\eta_j}{2}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\widetilde{\boldsymbol{\varphi}}_j \le -\frac{h_{j0}\eta_j}{2\lambda_{\max}\left(\boldsymbol{\Gamma}_j^{-1}\right)}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\boldsymbol{\Gamma}_j^{-1}\widetilde{\boldsymbol{\varphi}}_j \tag{47}$$

Substituting (46) and (47) into (45), we have

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$$\mathcal{L}V_n \le -\sum_{j=1}^{n} k_j h_{j0}\frac{z_j^4}{k_{b_j}^4(t)-z_j^4} - \frac{1}{2}\overline{\eta}_j\sum_{j=1}^{n}\widetilde{\boldsymbol{\varphi}}_j^{\mathrm{T}}\boldsymbol{\Gamma}_j^{-1}\widetilde{\boldsymbol{\varphi}}_j + \frac{n}{2} + \sum_{j=1}^{n}\frac{\overline{\delta}_j^2}{2h_{j0}} + \sum_{j=1}^{n}\frac{h_{j0}\eta_j}{2}\|\boldsymbol{\varphi}_j\|^2 \tag{48}$$

where $\overline{\eta}_j = \min\left\{\left(\left(h_{j0}\eta_j\right)/\left(\lambda_{\max}\left(\boldsymbol{\Gamma}_j^{-1}\right)\right)\right)|j=1,2...,n\right\}$.

Let $a=\min\left\{k_jh_{j0},\overline{\eta}_j,j-1,2,...,n\right\}$, $b=\frac{n}{2}+\sum_{j=1}^{n}\frac{\overline{\delta}_j^2}{2h_{j0}}+\sum_{j=1}^{n}\frac{h_{j0}\eta_j}{2}\|\boldsymbol{\varphi}_j\|^2$, yields

$$\mathcal{L}V_n \le -aV+b \tag{49}$$

4 | STABILITY ANALYSIS

Based on the above control scheme and design process, we can generalize the following theorem:

Theorem 1. *Under Assumptions 1–2, consider the closed-loop control system, which comprises the system (1), the control input (40), the intermediate control signals (17) and (29), and the adaptive law (44). For any initial condition, the following requirements are achieved:*

(i) The system output y can track the given reference signal y_d and the tracking error finally converges to a small neighborhood of the origin in the finite-time;
(ii) All the signals in the closed-loop system are SGUUB in probability and the system states satisfy the given limited conditions.

Proof:. From (9), (21) and (33), we have

$$V_n = \frac{1}{4}\sum_{i=1}^{n}\log\frac{k_{b_i}^4(t)}{k_{b_i}^4(t)-z_i^4} + \frac{1}{2}\sum_{i=1}^{n}h_{i0}\widetilde{\boldsymbol{\varphi}}_i^{\mathrm{T}}\boldsymbol{\Gamma}_i^{-1}\widetilde{\boldsymbol{\varphi}}_i \tag{50}$$

Combining (49) with Lemma 1, we have

$$E(V_n(t)) \le V_n(0)e^{-at}+\frac{b}{a} \tag{51}$$

The above inequality means that $E(V_n(t))$ is eventually bounded. Recalling (49), we obtain that all the signals in the closed-loop system are SGUUB in probability.

From (50) and (51), we obtain

$$\frac{1}{4}\log\frac{k_{b_i}^4(t)}{k_{b_i}^4(t)-z_i^4} \le V_n(0)e^{-at}+\frac{b}{a} \tag{52}$$

Taking exponentials on both sides of the (52), we have

$$|z_i| \le k_{b_i}\sqrt[4]{1-e^{-4[V_n(0)e^{-at}+b/a]}} \tag{53}$$

From (53), we obtain that $|z_1|<k_{b_1}=v(t)$. According to Definition 2, we can conclude that the tracking error finally converges to a small neighborhood of the origin in the finite-time.

