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Research Article

Adaptive Control Design with Assigned Tracking Accuracy for a Class of Nonlinearly Parameterized Input-Delayed Systems

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This paper addresses the adaptive control problem of a class of nonlinear systems with unknown parameters and input delay, and the tracking accuracy of the controlled system is assigned a priori. The Pade approximation method is introduced to deal with the problem from the input delay. By creating a group of nonnegative functions, an appropriate controller is designed with the backstepping technology. It is shown that under the obtained controller, the boundedness of all the closed-loop signals is guaranteed, and the tracking error especially can converge to the accuracy assigned a priori. Finally, a simulation example is given to verify the effectiveness of the proposed scheme.

1. Introduction

In the past few decades, the nonlinear parameterized systems played an important role in the engineering field, and many scholars paid more attention to these systems (see, e.g., [1–4]). The backstepping technique especially which was originally proposed in [5, 6] provides a systematic design method for these systems. Adaptive control method is often employed to study these control systems (see, e.g., [7–11]). The authors in [7] study the adaptive control for the whole nonlinear parameterized system using uncontrollable linearization. The authors address the adaptive control of compensation for uncertain nonlinear parameters in robot manipulator in [8]. The adaptive control problem of nonlinear multi-input and multioutput (MIMO) systems is presented in [11].

It is well known that the input delay phenomenon exists in many fields of engineering applications. Input delay has a bad effect on the output of the system and even damages the stability of the system. Therefore, it is very important to study the control problem of this system, and lots of interesting results have been obtained in recent years (see, e.g., [12–20]). Based on the constructed integral Lyapunov function, the authors in [13] study a class of unknown nonlinear time-delay systems by using the online approximation model of wavelet neural network. For a class of MIMO nonlinear delay systems, the authors address the adaptive neural control problem in [15]. A suboptimal learning control scheme has been proposed for nonlinear parametric time-delay systems in [19], and the high convergence speed of the trajectory tracking performance is achieved.

Although some related works have been reported for uncertain nonlinear systems with the given tracking accuracy (see, e.g., [21, 22]). It is noted that no control schemes have been proposed to solve the given accuracy control problem for nonlinear parametric system with input-delay phenomenon. The work of this article is to try to solve this issue. The framework of this paper is summarized as follows. (1) According to the given system, the Pade approximation method is introduced to deal with the problem from the input delay. (2) The appropriate adaptive controller is developed based on the nonnegative functions by using the backstepping design method. (3) A simulation example is given to verify the correctness of the proposed control scheme.

2. Preliminaries

Some symbols and lemmas are introduced in this section. R denotes one-dimensional real value space. R^i denotes i-dimensional Euclidean space. $\mathscr{C}^i$ is a continuous function of ith order. $\widehat{*}$ is a estimate of $*$ and $\widetilde{*}$ is the estimate error.

To design the desired control scheme, the following two functions are introduced:

$$\mathscr{N}_{n,\sigma}(m) = \begin{cases} \dfrac{(|m|-\sigma)^n}{n!}, & |m| > \sigma \\ 0, & |m| \le \sigma \end{cases} \quad (1)$$

and

$$\mathscr{S}_{n,\sigma}(m) = \begin{cases} \operatorname{sgn}(m), & |m| > \sigma \\ 1 - 2\cos^n\left(\dfrac{\pi}{2}\sin^n\left(\dfrac{\pi}{4\sigma}(m+\sigma)\right)\right), & |m| \le \sigma, \end{cases} \quad (2)$$

where σ is the given precision and n is an integer.

Lemma 1 (see [21, 22]). *Functions $\mathscr{N}_{n,\sigma}(m)$ and $\mathscr{S}_{n,\sigma}(m)$ have the following properties.*

(1) $\mathscr{N}_{n,\sigma}(m) \in \mathscr{C}^n$ and $\mathscr{S}_{n,\sigma}(m) \in \mathscr{C}^n$, where $\mathscr{C}^n$ is a set of continuous functions that are differentiable up to the order n.

(2) $\mathscr{N}_{n,\sigma}(m)$ is a function that is not less than zero, and $\mathscr{N}_{n,\sigma}(m) = 0$ if and only if $|m| \le \sigma$. The j-th order derivative of $\mathscr{N}_{n+1,\sigma}(m)$ is

$$\frac{d^j \mathscr{N}_{n+1,\sigma}(m)}{dm^j} = \mathscr{N}_{n-j+1,\sigma}(m)\left[\mathscr{S}_{n-j+1,\sigma}(m)\right]^j, \quad j = 1,\ldots,n. \quad (3)$$

(3) $\mathscr{N}_{j,\sigma}(m)[\mathscr{S}_{j,\sigma}(m)]^2 = \mathscr{N}_{j,\sigma}(m)$, where $j = 1,2,\ldots,n$.

The following lemmas are used to design the desired controller.

Lemma 2 (see [7]). *If $\mathscr{M}(s,t)$ is any continuous real valued function, there are four scalar smoothing functions, for example, $x(s) \ge 0$, $y(t) \ge 0$, $a(s) \ge 1$, and $b(t) \ge 1$ satisfying the following relationships:*

$$\begin{aligned} |\mathscr{M}(s,t)| &\le x(s) + y(t), \\ |\mathscr{M}(s,t)| &\le a(s)\, b(t), \end{aligned} \quad (4)$$

where $s, t \in R^n$.

Lemma 3 (see [7]). *If the following inequality is true,*

$$\begin{aligned} &\left|\rho_i(x_1,\ldots,x_i,\xi)\right| \\ &\quad \le \left(|x_1| + \cdots + |x_i|\right)\chi_i(x_1,x_2,\ldots,x_i,\xi), \end{aligned} \quad (5)$$

and at the same time the two functions $\phi_i(x_1,\ldots,x_i) \ge 1$ and $\vartheta_i(\xi) \ge 1$ are true, of course, the following inequality is also true:

$$\chi_i(x_1,x_2,\ldots,x_i,\xi) \le \phi_i(x_1,\ldots,x_i)\,\vartheta_i(\xi), \quad (6)$$

where $i = 1,2,\ldots,n$, ξ is a number that does not change over time, $\rho_i(x_1,\ldots,x_i,\xi) : R^i \times R \longrightarrow R$ and $\rho_i(0,\ldots,0,\xi) = 0$, $\chi_i(\cdot)$ is a function which is continuous and nonnegative, and $\vartheta_i(\xi)$ does not change.

