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Brief paper

Adaptive compensation for actuator failures with event-triggered input[☆]

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ABSTRACT

In this paper, we study the problem of event-triggered control for a class of uncertain nonlinear systems subject to actuator failures. The actuator failures are allowed to be unknown and the total number of failures could be infinite. To reduce the communication burden from the controller to the actuator, a novel event-triggered control law is designed. It is proved through Lyapunov analyses that the proposed control protocol ensures that all the signals of the closed-loop system are globally bounded and the system output tracking error can exponentially converge to a residual which can be made arbitrarily small.

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1. Introduction

In practical systems, the control signal is applied to a plant through actuators. Thus system stability is highly dependent on the normal working mode of the actuators. However, in practice actuators may experience gradual or abrupt failures/faults during system operation which can degrade the system performance or even cause catastrophic accidents. Therefore, the compensation of actuator faults is of both theoretical and practical importance. To solve this problem, a number of active approaches have been investigated such as fault diagnosis (Vemuri & Polycarpou, 1997), pseudo-inverse method (Gao & Antsaklis, 1991), sliding mode control (Corradini & Orlando, 2007), etc.

Adaptive control is also widely adopted to compensate for the effects of actuator failures, especially for systems with uncertain dynamics. In Tao, Chen, and Joshi (2002b) and Tao, Joshi, and Ma (2001), adaptive compensation protocols for linear systems were proposed. Based on the tuning function design scheme (Krstic, Kokotovic, & Kanellakopoulos, 1995), the results of Tao et al. (2001) and Tao et al. (2002b) were extended to strict-feedback nonlinear system in Cai, Wen, Su, and Liu (2013) and Tang, Tao, & Joshi (2007). In Tang, Tao, & Joshi (2005), a robust adaptive output feedback control scheme for a class of multi-input single-output nonlinear systems is proposed, and the results were extended to deal with actuator failures containing time-varying terms in Zhang, Xu, Guo, and Chu (2010). More results on adaptive control for actuator faults compensation can be found in Tao, Chen, and Joshi (2002a), Wang and Guo (2015), Wang and Wen (2010, 2011) and Wang, Wen, and Guo (2016).

Nowadays, network control has been widely studied because of its wide range of applications in practical systems (Lai, Liu, Zhang, & Chen, 2016; Wang, Chen, Lin, & Li, 2017; Wang, Chen, Lin, Zhang, & Meng, 2017; Xing, Wen, Su, Liu, & Cai, 2016). One of the main concerns is that the signal communication channel only has limited bandwidth, thus how to reduce the communication burden of the network control systems is of great significance. One way is to reduce the signal transmission frequency between the controller and actuators. However, note that all the above mentioned results for actuator faults compensation require that the control signals should be transmitted to the actuator continuously and thus may occupy large amount of capacity of the communication channel. Recently, event-triggered control has been proposed to reduce signal transmission while keeping satisfactory system performance, and some representative results of event-triggered control for linear/nonlinear systems can be found in Heemels, Johansson, and Tabuada (2012), Henningsson, Johannesson, and Cervin (2008), Liu

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and Jiang (2015a, b), Postoyan, Tabuada, Nesic, and Anta (2015), Tabuada (2007) and Xing, Wen, Guo, Liu, and Su (2016) and references therein. It should be noted that in the above results for nonlinear systems, the input-to-state stable (ISS) assumption for the measurement errors caused by the event-triggering rules is needed. However, such an assumption is not always easy to check and guarantee (Freeman, 1995). In addition, the systems studied in the above references are all known, while the system uncertainties, such as unknown system parameters, are not considered. In this case, the condition to check the ISS assumption would become even harder. Recently, the problem of event-triggered control for uncertain strict-feedback nonlinear systems is addressed in Xing, Wen, Liu, Su, and Cai (2017), and three different event-triggering mechanisms are also given. However, to the best of the author's knowledge, there is still no result investigating event-triggered control with actuator faults taking into consideration.

In this paper, we study the event-triggered control problem for a class of uncertain nonlinear systems with possible actuator failures. The actuators may fail at any unknown time and in any unknown mode during system operation. It should be noted that the existing results in event-triggered control cannot be applied to address this problem directly. The difficulties mainly lie in the following two aspects:

1. As the considered system contains unknown system parameters and the actuators may experience faults/failures, the ISS assumption with respect to the measurement errors is almost impossible to be verified. Thus, it is important to relax this assumption. However, how to compensate for the measurement errors caused by the event-triggering rules without the ISS assumption is a challenge task.
2. It is noted that most results only address adaptive compensation of finite number of actuator failures, due to possible jumps of their considered Lyapunov functions at failure instants. Clearly, the above problem becomes much harder when the number of actuator faults is allowed infinite.

To solve the problems, we design an event triggering rule based on the idea of relative threshold strategy (Garcia & Antsaklis, 2011) since it has varying threshold which depends on the size of the control signal. In overcoming the two challenges with the incorporation of the event triggering mechanism, we also introduce an intermediate variable such that the event-triggered control signal is blended into the actuator fault mode. Then, a novel adaptive controller is designed to compensate for both the actuator faults and the measurement errors, by estimating the bound of the actuator failure parameters instead of the parameters themselves. Through Lyapunov analyses, it is proved that the proposed event-triggered controller ensures the global boundedness of all the closed-loop signals, and the system output tracking error can be adjusted to an arbitrarily small set around zero.