According to (7), we know that $x_1=z_1+y_d(t)$, since $|z_1|<k_{b_1}$ and $y_d(t)\le A_1$, then, $|x_1|\le|z_1|+|y_d(t)|<k_{b_1}+A_1<k_{c_1}$. Similarly, we obtain that $x_i=z_i+\alpha_{i-1}$, $i=2,\cdots,n$, since $|z_i|<k_{b_i}$ and $\alpha_{i-1}\le A_i$, then $|x_i|\le|z_i|+|\alpha_{i-1}|<k_{b_i}+A_i<k_{c_i}$. Thus, the system constraints are not violated.

The proof of Theorem 1 is completed.

5 | SIMULATION RESULTS

In this section, two simulation examples are given to show the effectiveness of the proposed scheme in this paper.

Example 1. (Numerical example): Consider the second-order nonlinear stochastic system with time-varying state and finite-time output constraint

$$\begin{cases} dx_1 = \left(x_1^2\sin(x_1)+\left(1+x_1^2\right)x_2\right)dt+0.5x_1 d\boldsymbol{\omega} \\ dx_2 = \left(x_1x_2^2+2u\right)dt+0.5x_2 d\boldsymbol{\omega} \\ y=x_1 \end{cases} \tag{54}$$

with the initial state $[x_1(0)\ ,x_2(0)]^{\mathrm{T}}=[0,0]^{\mathrm{T}}$, and $y_d=\sin t$ is the given reference signal. The time-varying state constraint is $|x_2|\le 1.35+0.3\sin(1.3t)$.

By the controller design procedure, the actual control law, the intermediate control signal and the adaptive laws are chosen respectively as

$$u=-k_2z_2-\frac{1}{h_{20}}\overline{k}_2z_2-\widehat{\boldsymbol{\varphi}}_2^{\mathrm{T}}S_{m_2}(\mathbf{z}_2)$$
$$\alpha_1=-k_1z_1-\frac{1}{h_{10}}\overline{k}_1z_1-\widehat{\boldsymbol{\varphi}}_1^{\mathrm{T}}S_{m_1}(\mathbf{z}_1)$$
$$\dot{\widehat{\boldsymbol{\varphi}}}_j=\boldsymbol{\Gamma}_j\frac{z_j^3S_{m_j}(\mathbf{z}_j)}{\left(k_{b_j}^4(t)-z_j^4\right)^2}-\boldsymbol{\Gamma}_j\eta_j\widehat{\boldsymbol{\varphi}}_j$$

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where $j=1,2$, $\mathbf{z}_1=[z_1]^{\mathrm{T}}$, $\mathbf{z}_2=[z_1,z_2]^{\mathrm{T}}$, $z_1=x_1-y_d$, and $z_2=x_2-\alpha_1$. The FTPF is chosen in the following form

$$v(t)=\begin{cases}\left(v_0-\frac{t}{T_f}\right)e^{1-\frac{T_f}{T_f-t}}+v_{T_f}, & t\in[0,T_f)\\ v_{T_f}, & t\in[T_f,+\infty)\end{cases}$$

where $v_0=2$, $v_{T_f}=0.1$, $T_f=3$, and $v(0)=v_0+T_f=2.1$.

The design parameters are taken as follows: $k_1=10$, $k_2=8.5$, $\mathbf{\Gamma}_1=9\mathbf{I}_5$, $\mathbf{\Gamma}_2=5.5\mathbf{I}_9$. The simulation results of Example 1 are shown in Figures 1–4, respectively. Figure 1 illustrates trajectories of the reference signal y_d and the system output y. Figure 2 shows the response of control signal u. Figure 3 displays that the state variable x_2 satisfies the given constraints. Figure 4 depicts that the tracking error $y-y_d$ converges to a small neighborhood around the origin in the finite-time. The presented