Think of $\sum_{i=1}^n \vartheta_i(\xi)$ as a whole, and replace it with h. The following inequality can be obtained:

$$\left|\rho_i(x_1,\ldots,x_i,\xi)\right| \le \left(|x_1| + \cdots + |x_i|\right)\phi_i(x_1,\ldots,x_i)\,h, \quad (7)$$

where $h \ge 1$ and it is also a constant.

Lemma 4 ((Barbalat's lemma) [21]). *If the first derivative of $g_{(x)}$ is consistent, and it is also differentiable, and in the meantime $x \longrightarrow \infty$, $g(x)$ is limited, then $x \longrightarrow \infty$, $g(x) = 0$.*

Lemma 5 ((Young's inequality) [21]). *For $\forall(x,y) \in R^2$, the following inequality is true:*

$$xy \le \frac{v^s}{s}|x|^s + \frac{1}{tv^t}|y|^t, \quad (8)$$

where $v > 0$, $s > 1$, $t > 1$, and $(s-1)(t-1) = 1$.

3. Problem Statement, Controller Design, and Analysis Process

3.1. Problem Statement. The nonlinearly parameterized system with input delay considered in this paper is described as follows:

$$\begin{aligned} \dot{x}_i &= b_i x_{i+1} + Q_i(\overline{x}_i,\theta_i), \quad i = 1,\ldots,n-1 \\ \dot{x}_n &= b_n u(t-\tau) + Q_n(\overline{x}_n,\theta_n) \\ y &= x_1, \end{aligned} \quad (9)$$

where $\overline{x}_i = [x_1,x_2,\ldots,x_i]^T \in R^i$, $i = 1,2,\ldots,n$. y denotes the output of the system. $u(t)$ denotes the control input of the system, and τ denotes delay time. $Q_i(\overline{x}_i,\theta_{\rm i})$ is a known smooth nonlinear function containing unknown parameter θ_i, and b_i is an unknown constant, $i = 1,2,\ldots,n$.

Assumption 6. The reference trajectory $y_r(t)$ and its derivative $y_r^{(i)}(t)$ are continuous and bounded $i = 1,2,\ldots,n$.

Assumption 7. Although b_i is an unknown constant, its sign is determined. In order to lose generality, it is assumed that $b_i > 0$ holds all the time. Meanwhile it is supposed that there are $b_{\min} > 0$ and $b_{\max} > 0$ which satisfy $b_{\min} \le |b_i| \le b_{\max}$ all the time for $i = 1,2,\ldots,n$.

The purpose of this paper is to design an adaptive controller which can make the output of the system around the reference signal $y_r(t)$ within a given precision $\sigma > 0$.

Remark 8. Compared with our control problem statement and [23], the main difference is that in this paper, we design the desired adaptive controller making the tracking error within a given accuracy according to the actual demand. To achieve this control issue, some nonnegative switching functions are introduced in each backstepping design, and the control performance analysis is achieved by using Barbalat's lemma.

In order to solve the problem from the input delay, Pade approximation approach proposed in [24] is introduced:

$$\begin{aligned}\mathscr{L}[u(t-\tau)] &= \exp(-\tau v)\mathscr{L}[u(t)] \\ &= \frac{\exp(-\tau v/2)}{\exp(\tau v/2)}\mathscr{L}[u(t)] \\ &\approx \frac{1-\tau v/2}{1+\tau v/2}\mathscr{L}[u(t)],\end{aligned} \tag{10}$$

where $\mathscr{L}[u(t)]$ is the Laplace transform of $u(t)$, and v is Laplace variable. For further analysis, a new variable x_{n+1} is proposed which conforms to the following relation:

$$\mathscr{L}[u(t)]\frac{1-\tau v/2}{1+\tau v/2} = \mathscr{L}[x_{n+1}(t)] - \mathscr{L}[u(t)], \tag{11}$$

and then the following equation is obtained:

$$u - \frac{\tau}{2}\dot{u} = x_{n+1} + \frac{\tau}{2}\dot{x}_{n+1} - u - \frac{\tau}{2}\dot{u}. \tag{12}$$

That is, the following equation can be obtained:

$$\dot{x}_{n+1} = -\omega x_{n+1} + 2\omega u, \tag{13}$$

where $\omega = 2/\tau$.

According to the above information, we can rewrite system (9) as

$$\begin{aligned}\dot{x}_i &= b_i x_{i+1} + Q_i(\overline{x}_i, \theta_i), \quad i = 1,\dots,n-1 \\ \dot{x}_n &= b_n x_{n+1} - b_n u + Q_n(\overline{x}_n, \theta_n) \\ \dot{x}_{n+1} &= -\omega x_{n+1} + 2\omega u \\ y &= x_1.\end{aligned} \tag{14}$$

It is noted that x_{n+1} is not the real variable of the system. It leads to an uncertain ω. The specific analysis process appears in step n.

Remark 9. Recently the more general result has been reported in [25] where the global uniform input-to-state stabilization of nonlinear switched systems with time-varying and periodic dynamics is present. The differences of our approach in comparison with [25] can be presented as follows. (i) In [25], an interconnected switched system without time delay has been considered. However, in interconnection (14), the input delay case is considered, and then the Pade approximation method is introduced to design the adaptive controller. (ii) Different from [25], for interconnection system (14), we consider the practical tracking control problem; that is, the desired adaptive controller makes the tracking error within a given accuracy which can be assigned according to the actual demand.

3.2. Controller Design and Analysis Process. In this subsection, we present a new adaptive controller design method to ensure the control precision and stability of the whole controlled system by using the backstepping technique.

The error variables are defined as follows:

$$\begin{aligned}z_1 &= x_1 - y_r \\ z_i &= x_i - \alpha_{i-1}, \quad i = 2,3,\dots,n-1 \\ z_n &= x_n - \alpha_{n-1} + \frac{b_n}{\omega}x_{n+1},\end{aligned} \tag{15}$$

where α_{i-1} are virtual controllers which will be designed in each backstepping process.

To design the desired adaptive controller, the backsteping algorithm is presented as follows. Let us introduce the detailed design process from Step 1 to Step n.