The rest of paper is organized as follows. Section 2 presents the system model, the actuator faults modes and the control objective. Section 3 illustrates the design of the event-triggered controller, the proof of the system stability, and the avoidance of the Zeno behaviour. The effectiveness of our proposed control scheme is verified in Section 4 through simulation studies, while Section 5 concludes the paper.

2. Problem formulation

The following class of nonlinear systems with unknown parameters is considered, similar to Wang and Wen (2010):

$$\begin{aligned}\dot{x}_i &= x_{i+1} + f_i(\bar{x}_i) + \varphi_i^T(\bar{x}_i)\theta, \quad i = 1, \ldots, n-1\\ \dot{x}_n &= \sum_{j=1}^{m} b_j\eta_j(x,\xi)u_j + f_n(x,\xi) + \varphi_n^T(x,\xi)\theta\\ \dot{\xi} &= f(x,\xi) + \Phi(x,\xi)^T\theta\\ y &= x_1\end{aligned} \tag{1}$$

where $x = [x_1, \ldots, x_n]^T \in \mathbb{R}^n$, $\bar{x}_i = [x_1, \ldots, x_i]^T \in \mathbb{R}^i$ and $\xi \in \mathbb{R}^q$ are the state vectors, $\theta \in \mathbb{R}^r$ denotes the unknown system parameters, $\varphi_i(\cdot) : \mathbb{R}^i \to \mathbb{R}^r$ and $f_i(\cdot) : \mathbb{R}^i \to \mathbb{R}^1$, $(i = 1, \ldots, n)$ are known γ-th order ($\gamma \geq n+1-i$) smooth nonlinear functions. b_j is an unknown constant which represents the constant control gain, while $\eta_j(x,\xi)$ is a known function denoting the state-dependent control gain. u_j is the output of the jth actuator, i.e. the real control input signal implemented to the system.

In practice, since the actuators may encounter failures or faults during operation, we denote υ_j, which in this paper is the event-triggered input to be designed, as the input of the jth actuator. Similar to Wang and Guo (2015) and Wang and Wen (2010), when the actuators operate in a fault mode, it can be modeled as

$$\begin{aligned}&u_j = k_{j,h}\upsilon_j + \bar{u}_{j,h}, \quad t \in [T_{j,h}^s, T_{j,h}^e)\\ &k_{jh}\bar{u}_{j,h} = 0, \quad h = 1, 2, 3, \cdots\end{aligned} \tag{2}$$

where $0 < k_{jh} \leq 1$ and $\bar{u}_{j,h}$ are unknown constants denoting different actuator fault modes, $T_{j,h}^s$ and $T_{j,h}^e$ are the time at which the jth actuator fault begins and ends, respectively. Note that model (2) covers the following actuator operation modes:

1. $k_{jh} = 1$ and $\bar{u}_{j,h} = 0$. In this case, the actuator works normally.
2. $0 < k_{jh} < 1$ and $\bar{u}_{j,h} = 0$. This indicates that the actuator is undergoing partial loss of effectiveness (PLOE).
3. $k_{jh} = 1$ and $\bar{u}_{j,h} \neq 0$. This indicates the bias fault.
4. $k_{jh} = 0$ and $\bar{u}_{j,h} \neq 0$. In this case, the jth actuator's output u_j is no longer influenced by the input υ_j, i.e. the actuator works in the total loss of effectiveness (TLOE) mode.

Thus, substituting (2) into (1) gives

$$\begin{aligned}\dot{x}_i &= x_{i+1} + f_i(\bar{x}_i) + \varphi_i^T(\bar{x}_i)\theta, \quad i = 1, \ldots, n-1\\ \dot{x}_n &= \sum_{j=1}^{m} b_j\eta_j(x,\xi)(k_{j,h}\upsilon_j + \bar{u}_{j,h}) + f_n(x,\xi) + \varphi_n^T(x,\xi)\theta\\ \dot{\xi} &= f(x,\xi) + \Phi(x,\xi)^T\theta\\ y &= x_1.\end{aligned} \tag{3}$$

The objective of this paper is to propose an event-triggered adaptive compensation control scheme to make the output signal y track a reference signal $r(t)$, while all the other signals are globally bounded. To this end, the following assumptions are needed.

Assumption 1. Only up to $m-1$ actuators are allowed to undergo TLOE at the same time.

Assumption 2. For the mode of PLOE, $k_{j,h} > \mu_j > 0$, where μ_j is an unknown constant, $j = 1, \ldots, m$.

Assumption 3. The reference signal $r(t)$ and its first $(n+1)$th order derivatives are piecewise continuous, known and bounded.

Assumption 4. $\eta_j(x,\xi) \neq 0$, and the signs of $b_j, j = 1, \ldots, m$, are known.

Assumption 5. The subsystem $\dot{\xi} = f(x,\xi) + \Phi(x,\xi)^T\theta$ is input-to-state stable with x as the input.

Remark 1. Note that $\xi \in \mathbb{R}^q$ represents the states of zero dynamics of system (1). As discussed in Krstic et al. (1995), Cai et al. (2013), Tang et al. (2007), Wang and Wen (2010) and Wang and Guo (2015), many practical systems can be described as or transformed into the form of system (1). Assumptions 1–5 are very common in existing relevant literatures, see Tang et al. (2007) and Tao et al. (2002a) for examples. Assumption 1 is a basic condition to guarantee the controllability of system (1), while all actuators are allowed to work as the PLOE mode simultaneously. In practice, many signals satisfy Assumption 3 with sinusoidal signals being typical examples.

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