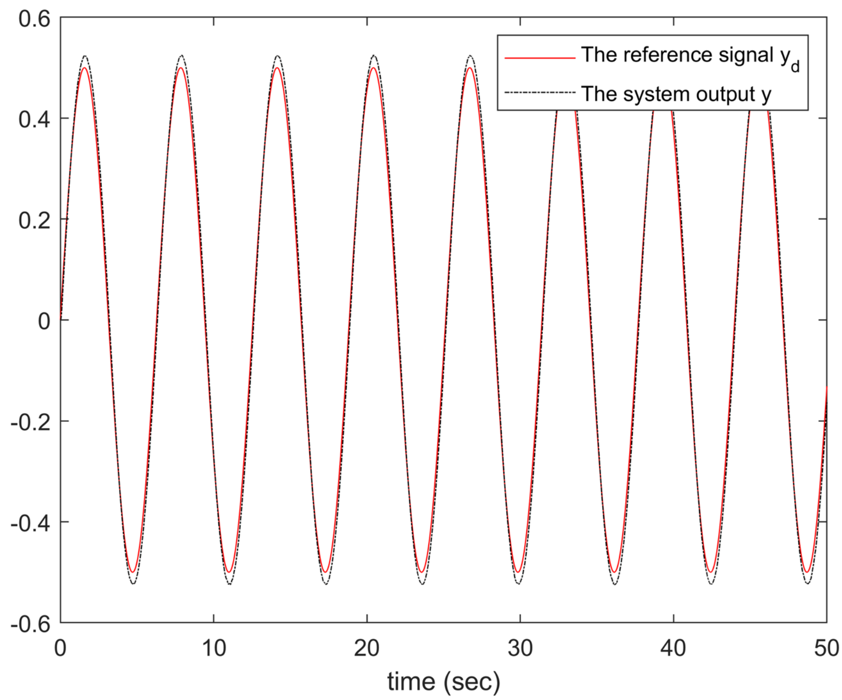

FIGURE 1 The trajectories of system output y and the reference signal y_d [Color figure can be viewed at wileyonlinelibrary.com]

