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ADAPTIVE NEURAL COMMAND FILTERED FAULT-TOLERANT CONTROL FOR A TWIN ROLL INCLINED CASTING SYSTEM

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The essay studies the adaptive neural network fault tolerant control problem based on command filtering, which is aimed at twin-roll inclined casting system (TRICS). A command filter adaptive neural fault-tolerant control scheme for compensating actuator faults is come forward, and meanwhile, the compensating signal is designed to the error of the compensation filter due to the effect of virtual control. Furthermore,the application of Lyapunov stability theory have proved that all the signals in the closed loop system possessed the property of being bounded and stable. Finally, the effectiveness of the control scheme can be verified by means of simulation example.

Keywords: twin roll, inclined casting system, fault-tolerant, command filter, stability theory

INTRODUCTION

On account of its numerous advantages, the twin-roll casting process has been widely concerned and developed rapidly in recent decades [1,2], but the expected results cannot be achieved for the general control methods. With adaptive control widely used in various fields and achieved good results,the method of adaptive control can automatically reach commendable control effects when applied to the twin-roll casting process [3,4].

It is well known that the nonlinear non-affine system obtained by modeling the two-roll casting process is strongly coupled by parameters, and as seen in [5], the system can be simplified by decoupling using the implicit function theorem and the mean value theorem. There are many adaptive control schemes for nonlinear systems with various uncertainties that have developed because fuzzy logic systems (FLS) and neural networks (NN) can approximate nonlinear functions well. Peculiarly, for higher order nonlinear systems, the combination of backstepping techniques could be used to process a class of nonlinear systems that do not satisfy matching conditions. However, the obvious shortcoming of backstepping technology is the proliferation of complexity caused by the continuous differentiation of virtual control rate. In [6,7], the differential explosion problem is solved by introducing the command filter, but the command filter will bring errors. Therefore, compensation signals are designed to eliminate the errors caused by the filter.

In a general way, in practical application, the control system often has the problem of actuator failure, which can even lead to disastrous consequences in severe cases, and a fuzzy adaptive command filter fault-tolerant control scheme for nonlinear systems with actuator faults is proposed in [8]. Inspired by the above studies, it is a very meaningful research that an adaptive command filter fault-tolerant control scheme based on two roll inclined casting system (TRICS) is proposed in this paper.

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TWIN ROLL INCLINED CASTING SYSTEM MODEL

According to references [5,6], twin-roll inclined casting schematic diagram is shown in Figure 1. The following twin-roll inclined casting nonaffine nonlinear system is constructed by introducing coordinate transformation.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \tau u + f(x,u) \\ y = x_1 \end{cases} \tag{1}$$

where $x = [x_1, x_2]^T$ is state vector, u is control input, y is output of the system.

Actuator faults are described as follows

$$\begin{aligned} u(t) &= \rho \bar{u}(t) + \psi \\ \rho\psi &= 0 \end{aligned} \tag{2}$$

(1) ρ = 1 and ψ = 0. The fault-free case.
(2) 0 < ρ < 1 and ψ = 0. The partial loss of effectiveness fault.
(3) ρ = 0 and $\psi \neq 0$. In this case, $u(t)$ can no longer be influenced by the control input $u(t)$. This implies the total loss of effectiveness (TLOE) fault.

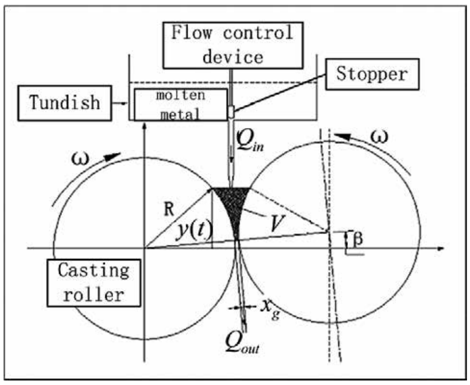

Figure 1 Schematic view of the twin-roll inclined casting with an inclined angle

Assumption 1: For the above system, there are unknown positive constants $\bar{A}_1$ and $\bar{A}_2$, such that $y_r \le \bar{A}_1$, $\dot{y}_r \le \bar{A}_2$.