Step 1. According to the error description in (15), and combining with system (14), we can have

$$\dot{z}_1 = b_1 x_2 + Q_1(\overline{x}_1, \theta_1) - \dot{y}_r. \tag{16}$$

Choose the nonnegative function as follows:

$$V_1 = \frac{n!\mathscr{N}_{n+1,\sigma}(z_1)}{b_1}, \tag{17}$$

and the following equation is obtained:

$$\begin{aligned}\frac{dV_1}{dt} &= \frac{d\mathscr{N}_{n+1,\sigma}(z_1)}{dz_1}\frac{\dot{z}_1 n!}{b_1} \\ &= \frac{\mathscr{N}_{n,\sigma}(z_1)\mathscr{S}_{n,\sigma}(z_1)n!}{b_1}\left[b_1 x_2 + Q_1(\overline{x}_1,\theta_1) - \dot{y}_r\right].\end{aligned} \tag{18}$$

The following inequalities can be obtained by using Lemma 3 and the Young's inequality:

$$\begin{aligned}&\frac{\mathscr{N}_{n,\sigma}(z_1)\mathscr{S}_{n,\sigma}(z_1)n!}{b_1}\left|Q_1(\overline{x_1},\theta_1)\right| \\ &\le \mathscr{N}_{n,\sigma}(z_1)\left[\mathscr{S}_{n,\sigma}(z_1)\right]^2 n!\frac{\eta_1}{b_1}\varphi_1(\overline{x}_1) \\ &\le \mathscr{N}_{n,\sigma}(z_1)\left[\mathscr{S}_{n,\sigma}(z_1)\right]^2 n!\left[\frac{1}{2}\left(\frac{\eta_1}{b_1}\right)^2 + \frac{1}{2}\varphi_1{}^2(\overline{x}_1)\right] \\ &= \mathscr{N}_{n,\sigma}(z_1)\left[\mathscr{S}_{n,\sigma}(z_1)\right]^2 n!\left[h_1 + \phi_1(\overline{x}_1)\right]\end{aligned} \tag{19}$$

and

$$\begin{aligned}&-\frac{\mathscr{N}_{n,\sigma}(z_1)\mathscr{S}_{n,\sigma}(z_1)n!}{b_1}\dot{y}_r \\ &\le \frac{\mathscr{N}_{n,\sigma}(z_1)\left[\mathscr{S}_{n,\sigma}(z_1)\right]^2 n!}{b_1}\left(\dot{y}_r^2 + 1\right) \\ &\le \mathscr{N}_{n,\sigma}(z_1)\left[\mathscr{S}_{n,\sigma}(z_1)\right]^2 n!\frac{1}{b_{\min}}\left(\dot{y}_r^2 + 1\right),\end{aligned} \tag{20}$$

where $h_1 = (1/2)(\eta_1/b_1)^2$ and $\phi_1(\overline{x}_1) = (1/2)\varphi_1{}^2(\overline{x}_1)$. So (18) can be changed into

$$\frac{dV_1}{dt} \le \mathcal{N}_{n,\sigma}(z_1)\,\mathcal{S}_{n,\sigma}(z_1)\,n!\Big[z_2 + \alpha_1 + h_1\mathcal{S}_{n,\sigma}(z_1) + \phi_1(\overline{x}_1)\,\mathcal{S}_{n,\sigma}(z_1) - \frac{1}{b_{\min}}\left(\dot{y}_r^2 + 1\right)\mathcal{S}_{n,\sigma}(z_1)\Big]. \tag{21}$$

The above information is used to design the first virtual controller as

$$\begin{aligned}\alpha_1 = &-\left(k_1 + \frac{1}{4}\right)\mathcal{N}_{n,\sigma}(z_1)\,\mathcal{S}_{n,\sigma}(z_1)\,n! - \widehat{h}_1\mathcal{S}_{n,\sigma}(z_1) \\ &- \phi_1(\overline{x}_1)\,\mathcal{S}_{n,\sigma}(z_1) - (\sigma+1)\,\mathcal{S}_{n,\sigma}(z_1) \\ &+ \frac{1}{b_{\min}}\left(\dot{y}_r^2 + 1\right)\mathcal{S}_{n,\sigma}(z_1),\end{aligned} \tag{22}$$

where $k_1 > 0$, and it is an invariant.

Substituting (22) into (21) yields

$$\begin{aligned}\frac{dV_1}{dt} \le{}& \mathcal{N}_{n,\sigma}(z_1)\,\mathcal{S}_{n,\sigma}(z_1)\,n!\Big[z_2 + \left(h_1 - \widehat{h}_1\right)\mathcal{S}_{n,\sigma}(z_1) \\ &- \left(k_1 + \frac{1}{4}\right)\mathcal{N}_{n,\sigma}(z_1)\,\mathcal{S}_{n,\sigma}(z_1)\,n! \\ &- (\sigma+1)\,\mathcal{S}_{n,\sigma}(z_1)\Big] \le -\left(k_1 + \frac{1}{4}\right)\left[\mathcal{N}_{n,\sigma}(z_1)\,n!\right]^2 \\ &+ \widetilde{h}_1\left[\mathcal{S}_{n,\sigma}(z_1)\right]^2\mathcal{N}_{n,\sigma}(z_1)\,n! + \mathcal{N}_{n,\sigma}(z_1)\,n!\,\big[|z_2| \\ &- (\sigma+1)\big],\end{aligned} \tag{23}$$

where $\widetilde{h}_1 = h_1 - \widehat{h}_1$, and the third property of Lemma 1 is used in (23).