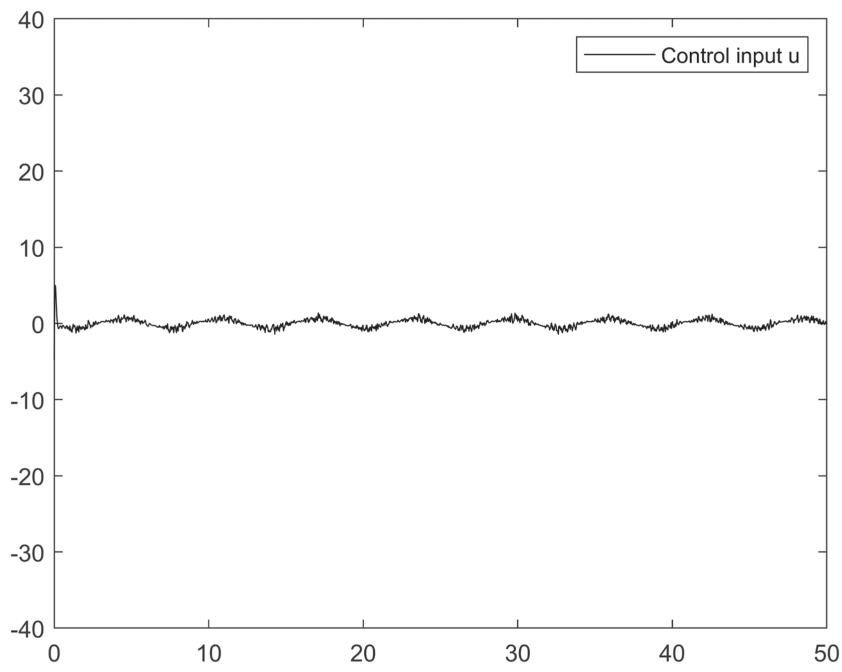

FIGURE 2 The trajectory of system control input u

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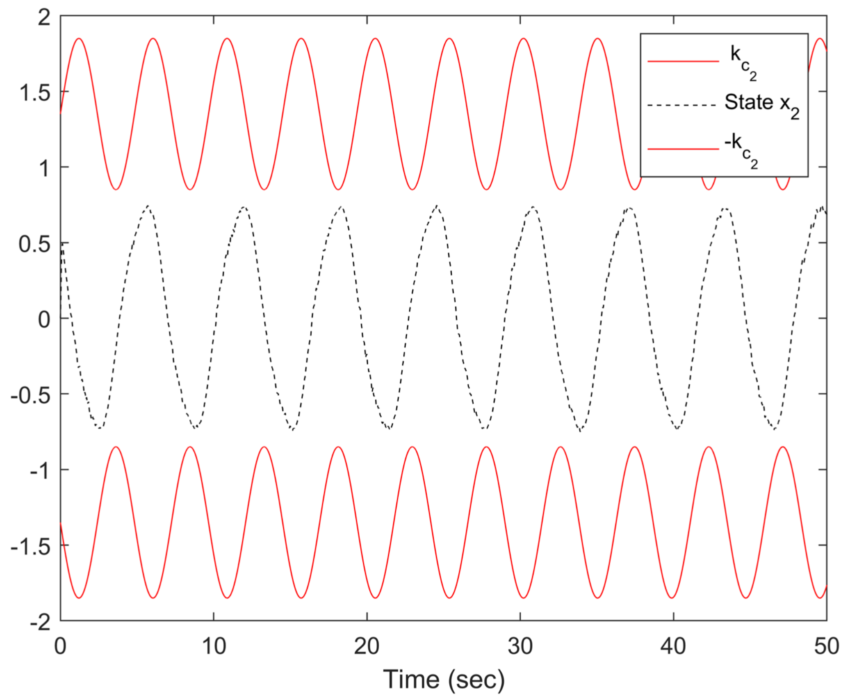

FIGURE 3 The trajectories of system state variable x_2 and constraint conditions [Color figure can be viewed at wileyonlinelibrary.com]

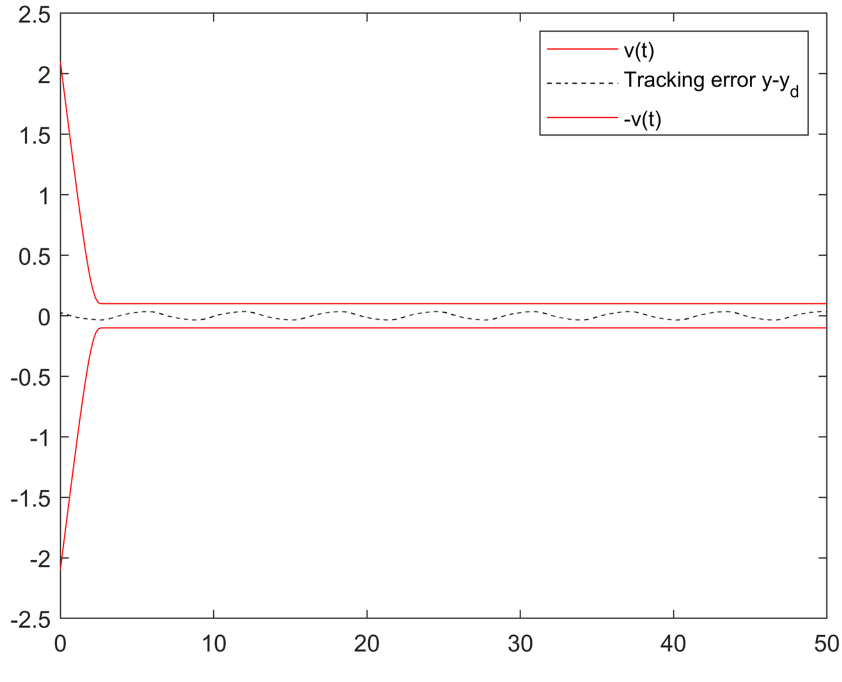

FIGURE 4 The trajectories of $v(t)$ and tracking error $y - y_d$ [Color figure can be viewed at wileyonlinelibrary.com]

simulation results illustrate the effectiveness of the proposed approach in this paper.

