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Brief paper

Decentralized output-feedback adaptive control for a class of interconnected nonlinear systems with unknown actuator failures☆

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ABSTRACT

In this paper, a decentralized output-feedback adaptive backstepping control scheme is proposed for a class of interconnected nonlinear systems with unknown actuator failures. By introducing a kind of high-gain K-filters, a bound estimation approach and some smooth functions, the effect of actuator failures and interactions among subsystems is successfully compensated for and the actuators are allowed to change among the normal operation case and different failure cases infinitely many times. The proposed scheme is able to guarantee the global stability of the overall closed-loop system, regardless of the possibly infinite number of unknown actuator failures. An initialization technique is also introduced so that the $\mathcal{L}_\infty$ performance of tracking errors can be adjusted no matter if there exist unknown actuator failures. Simulation results performed on double inverted pendulums are presented to illustrate the effectiveness of the proposed scheme.

1. Introduction

Decentralized adaptive control for uncertain interconnected systems has long been an active issue in the control community. Different from centralized controllers, decentralized controllers are designed independently for subsystems and use only local signals for feedback, which brings challenge to the design and analysis in face of uncertain interactions among subsystems. With the development of backstepping design (Krstic, Kanellakopoulos, & Kokotovic, 1995), the research has been accelerated and considerable achievements have been made over the past two decades; see, for instance, Jiang (2000), Wang and Lin (2015) and Wen (1994) and the references therein for more details.

On the other hand, in practical control systems, actuators may encounter abrupt failures during operation. For the sake of safety and reliability, the compensation of unknown actuator failures has received an increasing amount of attention. Roughly speaking, existing compensation schemes can be classified into two categories, i.e., passive and active ones. Using fixed controllers designed mainly by robust control theory, passive schemes aim at achieving insensitivity of the system to actuator failures and have relatively less computational burden (Yang, Wang, & Soh, 2001; Zhao & Jiang, 1998). However, they can only handle some presumed failures and thus the fault-tolerant capability is limited. In contrast to passive schemes, active schemes react to failures actively by adjusting parameters and/or structure of controllers so that stability and acceptable performance can be maintained. Many active schemes have been developed based on various approaches such as multiple-model (Boskovic & Mehra, 2002), eigenstructure assignment (Jiang, 1994), sliding mode control (Corradini & Orlando, 2007), and so on.

Adaptive control is also an effective active way for actuator failure compensation, and is specially suitable for systems with uncertainties in both system dynamics and actuator failures. In Tao, Chen, and Joshi (2002a,b), Tao, Joshi, and Ma (2001), a class of direct adaptive compensation schemes was proposed for linear time-invariant systems. Different from many other active approaches, these schemes need neither explicit fault detection/diagnosis nor controller reconstruction, which significantly simplifies the closed-loop system. Besides, the uncertainties caused by failures and system parameters can be handled simultaneously. With the aid of backstepping design, the results of Tao et al. (2001, 2002a,b) were extended in Cai, Wen, Su, and Liu (2013), Tang, Tao, and Joshi (2003, 2007) and Wang and Wen (2010) to nonlinear systems

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via state-feedback. Employing K-filters to estimate unmeasured states, the output-feedback case was investigated in Tang and Tao (2009), Tang, Tao, and Joshi (2005), Zhang and Chen (2009) and Zhang, Xu, Guo, and Chu (2010). A common feature of Cai et al. (2013), Tao et al. (2001, 2002a,b), Tang et al. (2003, 2005, 2007), Tang and Tao (2009), Wang and Wen (2010), Zhang and Chen (2009) and Zhang et al. (2010) lies in that the Lyapunov functions constructed for the closed-loop system experience jumps when failures take place and, in order to ensure the stability, the total number of failures is restricted to be finite. In fact, it is assumed in these schemes that one actuator may fail only once and the failure mode does not change afterward. However, in practice an actuator may change among the normal operation case and different failure cases intermittently, and the number of failures may increase towards infinity with the passage of time. Compared with the finite case, the problem of adaptive compensation for a possibly infinite number of unknown actuator failures is much more challenging and it is only recently that some progress was made. In Wang and Wen (2011), a modular design method was developed to address this problem and global stability was ensured under the assumption that the bounds of all uncertainties are known.

In spite of the progress, it is noticed that all the above adaptive compensation schemes cannot be directly applied to decentralized control of interconnected systems. Aiming at a class of interconnected nonlinear systems with a possibly infinite number of unknown actuator failures, in our recent work (Wang, Wen, & Lin, 2015), a decentralized adaptive backstepping control scheme was proposed, which, by introducing a bound estimation approach to handle the failure uncertainties, is able to guarantee global stability without the bound knowledge of uncertainties required in Wang and Wen (2011). Nevertheless, the result in Wang et al. (2015) is only applicable to output regulation and lacks transient performance analysis. When considering decentralized output tracking, the task becomes more complicated because the nonzero desired trajectories to be tracked will affect the dynamics of other subsystems through interactions. Besides, it is well known that the standard backstepping design provides a promising way to guarantee the transient performance in terms of $\mathcal{L}_\infty$ norms after incorporating certain initialization techniques (Krstic et al., 1995). A nature and interesting question is that whether it can be extended to adaptive systems with unknown actuator failures. However, to the best of our knowledge, there is still no such extension available in the literature, mainly because if the failure uncertainties are directly estimated as in Cai et al. (2013), Tao et al. (2001, 2002a,b), Tang et al. (2003, 2005, 2007), Tang and Tao (2009), Wang and Wen (2010, 2011), Zhang and Chen (2009) and Zhang et al. (2010), the jumps in Lyapunov functions may require repeated initialization at the time instants when failures occur. This is unrealistic since the occurrence time, value and pattern of failures are unknown, especially when the total number of failures is not restricted to be finite. Moreover, we point out that both the schemes in Wang and Wen (2011) and Wang et al. (2015) require the measurement of full states and cannot be applied to the output-feedback case where only the system output is measured.