Lemma 1: Similar to reference [5], the neural network can uniformly approximate the continuous nonlinear function $f(x)$ with arbitrary precision on the compact set Ω_x as follows

$$f(x) = \theta^T \phi(x) + \varepsilon(x) \tag{3}$$

where $x \in \Omega_x$, $\varepsilon(x)$ is approximate error, and satisfy $|\varepsilon(x)| < \varepsilon$, θ^* is a given ideal parametric regression vector, can be expressed as

$$\theta^* = \arg\min_{\theta \in \Omega_\theta} \{\sup_{x \in \Omega_x} |f(x) - \theta^T \phi(x)|\} \tag{4}$$

Lemma 2 [8]**:** The command filter is defined as

$$\begin{aligned} \dot{\varphi}_1 &= w_n \varphi_2 \\ \dot{\varphi}_2 &= -2\zeta w_n \varphi_2 - w_n(\varphi_1 - \alpha_1) \end{aligned} \tag{5}$$

If the input signal α_1 satisfies $|\dot{\alpha}_1| \le \bar{\kappa}_1$ and $|\ddot{\alpha}_1| \le \bar{\kappa}_2$ for all $t \ge 0$, where κ_1, κ_2 are positive constants and $\varphi_1(0) = \alpha_1(0)$, $\varphi_2(0) = 0$, then for any $\mu > 0$, there exist $0 < \zeta \le 1$, $w_n > 0$, such that $|\varphi_1 - \alpha_1| \le \mu$, $|\dot{\varphi}_1$, $|\ddot{\varphi}_1$ and $|\dddot{\varphi}_1$ are bounded.

COMMAND FILTERED ADAPTIVE FAULT-TOLERANT CONTROLLER DESIGN AND STABILITY ANALYSIS

Controller design

In this section, a command filtered adaptive neural backstepping fault tolerant design scheme is proposed to ensure the control objective.

Design the following coordinate transformation:

$$\begin{aligned} z_1 &= x_1 - y_r \\ z_2 &= x_2 - x_{2,c} \end{aligned} \tag{6}$$

where z_i (i = 1,2) is the tracking error, y_r is reference signal and $x_{2,c}$ is the output of command filter with α_1 as input. The command filter is defined as

$$\begin{aligned} \dot{\varphi}_{1,1} &= w_2 \varphi_{1,2} \\ \dot{\varphi}_{1,2} &= -2\zeta w_2 \varphi_{1,2} - w_2(\varphi_{1,1} - \alpha_1) \end{aligned} \tag{7}$$

Where $x_{2,c} = \varphi_{1,1}$ as the output of filter and the filter input signal is α_1 The initial conditions are $\varphi_{1,1} = \alpha_1(0)$ and $\varphi_{1,2}(0) = 0$. For the error caused by the command filter, the following compensation signals are designed to eliminate the error.

$$\begin{aligned} \dot{\xi}_1 &= -c_1\xi_1 + \xi_2 + x_{2,c} - \alpha_1 \\ \dot{\xi}_2 &= -c_2\xi_2 \end{aligned} \tag{8}$$

According to reference [7], the compensating signals $\xi_i (i=1,2)$ is bounded. Then, the compensated tracking error signals $v_i (i=1,2)$ can be defined as

$$\begin{aligned} v_1 &= z_1 - \xi_1 \\ v_2 &= z_2 - \xi_2 \end{aligned} \tag{9}$$

Step 1: The derivative of v_1 is

$$\begin{aligned} \dot{v}_1 &= \dot{z}_1 - \dot{\xi}_1 \\ &= \dot{x}_1 - \dot{y}_r + c_1\xi_1 - \xi_2 - x_{2,c} + \alpha_1 \\ &= v_2 - \dot{y}_r - c_1 v_1 + c_1 z_1 + \alpha_1 \end{aligned} \tag{10}$$

Consider establishing the following Lyapunov function

$$V_1 = \frac{1}{2} v_1^2 \tag{11}$$

Then time derivative of V_1 can gain

$$\begin{aligned} \dot{V}_1 &= v_1 \dot{v}_1 \\ &= v_1(v_2 - \dot{y}_r - c_1 v_1 + c_1 z_1 + \alpha_1) \\ &= -c_1 v_1^2 + v_1 v_2 + v_1(c_1 z_1 - \dot{y}_r + \alpha_1) \end{aligned} \tag{12}$$

Construct the virtual control α_1 as

$$\alpha_1 = -c_1 z_1 + \dot{y}_r \tag{13}$$

Utilization of (13), yields

$$\dot{V}_1 = -c_1 v_1^2 + v_1 v_2 \tag{14}$$

Step 2: By taking the derivative of v_2 is

$$\begin{aligned} \dot{v}_2 &= \dot{z}_2 - \dot{\xi}_2 \\ &= \dot{x}_2 - \dot{x}_{2,c} + c_2\xi_2 \\ &= \tau(\rho\bar{u} + \psi) - \dot{x}_{2,c} + c_2\xi_2 \\ &= \tau\rho(\bar{u} + \frac{\psi}{\rho} - \frac{1}{\tau\rho}\dot{x}_{2,c} + \frac{1}{\tau\rho}c_2 z_2) - c_2 v_2 \end{aligned} \tag{15}$$