Example 2. (Practical example): Considering a one-link manipulator system with time-varying state constraints and finite-time output constraint. According to [50], the system can be described by

$$\begin{cases} dx_1 = x_2 dt \\ dx_2 = (x_3 - 2\sin(x_1) - x_2)dt + \sin\left(x_1^2\right) d\omega \\ dx_3 = (u - 2x_2 - x_3)dt \\ y = x_1 \end{cases} \tag{55}$$

with the initial state $[x_1(0), x_2(0), x_3(0)]^{\mathrm{T}} = [0,0,0]^{\mathrm{T}}$. x_1 denotes the link angular position, x_2 denotes

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velocity, and x_3 denotes acceleration. $y_d = 0.5\sin t$ is the given reference signal. The time-varying state constraints are $|x_2| \le 1 + 0.1\sin(1.5t)$ and $|x_3| \le 4 + 0.3\sin(1.1t)$.

By the controller design procedure, the actual control law, the intermediate control signals and the adaptive laws are chosen, respectively, as

$$u = -k_3 z_3 - \frac{1}{h_{30}} \bar{k}_3 z_3 - \hat{\boldsymbol{\varphi}}_3^{\mathrm{T}} S_{m_3}(\mathbf{z}_3)$$

$$\alpha_j = -k_j z_j - \frac{1}{h_{j0}} \bar{k}_j z_j - \hat{\boldsymbol{\varphi}}_j^{\mathrm{T}} S_{m_j}(\mathbf{z}_j)$$

$$\dot{\hat{\boldsymbol{\varphi}}}_i = \boldsymbol{\Gamma}_i \frac{z_i^3 S_{m_i}(\mathbf{z}_i)}{\left(k_{b_j}^4(t) - z_j^4\right)^2} - \boldsymbol{\Gamma}_i \eta_i \hat{\boldsymbol{\varphi}}_i$$

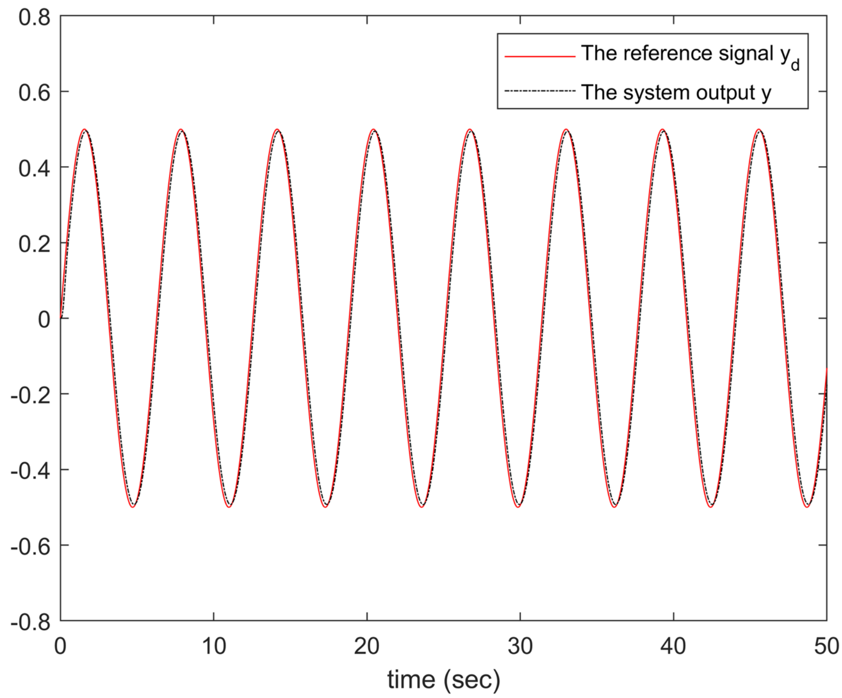

FIGURE 5 The trajectories of system output y and the reference signal y_d [Color figure can be viewed at wileyonlinelibrary.com]