Furthermore, choose $\overline{V}_1 = V_1 + (1/2\lambda_1)\widetilde{h}_1^2$ and

$$\dot{\widehat{h}}_1 = \lambda_1\mathcal{N}_{n,\sigma}(z_1)\left[\mathcal{S}_{n,\sigma}(z_1)\right]^2 n!. \tag{24}$$

Obviously, the following inequalities can be gained:

$$\begin{aligned}\frac{d\overline{V}_1}{dt} &= \frac{dV_1}{dt} - \frac{1}{\lambda_1}\widetilde{h}_1\dot{\widehat{h}}_1 \\ &\le -\left(k_1 + \frac{1}{4}\right)\left[\mathcal{N}_{n,\sigma}(z_1)\,n!\right]^2 \\ &\quad + \widetilde{h}_1\left[\mathcal{S}_{n,\sigma}(z_1)\right]^2\mathcal{N}_{n,\sigma}(z_1)\,n! \\ &\quad + \mathcal{N}_{n,\sigma}(z_1)\,n!\left[|z_2| - (\sigma+1)\right] - \frac{1}{\lambda_1}\widetilde{h}_1\dot{\widehat{h}}_1 \\ &\le -\left(k_1 + \frac{1}{4}\right)\left[\mathcal{N}_{n,\sigma}(z_1)\,n!\right]^2 \\ &\quad + \mathcal{N}_{n,\sigma}(z_1)\,n!\left[|z_2| - (\sigma+1)\right] \\ &\quad - \frac{1}{\lambda_1}\widetilde{h}_1\left\{\dot{\widehat{h}}_1 - \lambda_1\mathcal{N}_{n,\sigma}(z_1)\left[\mathcal{S}_{n,\sigma}(z_1)\right]^2 n!\right\} \\ &\le -\left(k_1 + \frac{1}{4}\right)\left[\mathcal{N}_{n,\sigma}(z_1)\,n!\right]^2 \\ &\quad + \mathcal{N}_{n,\sigma}(z_1)\,n!\left[|z_2| - (\sigma+1)\right],\end{aligned} \tag{25}$$

where $\lambda_1 > 0$ is an adaptive coefficient.

Step i $(i = 2, 3, \ldots, n-1)$. We can see the following equation from (14) and (15):

$$\dot{z}_i = \dot{x}_i - \dot{\alpha}_{i-1} = b_i x_{i+1} + Q_i(\overline{x}_i, \theta_i) - \dot{\alpha}_{i-1}, \tag{26}$$

where $\dot{\alpha}_{i-1} = \sum_{j=1}^{i-1}(\partial\alpha_{i-1}/\partial\widehat{h}_j)\dot{\widehat{h}}_j + \sum_{j=1}^{i-1}(\partial\alpha_{i-1}/\partial x_j)[Q_j(\overline{x}_j, \theta_j) + b_j x_{j+1}] + \sum_{j=0}^{i-1}(\partial\alpha_{i-1}/\partial y_r^{(j)})y_r^{(j+1)}$.

Choose the nonnegative functions as follows:

$$\begin{aligned}V_i &= \overline{V}_{i-1} + \frac{\mathcal{N}_{n-i+2,\sigma}(z_i)\,(n-i+1)!}{b_i}, \\ \overline{V}_i &= V_i + \frac{1}{2\lambda_i}\widetilde{h}_i^2,\end{aligned} \tag{27}$$

and we can get

$$\begin{aligned}\frac{dV_i}{dt} &= \frac{d\overline{V}_{i-1}}{dt} + \frac{d\mathcal{N}_{n-i+2,\sigma}(z_i)}{dz_i}\frac{\dot{z}_i\,(n-i+1)!}{b_i} \\ &= \frac{d\overline{V}_{i-1}}{dt} + \frac{\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)!}{b_i} \\ &\quad\times\left\{b_i x_{i+1} + Q_i(\overline{x}_i, \theta_i) - \sum_{j=0}^{i-1}\frac{\partial\alpha_{i-1}}{\partial y_r^{(j)}}y_r^{(j+1)}\right. \\ &\quad\left. - \sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\widehat{h}_j}\dot{\widehat{h}}_j - \sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\left[Q_j\left(\overline{x}_j, \theta_j\right) + b_j x_{j+1}\right]\right\}.\end{aligned} \tag{28}$$

By using the Young's inequality, we have

$$\begin{aligned}&\frac{\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)!}{b_i}\left|Q_i(\overline{x}_i, \theta_i)\right| \\ &\quad\le \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2(n-i+1)!\frac{\eta_i}{b_i}\varphi_i(\overline{x}_i) \\ &\quad\le \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2(n-i+1)! \\ &\qquad\times\left[\frac{1}{2}\left(\frac{\eta_i}{b_i}\right)^2 + \frac{1}{2}\varphi_i{}^2(\overline{x}_i)\right] \\ &\quad= \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2(n-i+1)! \\ &\qquad\times\left[\frac{1}{2}\left(\frac{\eta_i}{b_i}\right)^2 + \phi_i(\overline{x}_i)\right],\end{aligned} \tag{29}$$

with $\phi_i(\overline{x}_i) = (1/2)\varphi_i{}^2(\overline{x}_i)$,

$$
\begin{aligned}
&-\frac{\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)!}{b_i}\left[\sum_{j=0}^{i-1}\frac{\partial\alpha_{i-1}}{\partial y^{(j)}_r}y_r^{(j+1)}+\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\hat{h}_j}\dot{\hat{h}}_j\right] \\
&\le \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2(n-i+1)!\left\{\frac{1}{b_{\min}}\sum_{j=0}^{i-1}\frac{\partial\alpha_{i-1}}{\partial y^{(j)}_r}\left[\left(y_r^{(j+1)}\right)^2+1\right]+\frac{1}{b_{\min}}\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial\hat{h}_j}\left[\left(\dot{\hat{h}}_j\right)^2+1\right]\right\},
\end{aligned} \tag{30}
$$

and

$$
\begin{aligned}
&-\frac{\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)!}{b_i}
\cdot\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\left|Q_j\left(\overline{x}_j,\theta_j\right)\right| \le \mathcal{N}_{n-i+1,\sigma}(z_i) \\
&\cdot\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial x_j}\left[\frac{\eta_j}{b_i}\varphi_j\left(\overline{x}_j\right)\right] \\
&\le \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2 \\
&\times\sum_{j=1}^{i-1}\left\{\frac{1}{2}\left(\frac{\eta_j}{b_i}\right)^2+\frac{1}{2}\left[\frac{\partial\alpha_{i-1}}{\partial x_j}\varphi_j\left(\overline{x}_j\right)\right]^2\right\} \\
&= \mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2\sum_{j=1}^{i-1}\frac{1}{2}\left(\frac{\eta_j}{b_i}\right)^2 \\
&+\mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2 \\
&\cdot\sum_{j=1}^{i-1}\left(\frac{\partial\alpha_{i-1}}{\partial x_j}\right)^2\phi_j\left(\overline{x}_j\right),
\end{aligned} \tag{31}
$$

where $\phi_j(\overline{x}_j)=(1/2)\varphi_j^2(\overline{x}_j)$.

