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Brief paper

Adaptive compensation for infinite number of actuator failures based on tuning function approach☆

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ABSTRACT

In controlling nonlinear uncertain systems, compensating for infinite number of actuator failures/faults based on the well-known tuning function approach is an important, yet challenging problem in the field of adaptive control. In fact, it has been illustrated through simulation examples that instability is observed when an existing tuning function based scheme designed for compensating finite number of actuator failures is applied to an infinite number case. So far, there is still no solution to this problem. In this paper, we address this issue by proposing a novel adaptive scheme. Technically, our scheme is developed from a new piecewise Lyapunov function analysis, the parameter projection and a modified tuning function method. It is proved that all closed-loop signals are ensured bounded by the control scheme even there is a possibility that the actuator failures take place infinitely, provided that the minimum time interval between two successive failures is bounded below by any positive scalar. Moreover, the ultimate bound of tracking error can be reduced arbitrarily small even for relatively frequent failures. In addition, a guideline for improving transient performance in terms of L_2-norm of tracking error is also established. Perfect asymptotic tracking is obtained when the total number of actuator failures becomes finite.

1. Introduction

In a practical control system, an actuator used to bridge the controller and the plant may experience failures of suddenly stucking or losing partial effectiveness. These failures/faults could impose significant damaging on system performance, and even cause instability or catastrophic accidents if they are not well suppressed. Over lastest decades, growing demands for the reliability and safety of life-critical systems such as aircraft and manned spacecraft stimulate the study of actuator failure compensation. Up to date, a number of active approaches have been reported, for example, fault diagnosis (Vemuri & Polycarpou, 1997), pseudo-inverse method (Gao & Antsaklis, 1991), multiple model (Boskovic, Jackson, Mehra, & Nguyen, 2009; Boskovic & Mehra, 1999, 2002), model predictive control (Kale & Chipperfield, 2005), learning-based method (Diao & Passino, 2001), and sliding mode control (Corradini & Orlando, 2007). In addition to these, adaptive control is also a promising technique in the compensation for actuator failures/faults as revealed in Ahmed-Zaid, Ioannou, Gousman, and Rooney (1991) and Bodson and Groszkiewicz (1997).

As a remarkable feature of using adaptive control to handle actuator failures, both the unknown faults-related information and the system uncertainties are estimated online for adaptively adjusting the controller parameters. In Tao, Chen, and Joshi (2002), Tao, Joshi, and Ma (2001) and Chen, Tao, and Joshi (2004), a direct adaptive control methodology was proposed for the compensation of complete actuator failures in linear systems with single output or multiple outputs. It has been commonly believed that the backstepping (Krstic, Kanellakopoulos, & Kokotovic, 1995; Chen, Wen, Liu, & Liu, 2016) is a prominent controller design technique for nonlinear systems. With recourse of backstepping iteration, the results in Chen et al. (2004), Tao et al. (2001) and Tao et al. (2002), have been successfully generalized to the nonlinear systems with actuator failures (Tang & Tao, 2009; Tang, Tao, & Joshi, 2003, 2007). In Wang and Wen (2010), besides showing the closed-loop system stability and asymptotic tracking performance in the presence of actuator failures, a prescribed transient performance is also well guaranteed by a new backstepping-based adaptive compensation scheme. Furthermore, Cai, Wen, and Su (2015) and Cai, Wen, Su, Li, and Liu (2013), synthetically investigate adaptive failure compensation of hysteretic actuator for parametric uncertain nonlinear systems.

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In most of existing results on adaptive control for actuator failure compensation, such as those mentioned above, only the case with finite number of failures or faults is taken into consideration. As it is commonly assumed that each actuator can only change from normal pattern to completed failure or partial failure once, there must exist a finite time instant after which no further failures/faults will occur. This implies that, even if at failure instant the actuator parameters undergo some jumps, the jumping size is bounded. As a result, the possible increase of the considered Lyapunov function is bounded, which hereby establishes the asymptotic stability of closed-loop system (Tang et al., 2003, 2007; Tang & Tao, 2009; Wang & Wen, 2010). However, similar result cannot be obtained if the number of actuator failures is infinite due to two reasons. First, the accumulation of infinite number of jumps may result in the ceaseless increase of Lyapunov function, and finally the boundedness property is lost. Second, with infinite number of failures, even the boundedness of jumping size could not be retained, namely the size of jumping may also diverge. These two points well reveal the essential differences between finite number case and infinite case and thus results in a nontrivial task to find a solution to adaptive compensation control for infinite number of actuator failures. In Tang et al. (2007), the authors ever conjectured that their scheme could be applicable to infinite case as long as the time interval between two successive failures is sufficiently large, but rigorous analysis still remains open. So far, there are still very few results available in addressing this issue although it has been recognized being of practical and theoretical importance (Wang & Wen, 2011). Instead of using the typical tuning function design method as in Tang et al. (2003), Tang and Tao (2009) and Wang and Wen (2010), Wang and Wen (2011) proposed a modular design scheme for accommodating infinite number of actuator failures, where the control module and parameter estimator module are constructed separately. The proposed modular control scheme only ensures the boundedness of tracking error in the mean square sense, without an explicit bound of asymptotic tracking error. Thus the parameter selection guideline for improving asymptotic tracking performance is not available. These restrictions may be removed by employing the tuning function approach. However, as well documented in Wang and Wen (2011), it is still a challenging and outstanding problem to use tuning function design method like Tang et al. (2003), Tang and Tao (2009) and Wang and Wen (2010) to compensate for infinite number of actuator failures. Actually in Wang and Wen (2011), simulation studies are conducted by applying the-state-of-the-art tuning function based compensation scheme designed for finite number of failures in Wang and Wen (2010) to the situation of infinite number of failures. The results illustrate that instability is caused. Recently, Wang, Wen, and Lin (2015) tried to overcome this challenge but the developed robust control scheme may cause relatively large amplitude of control signal as the estimate of reciprocal value of minimal failure parameter is used in the design. In addition, a time-dependent function is incorporated into the designed controller, which implies the implementation of controller relies on the time variable.