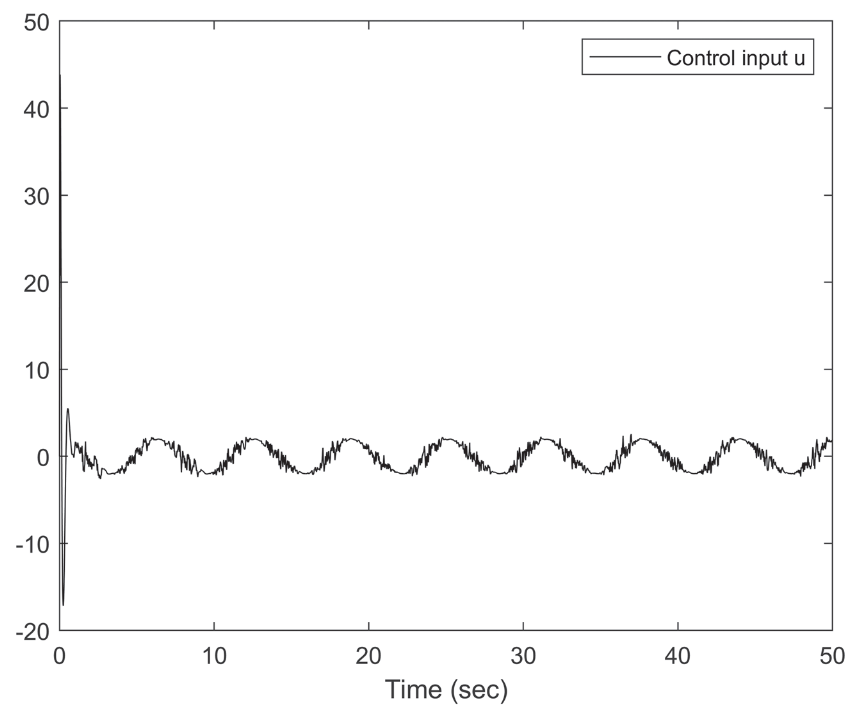

FIGURE 6 The trajectory of system control input u

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where $j = 1,2$, $1 \leq i \leq 3$, $\mathbf{z}_1 = [z_1]^{\mathrm{T}}$, $\mathbf{z}_2 = [z_1, z_2]^{\mathrm{T}}$, $\mathbf{z}_3 = [z_1, z_2, z_3]^{\mathrm{T}}$, $z_1 = x_1 - y_d$, $z_2 = x_2 - \alpha_1$, and $z_3 = x_3 - \alpha_2$. The FTPF is chosen in the following form

$$v(t) = \begin{cases} \left(v_0 - \frac{t}{T_f}\right) e^{1 - \frac{T_f}{T_f - t}} + v_{T_f}, & t \in [0, T_f) \\ v_{T_f}, & t \in [T_f, +\infty) \end{cases}$$

where $v_0 = 2$, $v_{T_f} = 0.1$, $T_f = 3$, and $v(0) = v_0 + T_f = 2.1$.

The design parameters are taken as follows: $k_1 = 80$, $k_2 = 100$, $k_3 = 100$, $\mathbf{\Gamma}_1 = 5\mathbf{I}_5$, $\mathbf{\Gamma}_2 = 10\mathbf{I}_9$, $\mathbf{\Gamma}_3 = 10\mathbf{I}_9$. The simulation results of Example 2 are shown in Figures 5–9, 9, respectively. The results show that the tracking control performance is still fairly satisfactory, which further verifies the effectiveness of the proposed control method in this paper.