Substituting (29)-(31) into (28) yields

$$
\begin{aligned}
\frac{dV_i}{dt} &\le \frac{d\overline{V}_{i-1}}{dt}+\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)! \\
&\times\left\{x_{i+1}+\mathcal{S}_{n-i+1,\sigma}(z_i)\left[\frac{1}{2}\left(\frac{\eta_i}{b_i}\right)^2+\phi_i\left(\overline{x}_i\right)\right]+\beta_i\right. \\
&+\mathcal{S}_{n-i+1,\sigma}(z_i) \\
&\left.\cdot\sum_{j=1}^{i-1}\left[\frac{1}{2}\left(\frac{\eta_j}{b_i}\right)^2+\left(\frac{\partial\alpha_{i-1}}{\partial x_j}\right)^2\phi_j\left(\overline{x}_j\right)\right]\right\} = \frac{d\overline{V}_{i-1}}{dt} \\
&+\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)!\times\left\{z_{i+1}\right. \\
&+\alpha_i+h_i\mathcal{S}_{n-i+1,\sigma}(z_i)+\beta_i+\mathcal{S}_{n-i+1,\sigma}(z_i) \\
&\left.\cdot\sum_{j=1}^{i}\left[\left(\frac{\partial\alpha_{i-1}}{\partial x_j}\right)^2\phi_j\left(\overline{x}_j\right)\right]\right\},
\end{aligned} \tag{32}
$$

where $h_i=\sum_{j=1}^{i}(1/2)(\eta_j/b_i)^2$, and $\beta_i=\mathcal{S}_{n-i+1,\sigma}(z_i)\{(1/b_{\min})\sum_{j=0}^{i-1}(\partial\alpha_{i-1}/\partial y^{(j)}_r)[(y_r^{(j+1)})^2+1]+(1/b_{\min})\sum_{j=1}^{i-1}(\partial\alpha_{i-1}/\partial\hat{h}_j)[(\dot{\hat{h}}_j)^2+1]+(b_{\max}/b_{\min})\sum_{j=1}^{i-1}(x_{j+1}^2+1)\}$.

Based on (32), the i-th virtual controller is designed as

$$
\begin{aligned}
\alpha_i = &-\left(k_i+\frac{5}{4}\right)\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)! \\
&-\hat{h}_i\mathcal{S}_{n-i+1,\sigma}(z_i)-\beta_i-(\sigma+1)\,\mathcal{S}_{n-i+1,\sigma}(z_i) \\
&-\mathcal{S}_{n-i+1,\sigma}(z_i)\sum_{j=1}^{i}\left[\left(\frac{\partial\alpha_{i-1}}{\partial x_j}\right)^2\phi_j\left(\overline{x}_j\right)\right],
\end{aligned} \tag{33}
$$

where $k_i>0$ is a design parameter.

Then, we can have

$$
\begin{aligned}
\frac{dV_i}{dt} &\le \frac{d\overline{V}_{i-1}}{dt}+\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)! \\
&\times\left[z_{i+1}+h_i\mathcal{S}_{n-i+1,\sigma}(z_i)-\hat{h}_i\mathcal{S}_{n-i+1,\sigma}(z_i)\right. \\
&-\left(k_i+\frac{5}{4}\right)\mathcal{N}_{n-i+1,\sigma}(z_i)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\,(n-i+1)! \\
&\left.-(\sigma+1)\,\mathcal{S}_{n-i+1,\sigma}(z_i)\right] \\
&\le -\sum_{j=1}^{i}k_j\left[\mathcal{N}_{n-j+1,\sigma}(z_j)\,(n-j+1)!\right]^2 \\
&+\mathcal{N}_{n-i+1,\sigma}(z_i)\left[\mathcal{S}_{n-i+1,\sigma}(z_i)\right]^2(n-i+1)!\tilde{h}_i \\
&-\frac{1}{4}\left[\mathcal{N}_{n-i+2,\sigma}(z_{i-1})\,(n-i+2)!\right]^2 \\
&+\mathcal{N}_{n-i+2,\sigma}(z_{i-1})\,(n-i+2)!\left[\left|z_i\right|-(\sigma+1)\right] \\
&-\frac{5}{4}\left[\mathcal{N}_{n-i+1,\sigma}(z_i)\,(n-i+1)!\right]^2+\mathcal{N}_{n-i+1,\sigma}(z_i)\,(n \\
&-i+1)!\left[\left|z_{i+1}\right|-(\sigma+1)\right].
\end{aligned} \tag{34}
$$

From the above information, choose $\overline{V}_i = V_i + (1/\lambda_i)\tilde{h}_i^2$ and then we can gain

$$\begin{aligned}\frac{d\overline{V}_i}{dt} &= \frac{dV_i}{dt} - \frac{1}{\lambda_i}\tilde{h}_i\dot{\hat{h}}_i \\ &\leq -\sum_{j=1}^{i} k_j\left[\mathcal{N}_{n-j+1,\sigma}\left(z_j\right)(n-j+1)!\right]^2 \\ &\quad - \frac{1}{4}\left[\mathcal{N}_{n-i+2,\sigma}\left(z_{i-1}\right)(n-i+2)!\right]^2 \\ &\quad + \mathcal{N}_{n-i+2,\sigma}\left(z_{i-1}\right)(n-i+2)!\left[\left|z_i\right| - (\sigma+1)\right] \\ &\quad - \frac{5}{4}\left[\mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\right]^2 \\ &\quad + \mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\left[\left|z_{i+1}\right| - (\sigma+1)\right] \\ &\quad + \mathcal{N}_{n-i+1,\sigma}\left(z_i\right)\left[\mathcal{S}_{n-i+1,\sigma}\right]^2(n-i+1)!\tilde{h}_i \\ &\quad - \frac{1}{\lambda_i}\tilde{h}_i\dot{\hat{h}}_i \\ &\leq -\sum_{j=1}^{i} k_j\left[\mathcal{N}_{n-j+1,\sigma}\left(z_j\right)(n-j+1)!\right]^2 + G_i \\ &\quad - \frac{1}{4}\left[\mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\right]^2 \\ &\quad + \mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\left[\left|z_{i+1}\right| - (\sigma+1)\right],\end{aligned} \tag{35}$$

where $G_i = -(1/4)[\mathcal{N}_{n-i+2,\sigma}(z_{i-1})(n-i+2)!]^2 + \mathcal{N}_{n-i+2,\sigma}(z_{i-1})(n-i+2)![|z_i|-(\sigma+1)]-[\mathcal{N}_{n-i+1,\sigma}(z_i)(n-i+1)!]^2$. The i-th adaptation law is designed as

$$\dot{\hat{h}}_i = \lambda_i\mathcal{N}_{n-i+1,\sigma}\left(z_i\right)\left[\mathcal{S}_{n-i+1,\sigma}\left(z_i\right)\right]^2(n-i+1)!, \tag{36}$$

where $\lambda_i > 0$.

