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Brief paper

Output feedback adaptive sensor failure compensation for a class of parametric strict feedback systems[☆]

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ABSTRACT

In this paper, an adaptive output feedback compensation control scheme is proposed for a class of nonlinear systems with unknown sensor failures. For estimating the unmeasured states, a novel switching-type adaptive observer is constructed, in which the observer gains are tuned in a switching manner. To compensate for the failure effects on transient performance, a new error signal which contains an adaptive compensation coefficient is introduced into backstepping procedure. It is shown that the proposed controller can guarantee the closed-loop system is globally uniformly ultimately bounded, and system output converges to an adjustable neighborhood of the origin. Simulation results are presented to illustrate the effectiveness of the proposed scheme.

1. Introduction

In practical control mechanisms, sensors are thought to break down as frequently as actuators, and sensor failures often bring serious and even disastrous situations. For reliability and safety reasons, sensor failure compensation has long been an active issue in the control community. In early stage, one typical design method for control of systems with sensor failures is based on the sensor redundancy, which is rendered by the measurements from multiple sensors. Such designs have been employed to some practical systems, such as hovercraft power system, aircraft systems (Guo & Nurre, 1991; Zhao, Ye, Zhang, & Sun, 1994). However, in many applications, sensor redundancy may not be available. Recently, considerable analytical redundancy based control approaches for tolerating sensor failure have been developed for linear and nonlinear systems, such as robust control (Aouaouda, Chadli, & Karimi, 2014; Dong & Yang, 2015; Yang & Ye, 2007), descriptor system approach (Gao & Ding, 2007), sliding mode control (Liu, Cao, & Shi, 2013) and adaptive compensation schemes (Li & Tao, 2009).

Since 1990s, global adaptive control of uncertain nonlinear systems has received great attention (Ionanou & Sun, 1996). Apart from them perhaps the most significant one is the development of adaptive backstepping control approach for a class of nonlinear systems in a triangular structure, called parametric strict-feedback systems (PSFSs). The reasons lie in its advantages such as the transient performance can be established and improved with explicit tuning of design parameters, and those nonlinear systems without satisfying the matching conditions can be dealt with effectively. A number of important results have been summarized in Krstic, Kanellakopoulos, and Kolotovic (1995). In recent years, the studies on adaptive backstepping control have been extended from PSFSs to more general classes of nonlinear systems, such as nonlinearly parameterized systems (Lin & Qian, 2002; Long, Wang, & Zhao, 2015; Ye, 2003), parameter-varying systems (Chiang & Fu, 2014; Marino & Tomei, 1993), time-delay systems (Zhou, Wen, & Wang, 2009). In addition, some important robustness issues have also been addressed, for example, robust control with input saturation (Fischer, Dani, Sharmab, & Dixon, 2013; Gong & Yao, 2000; Wen, Zhou, Liu, & Su, 2011), dead-zone (Zhang, Xu, & Zhang, 2014) and hysteresis (Zhou, Wen, & Zhang, 2004). The problem of adaptive actuator failure compensation for PSFSs was investigated in Tang, Tao, and Joshi (2003). To improve transient performance when failure occurs, the prescribed performance technique is incorporated into backstepping procedure (Wang & Wen, 2010). Furthermore, to remove the restrictions that the total number of failures is finite, a bound estimation approach is proposed in Wang, Wen, and Lin (2015). However, the effect of sensor failure has not been addressed with this approach, although it is of both theoretical and practical importance. The main challenges to find an adaptive solution to the problem of compensating for sensor failures lie in that all the state variables are unavailable for feedback design such

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that the standard backstepping technique (Krstic et al., 1995) is no longer feasible, and the control approaches obtained via failed measurement feedback cannot guarantee the adaptive systems achieve a desired transient performance.

In this paper, escaping from the framework of tuning function based backstepping design, a novel adaptive output-feedback failure compensation scheme is proposed for PSFSs with sensor failures. To circumvent the obstacle caused by unmeasured state variables, a switching-type adaptive state observer is designed where observer gains are tuned online in a switching manner according to the proposed logic switching rules. In controller design, a new error signal which contains an adaptive failure compensation coefficient is introduced into the backstepping produce. As a result, the effects of sensor failures can be compensated for and the transient system performance can also be tunable by adjusting design parameters. To the best our knowledge, this is the first adaptive backstepping scheme capable of tolerating unknown sensor failures, and this also enlarges the nonlinear systems currently studied by using backstepping approach.

2. Preliminaries and problem formulation

Consider the SISO nonlinear system which can be linearly parameterized by the parameter θ:

$$\begin{aligned}
\dot{x}_1 &= x_2 + \theta^T f_1(x_1)\\
\dot{x}_i &= x_{i+1} + \theta^T f_i(x_1, \bar{x}_i)\\
\dot{x}_n &= \beta(u+d) + \theta^T f_n(x_1, \bar{x}_n)\\
y &= x_1
\end{aligned} \tag{1}$$

where $i = 2, \ldots, n-1$, $\bar{x}_i = [x_2, \ldots, x_i]$, for $2 \le i \le n$, $x = [x_1, \bar{x}_n^T]^T$ is the state and $y \in R$ is the measured output by the sensor, $u \in R$ is the input of system, $f_1(x_1) \in R^p$ and $f_i(x_1, \bar{x}_i) \in R^p$ for $i = 2, \ldots, n$, are known smooth nonlinear vector-valued functions, $\theta \in R^p$ is unknown parameter vector, β is the known control gain, and $d(t) \in R$ denotes the external disturbance acting on the control input channel with unknown bound d_M, called input disturbance.