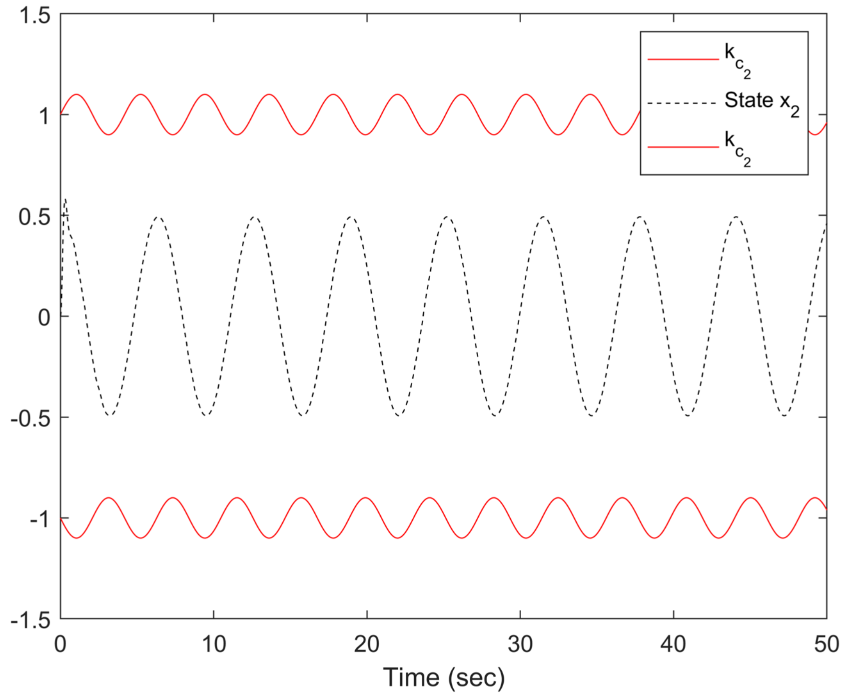

FIGURE 7 The trajectories of system state variables x_2 and constraint conditions [Color figure can be viewed at wileyonlinelibrary.com]

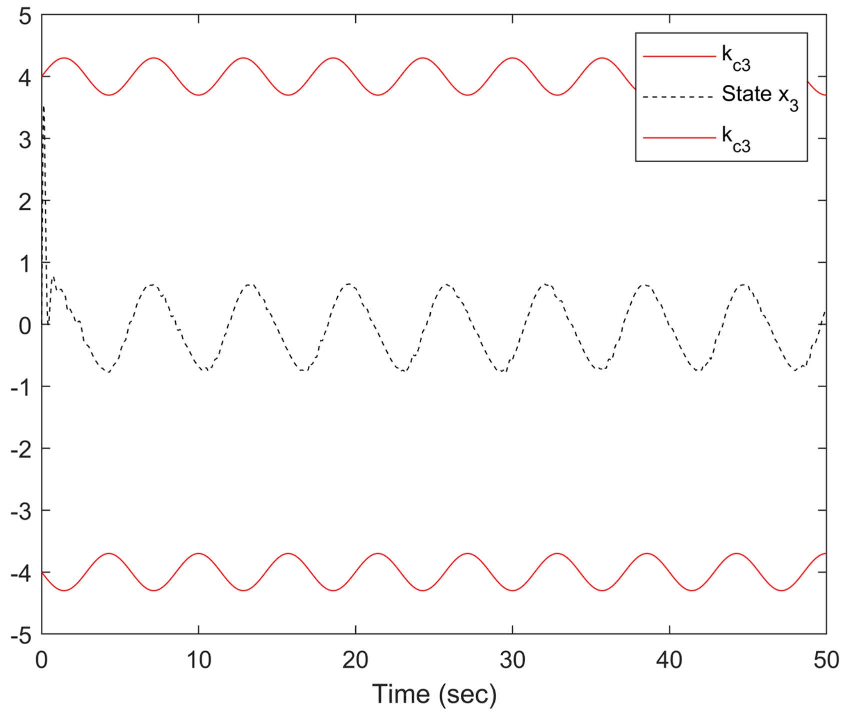

FIGURE 8 The trajectories of system state variables x_3 and constraint conditions [Color figure can be viewed at wileyonlinelibrary.com]