Next, we show that $G_i \leq 0$ is true all the time.

When $|z_i| \leq (\sigma+1)$, $G_i \leq 0$ is clearly right. When $|z_i| > (\sigma+1)$, we can use Young's inequality to prove it; that is,

$$\begin{aligned}G_i &\leq \left[\left|z_i\right| - (\sigma+1)\right]^2 - \left[\mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\right]^2 \\ &= \left[\left|z_i\right| - (\sigma+1)\right]^2 \\ &\quad - \left[\frac{\left(\left|z_i\right| - \sigma\right)^{n-i+1}}{(n-i+1)!}(n-i+1)!\right]^2 \\ &= \left[\left|z_i\right| - (\sigma+1)\right]^2 - \left[\left|z_i\right| - \sigma\right]^{2(n-i+1)} \\ &\leq \left(\left|z_i\right| - \sigma\right)^2 - \left(\left|z_i\right| - \sigma\right)^{2(n-i+1)} \\ &= \left(\left|z_i\right| - \sigma\right)^2\left[1 - \left(\left|z_i\right| - \sigma\right)^{2(n-i)}\right].\end{aligned} \tag{37}$$

So, $G_i \leq 0$ is true all the time.

From the above information, the inequality is clearly true as follows:

$$\begin{aligned}\frac{d\overline{V}_i}{dt} &\leq -\sum_{j=1}^{i} k_j\left[\mathcal{N}_{n-j+1,\sigma}\left(z_j\right)(n-j+1)!\right]^2 \\ &\quad - \frac{1}{4}\left[\mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\right]^2 \\ &\quad + \mathcal{N}_{n-i+1,\sigma}\left(z_i\right)(n-i+1)!\left[\left|z_{i+1}\right| - (\sigma+1)\right].\end{aligned} \tag{38}$$

Step n. Choose $\overline{V}_n = V_n + (1/2\lambda_n)\tilde{h}_n^2$, $V_n = \overline{V}_{n-1} + \mathcal{N}_{2,\sigma}(z_n)/b_n$, where $\tilde{h}_n = h_n - \hat{h}_n$, $h_n = (1/2)\sum_{j=1}^{n}(1/2)(\eta_j/b_n)^2$ is an unknown constant, and $\lambda_n > 0$ is a design parameter.

The actual controller is designed as

$$\begin{aligned}u &= -\left(k_n+1\right)\mathcal{N}_{1,\sigma}\left(z_n\right)\mathcal{S}_{1,\sigma}\left(z_n\right) - \hat{h}_n\mathcal{S}_{1,\sigma}\left(z_n\right) - \beta_n \\ &\quad - \mathcal{S}_{1,\sigma}\left(z_n\right)\sum_{j=1}^{n}\left(\frac{\partial\alpha_{n-1}}{\partial x_j}\right)^2\phi_j\left(\overline{x}_j\right),\end{aligned} \tag{39}$$

where $\beta_n = \mathcal{S}_{1,\sigma}(z_n)\{(1/b_{\min})\sum_{j=0}^{n-1}(\partial\alpha_{n-1}/\partial y^{(j)_r})[(y_r^{(j+1)})^2 + 1] + (1/b_{\min})\sum_{j=1}^{n-1}(\partial\alpha_{n-1}/\partial\hat{h}_j)[(\dot{\hat{h}}_j)^2 + 1] + (b_{\max}/b_{\min})\sum_{j=1}^{n-1}(x_{j+1}^2 + 1)\}$, and the n-th adaptive law is designed as

$$\dot{\hat{h}}_n = \lambda_n\mathcal{N}_{1,\sigma}\left(z_n\right)\left[\mathcal{S}_{1,\sigma}\left(z_n\right)\right]^2. \tag{40}$$

Then, we gain

$$\begin{aligned}\frac{d\overline{V}_n}{dt} &= \frac{d\overline{V}_{n-1}}{dt} + \frac{\mathcal{N}_{1,\sigma}\left(z_n\right)\mathcal{S}_{1,\sigma}\left(z_n\right)}{b_n}\left(\dot{x}_n - \dot{\alpha}_{n-1}\right. \\ &\quad \left. + \frac{b_n}{\omega}\dot{x}_{n+1}\right) - \frac{1}{\lambda_n}\tilde{h}_n\dot{\hat{h}}_n \leq \frac{d\overline{V}_{n-1}}{dt} \\ &\quad + \frac{\mathcal{N}_{1,\sigma}\left(z_n\right)\mathcal{S}_{1,\sigma}\left(z_1\right)}{b_n}\left[b_n x_{n+1} - b_n u + Q_n\left(\overline{x}_n,\theta_n\right)\right. \\ &\quad \left. + \frac{b_n}{\omega}\left(-\omega x_{n+1} + 2\omega u\right)\right]\mathcal{N}_{1,\sigma}\left(z_n\right)\mathcal{S}_{1,\sigma}\left(z_n\right)\beta_n - \frac{1}{\lambda_n} \\ &\quad \cdot\tilde{h}_n\dot{\hat{h}}_n \leq -\sum_{j=1}^{n} k_j\left[\mathcal{N}_{n-j+1,\sigma}\left(z_j\right)(n-j+1)!\right]^2 \\ &\quad - \frac{1}{4}\left[\mathcal{N}_{2,\sigma}\left(z_{n-1}\right)2!\right]^2 - \left[\mathcal{N}_{1,\sigma}\left(z_n\right)\right]^2 + \mathcal{N}_{2,\sigma}\left(z_{n-1}\right) \\ &\quad \cdot 2!\left[\left|z_n\right| - (\sigma+1)\right] \\ &\leq -\sum_{j=1}^{n} k_j\left[\mathcal{N}_{n-j+1,\sigma}\left(z_j\right)(n-j+1)!\right]^2.\end{aligned} \tag{41}$$

(41) indicates that the nonnegative function V is not increasing, and at the same time we can see that all the closed-loop signals are bounded. Furthermore, according to Lemma 4, the conclusion of (41) also shows that $|z_1(t)| \leq \sigma$ when $t \longrightarrow \infty$.