Another issue in compensating for actuator failures is the improvement of transient performance. Note that a promising L_2-norm method for improving transient performance has been proposed in Krstic et al. (1995) by performing trajectory initialization. However, at failure instants which are unknown, such initialization operation is almost impossible to be performed (Cai et al., 2015, 2013; Wang & Wen, 2010, 2011). In other words, even for the case of finite number of failures, the improvement of transient performance in term of L_2-norm still remains as an open challenging problem.

In this paper, we shall give solutions to above two challenging problems using the tuning function method. Our approaches are summarized as follows.

- We achieve the fusion of projection operator with tuning function method. Actually, such fusion is not a trivial work as pointed out in Cai, de Queiroz, and Dawson (2006), since it involves a major modification to typical tuning function scheme (Krstic et al., 1995; Wang & Wen, 2010). With the developed projection based tuning function design, both the system parameter estimation errors and the fault-related parameter estimation errors are always ensured bounded even in the presence of possible infinite number of actuator failures.
- With the proposed scheme and a new piecewise Lyapunov function analysis (PLFA), the jumping size of Lyapunov function at each failure instant cannot only be ensured bounded, but also reduced as small as desired by adjusting controller parameters. This result implies that it is possible to find an interval to lower bound the time period between two successive failures, such that the possible sudden increase of Lyapunov function at failure instant can be offset by its persistent declining in this time interval. Thus, the accumulation of infinite number of jumps will no longer lead to the ceaseless increase of Lyapunov function.
- With the PLFA, the relationships among the stability of closed-loop system, minimum failure time interval, and controller design parameters are established.

With the above approaches, it is proved that all signals of the closed-loop system are globally bounded under the condition that the minimum failure time interval is bounded below by an arbitrary positive number. It is also established that the tracking error is controlled into a residual around zero whose size can be arbitrarily reduced by adjusting the design parameters, even for the case of relatively frequent failures. Furthermore, with the adjustable jumping size of Lyapunov function at failure instant, the improvement of transient performance in term of L_2 norm, as an open problem in Cai et al. (2013), Cai et al. (2015) Tang et al. (2003), Tang et al. (2007), Tang and Tao (2009), Wang and Wen (2010), Wang and Wen (2011) and Wang et al. (2015), can be achieved no matter whether actuator failures occur finitely or infinitely. For the case with finite number of actuator failures, our scheme can further guarantee asymptotic convergence of tracking error to zero.

2. Problem statement

The same class of multi-input single-output nonlinear systems in Wang and Wen (2010) and Wang and Wen (2011) is considered. For completeness, the model is described as follows.

$$
\begin{aligned}
\dot{x}_i &= x_{i+1} + \theta^T \varphi_i(\bar{x}_i), \quad i = 1, \ldots, n-1 \\
\dot{x}_n &= \varphi_0(\bar{x}_n, \xi) + \theta^T \varphi_n(\bar{x}_n, \xi) + \sum_{j=1}^{m} b_j \beta_j(\bar{x}_n, \xi) u_j \\
\dot{\xi} &= \psi(\bar{x}_n, \xi) + \phi(\bar{x}_n, \xi)\theta \\
y &= x_1,
\end{aligned} \tag{1}
$$

where $\bar{x}_i = [x_1, \ldots, x_i]^T \in \mathbb{R}^i, \bar{x}_n = [x_1, \ldots, x_n]^T \in \mathbb{R}^n$, and $\xi \in \mathbb{R}^q$ are the state vectors. $y \in \mathbb{R}$ is the system output corresponding to the multiple system inputs $u_j \in \mathbb{R}, j = 1, \ldots, m$. In other words, u_j is also the output of jth actuator. $\varphi_0(\bar{x}_n, \xi) \in \mathbb{R}$, $\beta_j(\bar{x}_n, \xi) \in \mathbb{R}$, $\varphi_i(\bar{x}_i) \in \mathbb{R}^p$, and $\varphi_n(\bar{x}_n, \xi) \in \mathbb{R}^p$ are known smooth functions, while $\theta \in \mathbb{R}^p$ and b_j are unknown parameters.

We denote the jth actuator input by u_{cj}. Then under failure free case, the control input u_{cj} is equal to the actuator output u_j. But when the actuator is subjected to the failures/faults, it can be modeled as Cai et al. (2013), Cai et al. (2015), Wang et al. (2015),