In this paper, within the framework of backstepping design, a decentralized output-feedback adaptive control scheme is proposed for a class of interconnected nonlinear systems with unknown actuator failures. The proposed scheme has the following features:

- By estimating the bounds of those uncertainties caused by actuator failures, the Lyapunov function constructed for the overall closed-loop system has no jump when failures take place and the total number of failures is allowed to be infinite. In contrast to our previous work Wang et al. (2015), which is only applicable to decentralized output regulation via state-feedback, here the more challenging problem of decentralized output tracking via output-feedback is studied and the assumption on interactions is relaxed.
- The $\mathcal{L}_\infty$ tracking performance can be guaranteed. We show that by introducing an initialization technique and adjusting some design parameters, the $\mathcal{L}_\infty$ norms of tracking errors can be made arbitrarily small. The initialization technique is failure-independent and does not need to be performed repeatedly at the time instants when failures occur. To the best of our knowledge, this is the first adaptive scheme capable of guaranteeing the $\mathcal{L}_\infty$ tracking performance in the presence of unknown actuator failures.
- Instead of the traditional K-filters used in existing output-feedback adaptive compensation schemes (Tang & Tao, 2009; Tang et al., 2005; Zhang & Chen, 2009; Zhang et al., 2010), we construct a kind of high-gain K-filters to estimate the unmeasured states. Besides, some smooth functions are introduced to compensate for the interactions among subsystems and actuator failures. With the aid of such efforts, it is proved that all closed-loop signals are globally uniformly bounded.

The remainder of this paper is organized as follows. In Section 2, the control problem is introduced. In Section 3 the controller design is presented, followed by the stability and tracking performance analysis in Section 4. Simulation results are given in Section 5 to illustrate the effectiveness of the proposed scheme. Finally, we conclude in Section 6.

2. Problem formulation

Consider an interconnected nonlinear system consisting of N subsystems in output-feedback form, described by

$$\begin{aligned}\dot{x}_i &= A_i x_i + \varphi_i(y_i)\theta_i + b_i \sum_{j=1}^{\lambda_i} \eta_{i,j}(y_i)u_{i,j} + f_i(y_1,\dots,y_N,t),\\ y_i &= x_{i,1},\ i=1,\dots,N,\\ A_i &= \begin{bmatrix} 0 & \\ \vdots & I_{n_i-1} \\ 0 & \cdots 0\end{bmatrix} \in \mathbb{R}^{n_i\times n_i}, \qquad b_i = [0\cdots 0\ \bar{b}_i^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^{n_i},\end{aligned} \tag{1}$$

where $x_i = [x_{i,1},\dots,x_{i,n_i}]^{\mathrm{T}} \in \mathbb{R}^{n_i}$, $u_i = [u_{i,1},\dots,u_{i,\lambda_i}]^{\mathrm{T}} \in \mathbb{R}^{\lambda_i}$ (the outputs of actuators) and $y_i \in \mathbb{R}$ are the states, inputs and output of the ith subsystem, respectively; I_{n_i-1} is the $(n_i-1)\times(n_i-1)$ identity matrix; $\theta_i \in \mathbb{R}^{p_i}$ and $\bar{b}_i = [b_{i,m_i},\dots,b_{i,0}]^{\mathrm{T}} \in \mathbb{R}^{m_i+1}$ with $b_{i,m_i} \neq 0$ are unknown constants; $\varphi_i(y_i) = [\varphi_{i,1}(y_i),\dots,\varphi_{i,n_i}(y_i)]^{\mathrm{T}} \in \mathbb{R}^{n_i\times p_i}$ with $\varphi_{i,q}(y_i) \in \mathbb{R}^{p_i}$ and $\eta_{i,j}(y_i) \in \mathbb{R}$ with $\eta_{i,j}(y_i) \neq 0$ are known smooth functions; $f_i = [f_{i,1},\dots,f_{i,n_i}]^{\mathrm{T}} \in \mathbb{R}^{n_i}$ are unknown interactions among subsystems, which are locally Lipschitz in $y_1,\dots,y_N$ and piecewise continuous in t; and n_i, m_i, λ_i, p_i are known integers with $\rho_i := n_i - m_i > 1$. The states $x_{i,2},\dots,x_{i,n_i}$ are unmeasured.

Let the input of the (i,j)th actuator be denoted as $v_{i,j}$, which is to be designed. The failures that may occur on the (i,j)th actuator can be modeled as (Wang & Wen, 2011)

$$\begin{aligned}u_{i,j}(t) &= g_{i,j,h}v_{i,j}(t) + \bar{u}_{i,j,h}(t), \quad t\in[T^s_{i,j,h}, T^e_{i,j,h}),\\ g_{i,j,h}\bar{u}_{i,j,h}(t) &= 0, \quad h=1,2,3,\dots,\end{aligned} \tag{2}$$

where $g_{i,j,h}$, $T^s_{i,j,h}$ and $T^e_{i,j,h}$ are all unknown constants with $0 \le g_{i,j,h} < 1$ and $0 \le T^s_{i,j,1} < T^e_{i,j,1} \le T^s_{i,j,2} < T^e_{i,j,2} \le \cdots \le +\infty$, and $\bar{u}_{i,j,h}(t)$ are unknown, piecewise continuous and bounded signals. Eq. (2) covers the following two types of failures:

- $0 < g_{i,j,h} < 1$ and $\bar{u}_{i,j,h}(t) = 0$. In this case, $u_{i,j}(t) = g_{i,j,h}v_{i,j}(t)$ and the actuator is called partial loss of effectiveness (PLOE).