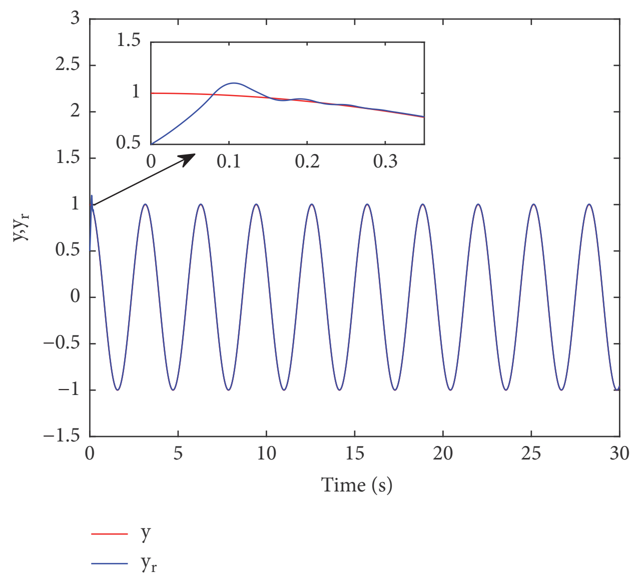

FIGURE 1: The reference trajectory $y_r(t)$ and the output signal $y(t)$.

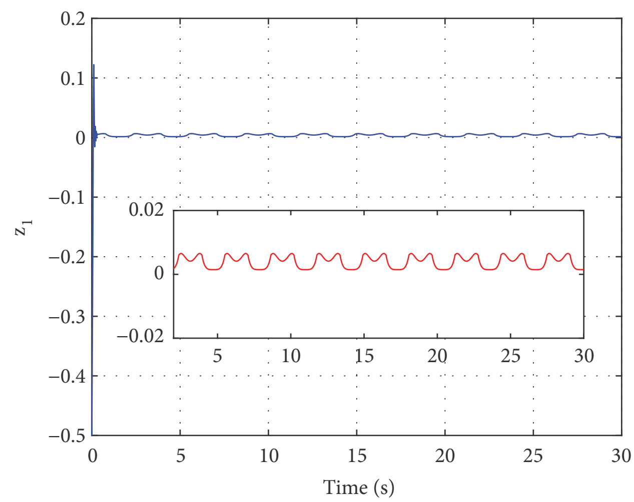

FIGURE 2: The tracking error signal $z_1(t)$.

Theorem 10. *Under Assumptions 6 and 7 and considering the virtual controllers (22) and (33), the actual controller (39), and the parameters adaption laws (24), (36), and (40) for system (9), we can have*

(i) *all the closed-loop signals are bounded,*

(ii) *the tracking error* $|z_1(t)| \leq \sigma$ *holds as* $t \longrightarrow \infty$.

4. Simulation Example

Consider the following nonlinear system:

$$\begin{aligned}\dot{x}_1 &= b_1 x_2 + Q_1(\overline{x}_1, \theta_1)\\ \dot{x}_2 &= b_2 u(t-\tau) + Q_2(\overline{x}_2, \theta_2)\\ y &= x_1,\end{aligned} \quad (42)$$

where $\overline{x}_2 = [x_1, x_2]^T \in R^2$ and y denotes the system state vector and the system output. u is the system control input and τ is the input delay. In this example, we suppose that the reference trajectory $y_r = \cos(2t)$ is given a priori.

It is shown that Assumptions 6 and 7 hold. Here a set of known functions are $Q_1(\overline{x}_1, \theta_1) = \sin(x_1\theta_1)$ and $Q_2(\overline{x}_2, \theta_2) = \sin(x_1 x_2 \theta_2) + 2$. By using Lemmas 2 and 3, the following functions are acquired $\varphi_1(\overline{x}_1) = |x_1| + 2$ and $\varphi_2(\overline{x}_1) = |x_1 x_2| + 2$. By adopting the proposed control algorithm, the actual and virtual controllers are, respectively, designed as (39) with $n = 2$ and (22), and the adaptive laws are selected as (40) with $n = 2$ and (24).

The initial conditions are chosen as $x_1(0) = 1.5, x_2(0) = 0.5$ and $\hat{h}_1(0) = \hat{h}_2(0) = 0$. The rest of the design parameters are selected as $k_1 = 5, k_2 = 10$ and $\lambda_1 = 2, \lambda_2 = 5$. The input delay is chosen as $\tau = 0.0027$. The tracking accuracy is prescribed as $\sigma = 0.02$; that is, $|y(t) - y_r(t)| \leq 0.02$ as $t \longrightarrow \infty$.

The simulated results are presented in Figures 1–5. From Figure 1, the output state y tracks the reference trajectory y_r

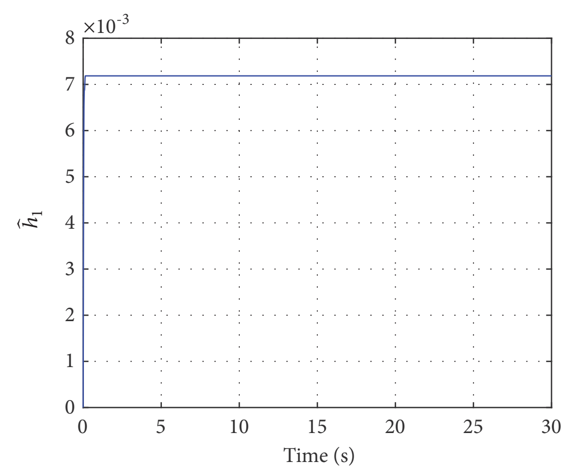

FIGURE 3: The adaptation law $\hat{h}_1$.