Using the Neural Network to approximate the unknown part as

$$\frac{\psi}{\rho} - \frac{1}{\tau\rho}\dot{x}_{2,c} + \frac{1}{\tau\rho}c_2 z_2 = \theta^T \phi + \varepsilon \tag{16}$$

Seeing that the Lyapunov function V_2 as follows

$$V_2 = V_1 + \frac{1}{2\tau\rho} V_2^2 + \frac{1}{2\gamma}\tilde{\theta}^2 \tag{17}$$

where $\rho > 0$ and $\gamma > 0$ are the design parameters, $\hat{\theta}$ is estimation of θ, and define error $\tilde{\theta} = \theta - \hat{\theta}$.

The time derivative of V_2 along the solutions of (15) and (16) is

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + \frac{1}{\tau\rho}\nu_2\dot{\nu}_2 + \frac{1}{\gamma}\tilde{\theta}\dot{\tilde{\theta}} \\ &= \dot{V}_1 + \nu_2(\bar{u} + \theta^T\phi + \varepsilon) \\ &\quad - \frac{1}{\tau\rho}c_2\nu_2^2 - \frac{1}{\gamma}\tilde{\theta}\dot{\hat{\theta}}\end{aligned} \tag{18}$$

Using Young's inequality

$$\begin{aligned}\nu_2\varepsilon &\le \frac{1}{2}\nu_2^2 + \frac{1}{2}\varepsilon^2 \\ \nu_2\theta^T\phi &\le \frac{1}{\eta}\theta\phi^T\phi\nu_2^2 + \frac{\eta}{4}\end{aligned} \tag{19}$$

where $\eta > 0$ is the design parameter.

Substituting (19) into (18), yields

$$\begin{aligned}\dot{V}_2 &\le -c_1\nu_1^2 - \frac{1}{\tau\rho}c_2\nu_2^2 + \nu_1\nu_2 \\ &\quad + \nu_2(\bar{u} + \frac{1}{2}\nu_2 + \frac{1}{\eta}\hat{\theta}\phi^T\phi\nu_2) \\ &\quad + \tilde{\theta}(\frac{1}{\eta}\phi^T\phi\nu_2^2 - \frac{1}{\gamma}\dot{\hat{\theta}}) + \frac{\eta}{4} + \frac{1}{2}\varepsilon^2\end{aligned} \tag{20}$$

Choosing the actual control $\bar{u}$ as

$$\bar{u} = -\nu_1 - \frac{1}{2}\nu_2 - \frac{1}{\eta}\hat{\theta}\phi^T\phi\nu_2 \tag{21}$$

Choosing the adaptive law $\hat{\theta}$ of

$$\dot{\hat{\theta}} = \frac{\gamma}{\eta}\phi^T\phi\nu_2^2 - \Gamma\hat{\theta} \tag{22}$$

where $\Gamma > 0$ is the design parameter.

Invoking (21) and (22), (20) becomes

$$\begin{aligned}\dot{V}_2 &\le -c_1\nu_1^2 - \frac{1}{\tau\rho}c_2\nu_2^2 + \frac{\Gamma}{\gamma}\tilde{\theta}\hat{\theta} \\ &\quad + \frac{\eta}{4} + \frac{1}{2}\varepsilon^2\end{aligned} \tag{23}$$

Stability analysis

Theorem 1: For twin roll inclined casting system with actuator fault (1), under the condition that Assumption 1, Lemma 1, Lemma 2, we can choose the command filter (7), the error compensation signals (8), the virtual control (13) and the actual control (21), the adaptive law (22), such that all signals in the closed-loop system are bounded.

Proof: It is not difficult to arrive at the following inequality

$$\frac{\Gamma}{\gamma}\tilde{\theta}\hat{\theta} \le -\frac{\Gamma}{\gamma}\tilde{\theta}^2 + \frac{\Gamma}{\gamma}\theta^2 \tag{24}$$

Substituting (24) into (23), have

$$\begin{aligned}\dot{V}_2 &\le -c_1\nu_1^2 - \frac{1}{\tau\rho}c_2\nu_2^2 - \frac{\Gamma}{\gamma}\tilde{\theta}^2 \\ &\quad + \frac{\Gamma}{\gamma}\theta^2 + \frac{\eta}{4} + \frac{1}{2}\varepsilon^2 \\ &\le -aV_2 + b\end{aligned} \tag{25}$$

where

According to (25), we can conclude that ν_i $(i = 1,2)$ is bounded, and since $z_i = \nu_i + \zeta_i$ and ζ_i is bounded, z_i is bounded. This completes the proof.