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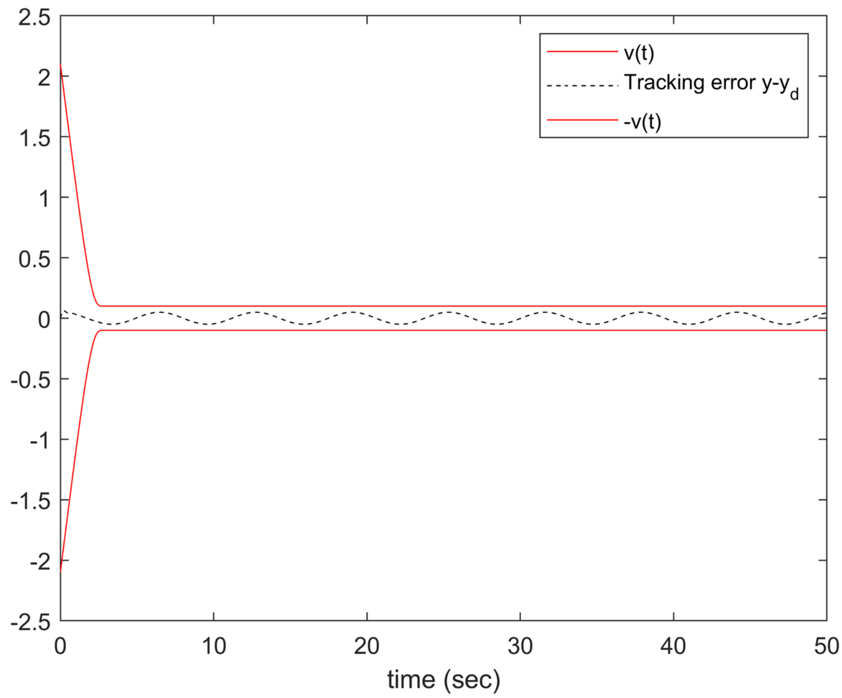

FIGURE 9 The trajectories of $v(t)$ and tracking error $y - y_d$ [Color figure can be viewed at wileyonlinelibrary.com]

Remark 3. In order to obtain good tracking performance, design parameters should be selected appropriately. In general, the tracking error converges to a small residual set near the origin by properly adjusting the parameters k_i and matrix $\mathbf{\Gamma}_i$.

6 | CONCLUSION

In this paper, a new adaptive MTN backstepping control scheme is developed to solve the problem of tracking control for nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint. The MTNs are applied to handle the unknown functions, which greatly reduces the computation complexity of the proposed control scheme. The FTPF and the TVBLFs are introduced to achieve the finite-time output constraint and full state time-varying constraints, respectively. Different from the existing finite-time results, the proposed scheme can guarantee that the tracking error converges to an arbitrarily small region at a settling time. Finally, the simulation results of two examples demonstrate the effectiveness of the proposed control scheme in this paper.

In our future research, we could further focus on the problem of globally uniformly ultimately bounded (GUUB) in probability of the nonlinear stochastic system of this paper and the adaptive finite-time MTN control problems for the other nonlinear stochastic systems such as switch systems and input dead-zone systems.

ACKNOWLEDGEMENTS

This work was supported by the Shandong Provincial Natural Science Foundation, China (No. ZR2020QF055), and the Open Fund of the Key Laboratory of Ocean Circulation and Waves, Chinese Academy of Sciences (No. KLOCW2003).

AUTHOR CONTRIBUTIONS

Ming-Xin Wang: Conceptualization, formal analysis, visualization. **Shan-Liang Zhu:** Methodology, project administration, supervision. **Yu-Qun Han:** Conceptualization, formal analysis, funding acquisition, supervision.

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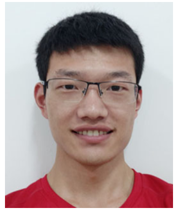

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How to cite this article: M.-X. Wang, S.-L. Zhu, and Y.-Q. Han, *Multi-dimensional Taylor network-based control for a class of nonlinear stochastic systems with full state time-varying constraints and the finite-time output constraint*, Asian J Control (2022), 1–15. https://doi.org/10.1002/asjc.2720

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