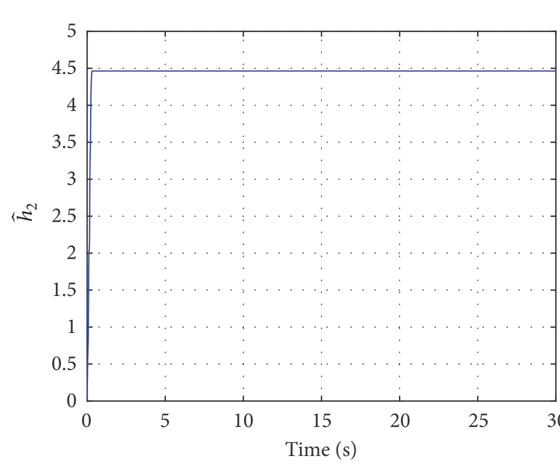

FIGURE 4: The adaptation law $\hat{h}_2$.

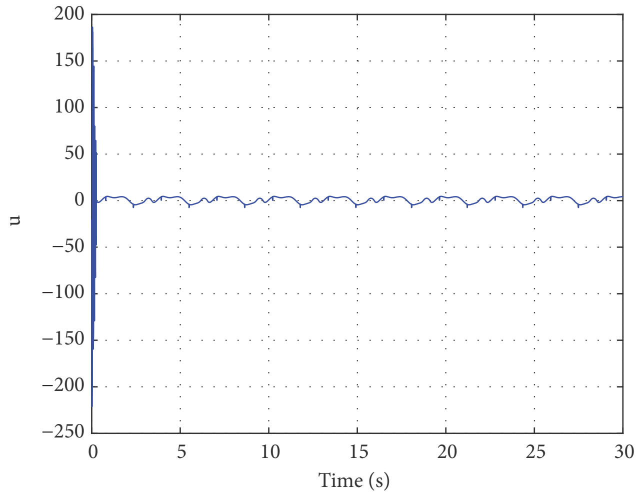

Figure 5: The control input $u(t)$.

with the prescribed accuracy 0.02 quickly. From Figure 2, the tracking error z_1 falls into a priori known domain finally. The actual control signal $u(t)$ is displayed in Figure 5. The adaptation laws are shown in Figures 3 and 4.

5. Conclusions

This paper deals with the tracking control problem of nonlinear parameterized system with input time delay. A new method about the adaptive control is proposed by using the backstepping technique. Some special nonnegative functions are introduced to design desired controller such that the tracking error of the delayed system satisfies the assigned tracking accuracy, and all the closed-loop signals are bounded. The simulation is given to verify the effectiveness of the proposed method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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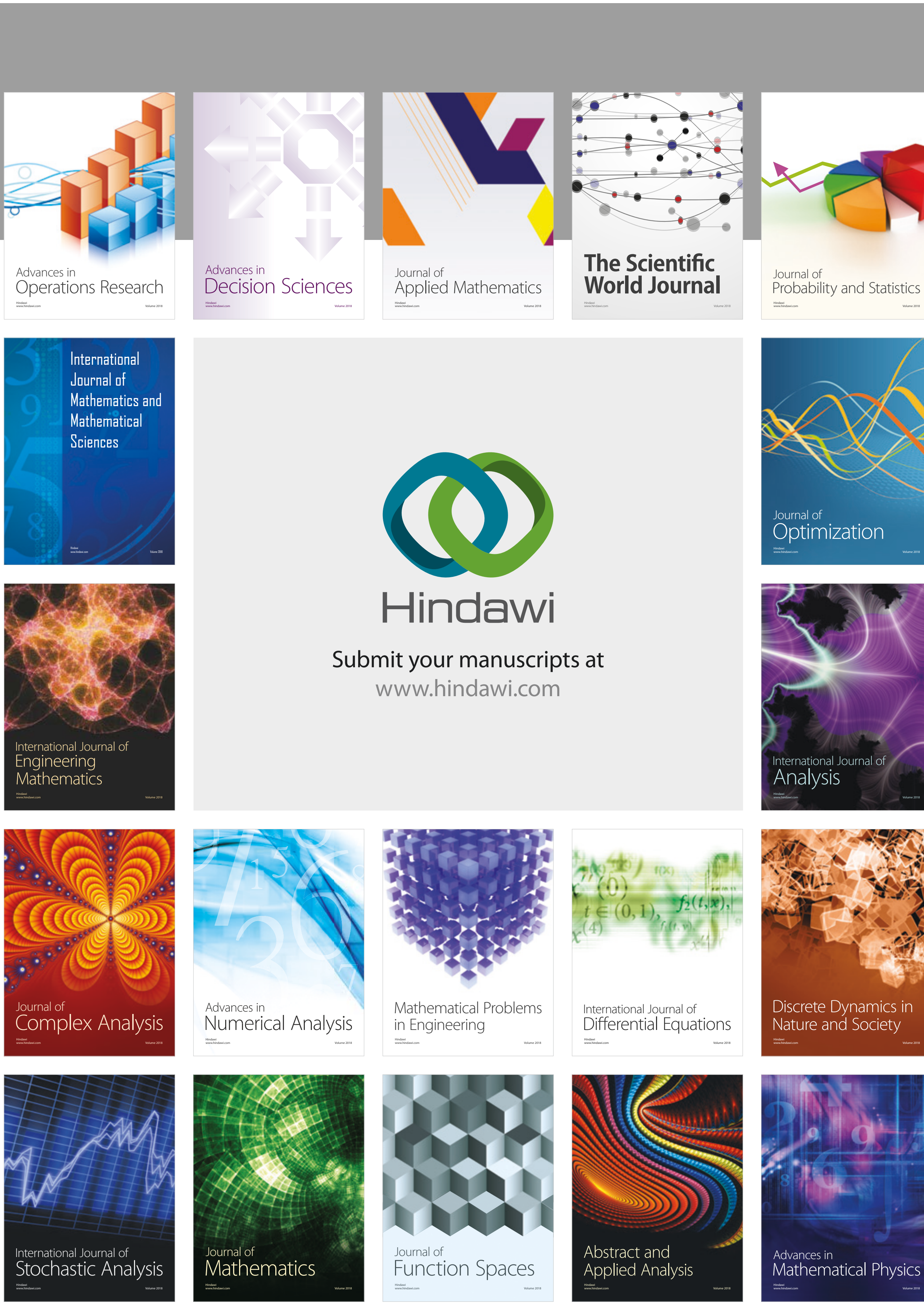
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