Remark 1. System (1) has been widely investigated in many references Wen et al. (2011), Zhang et al. (2014) and Zhou et al. (2004). It can be used to describe many practical nonlinear systems such as chemical reactors, wind tunnel and robotic systems.

In this paper, multiplicative sensor failures are considered, the definition of which is given as follows.

Definition 1 (*Sensor Multiplicative Fault Dong & Yang, 2015, Wu & Zhang, 2005*)**.** The sensor for measuring system variable $\gamma(t) \in R$ is said to have fault at the time T_f, if the output of the sensor

$$\gamma^F(t) = \rho\gamma(t),\ \ 0 < \rho < 1,\ \ \forall t > T_f \tag{2}$$

According to Definition 1, the failures that may occur on the sensor in system (1) are modeled as

$$y^F(t) = \rho y(t),\ \ 0 < \rho < 1,\ \ \forall t > T_f \tag{3}$$

The control objective is to design an observer-based adaptive failure compensation controller such that the resulting closed-loop system is globally uniformly ultimately bounded (GUUB) in the presence of sensor failure (3), while guaranteeing the system output y converges to an adjustable neighborhood of the origin.

To achieve the control objective, the following assumptions are imposed.

Assumption 1. For the considered sensor fault model (3), the failure factor ρ satisfies $\rho \ge \underline{\rho}$, where $\underline{\rho}$ is a known positive constant.

Remark 2. For sensor failure, mainly three situations are considered: partial failure case, i.e., partial degradation of the sensor, the outage case and the stuck fault, which makes the output of a sensor stay at a constant value. In case of the latter two failures, the control system is no longer observable. Therefore, a partial failure case model described by Eq.(3) is used in this paper.

Define $\chi_1 = \rho x_1$ and $\kappa = 1/\rho$. Then system (2) is equivalent to

$$\begin{aligned}
\dot{\chi}_1 &= \rho x_2 + \theta_1^T f_1(\kappa\chi_1)\\
\dot{x}_i &= x_{i+1} + \theta_2^T f_i(\kappa\chi_1, \bar{x}_i),\\
\dot{x}_n &= \beta(u+d) + \theta_n^T f_n(\kappa\chi_1, x)\\
y^F &= \chi_1
\end{aligned} \tag{4}$$

where $i = 2, \ldots, n-1, \theta_1 = \rho\theta, \theta_i = \theta, i = 2, \ldots, n$. In addition, for convenience, we define $\theta_i = [\theta_{i1}, \ldots, \theta_{ip}]^T$ in the following. Note that only χ_1 is available for controller design.

Next, we focus on the adaptive sensor failure compensation controller design for system (4). To facilitate the control system design, we need the following extra assumptions for system (4).

Assumption 2. Assume that functions $f_i, i = 1, \ldots, n$ satisfy the global Lipschitz condition, that is, there exist some known constants L_i, such that for $\forall X_1, X_2$, the following inequality holds:

$$\|f_i(X_1) - f_i(X_2)\| \le L_i\|X_1 - X_2\|$$

where $\|X\|$ denotes the 2-norm of a vector X.

Assumption 3. There exists a known positive constant θ_M such that $\|\theta\| \le \theta_M$.

Remark 3. Assumption 2 is a similar assumption in the study of output feedback controller design for nonlinear strict-feedback systems in Li, Tong, and Li (2014) and Tong, Huo, and Li (2014). Assumption 3 can be found in references Adetola, DeHaan, and Guay (2009) and Loh, Annaswamy, and Skantze (1999).

The following lemma is important for developing our results.

Lemma 2.1 (*Lin & Qian, 2002*)**.** *For any real-valued continuous function $f(x, y)$ where $x \in R^m$, $y \in R^n$, there are smooth real-valued functions $c(x) \ge 1$, $d(y) \ge 1$ such that $|f(x, y)| \le c(x)d(y)$.*

3. Adaptive state observer design

Noting that all states $x_1, \ldots, x_n$ in system (4) are not available for feedback design, therefore, a state observer should be established to estimate the states, and then an adaptive output feedback failure compensation scheme is investigated based on the designed state observer.

The state observer is designed for (4) as follows

$$\begin{aligned}
\dot{\hat{x}}_1 &= \hat{\rho}\hat{x}_2 + \hat{\theta}_1^T f_1(\hat{\kappa}\chi_1) + k_1(y^F - \hat{x}_1)\\
\dot{\hat{x}}_i &= \hat{x}_{i+1} + \hat{\theta}_i^T f_i(\hat{\kappa}\chi_1, \bar{\hat{x}}_i) + k_i(y^F - \hat{x}_1)\\
\dot{\hat{x}}_n &= \beta u + \hat{\theta}_n^T f_n(\hat{\kappa}\chi_1, \hat{x}) + k_n(y^F - \hat{x}_1)
\end{aligned} \tag{5}$$

where $i = 2, \ldots, n-1$, $\hat{x}_1$ is the estimate of χ_1, $\bar{\hat{x}}_i = [\hat{x}_2, \ldots, \hat{x}_i]^T$ is the estimate of $\bar{x}_i = [x_2, \ldots, x_i]^T$, and $\hat{\theta}_i$, $\hat{\rho}$ and $\hat{\kappa}$ are the estimates of θ_i, ρ and κ, respectively.

Construct observer error as $e = [e_1, \ldots, e_n]^T$ with $e_1 = \chi_1 - \hat{x}_1$ and $e_i = x_i - \hat{x}_i$, $2 \le i \le n$. Then from (4) and (5), the observer error equation is expressed as

$$\dot{e} = Ae + B_1\tilde{\rho}\hat{x}_2 + F^T(\hat{\kappa}_1\chi_1, \bar{\hat{x}}_n)\tilde{\Theta} + \Delta F^T\Theta + B_n\beta d \tag{6}$$