SIMULATION STUDIES

In this section, simulation studies are used to illustrate the effectiveness of the proposed scheme. For twin roll casting model, The system (1) parameters are chosen as $R = 150\ m$, $L_r = 200\ m$, $\omega = 10$ mpm and $\beta = 5°$. The reference signal is $y_r = 0{,}5\ (\sin t + \sin 0{,}5t)$.

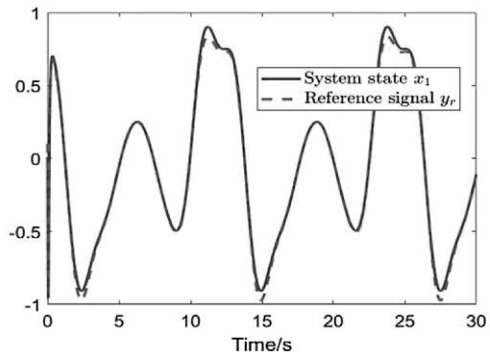

Figure 2 State trajectories of x_1 and y_r

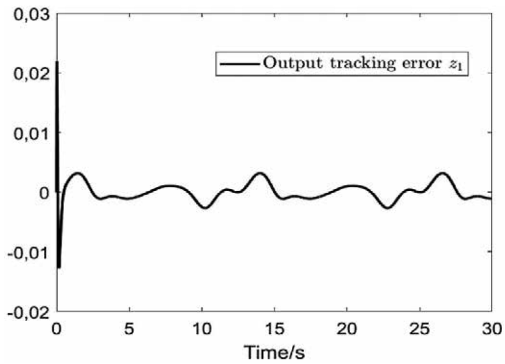

Figure 3 tracking error trajectories of z_1

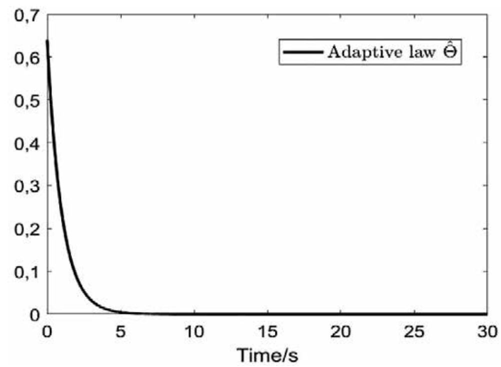

Figure 4 Adaptive parameter $\hat{\theta}$

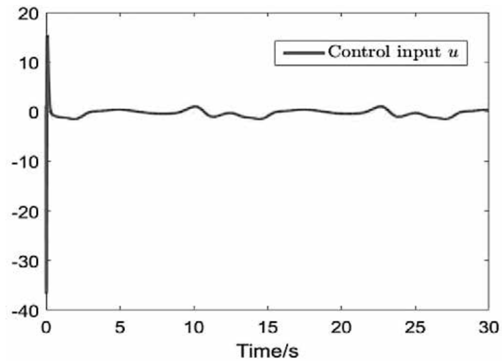

Figure 5 control input *u*

The system control parameters are designed as c_1 = 10, c_2 = 15, ρ = 0,5, ψ = 0, τ = 0,9, ζ = 0,4, w_2 = 40, γ = 0,1, η = 10, Γ = 0,5.

The initial values are chosen as $x_1(0) = 0,01$, $x_2(0) = 0,2$, $\hat{\theta}(0) = 0,8$, $\xi_1(0) = \xi_2(0) = 0$.

The simulation results are show in Figure 2-5.

CONCLUSIONS

In this paper, adaptive command filter fault tolerance control for double roll inclined casting system is studied. Firstly, the non-affine terms are decoupled, and then the unknown functions are approximated by neural networks. The proposed control method solves the differential explosion problem in traditional backstepping, and designing that compensating signal to eliminate the error caused by the filter. Next, by means of Lyapunov stability theory it is proved that all closed-loop signals are bounded and the tracking error of molten steel level can converge to a neighborhood near zero. At last, Simulation results verify the effectiveness of the proposed scheme.

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