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Joint state and fault estimation for time-varying nonlinear systems with randomly occurring faults and sensor saturations ☆

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ABSTRACT

This paper is concerned with the joint state and fault estimation problem for a class of uncertain time-varying nonlinear stochastic systems with randomly occurring faults and sensor saturations. A random variable obeying the Bernoulli distribution is used to characterize the phenomenon of the randomly occurring faults and the signum function is employed to describe the sensor saturation due to physical limits on the measurement output. The aim of this paper is to design a locally optimal time-varying estimator to simultaneously estimate both the system states and the fault signals such that, at each sampling instant, the covariance of the estimation error has an upper bound that is minimized by properly designing the estimator gain. The explicit form of the estimator gain is characterized in terms of the solutions to two difference equations. It is shown that the developed estimation algorithm is of a recursive form that is suitable for online computations. In addition, the performance analysis of the proposed estimation algorithm is conducted and a sufficient condition is given to verify the exponential boundedness of the estimation error in the mean square sense. Finally, an illustrative example is provided to show the usefulness of the developed estimation scheme.

1. Introduction

In modern large-scale industrial systems, the system states are not always available and the measurement outputs are often subject to stochastic noises mainly due to physical constraints, costs for measuring and environmental complexities (Caballero-Águila, Hermoso-Carazo, Jiménez-López, Linares-Pérez, & Nakamori, 2010; Gao & Ho, 2006). Therefore, the state estimation or filtering problem has long been one of the foundational research problems in signal processing and control areas that have received a great deal of research attention (Hu, Wang, Alsaadi, & Hayat, 2017; Shi, Zhang, Chadli, & Agarwal, 2016). The past decades have witnessed the rapid development of various estimation and filtering algorithms that have been successfully applied in engineering practice such as signal processing, navigation and control of vehicles, guidance and econometrics. According to the performance indices, the filtering algorithms can be generally categorized into the main streams of Kalman filtering (Caballero-Águila, Hermoso-Carazo, & Linares-Pérez, 2015; Kalman, 1960), extended Kalman filtering (Reif, Günther, Yaz, & Unbehauen, 1999; Wang, Liu, Liu, Liang, & Vinciotti, 2009), particle filtering (Xia, Deng, Li, & Geng, 2013), set-valued filtering (Calafiore, 2005), H_∞ filtering (Wang, Shen, & Liu, 2012; Zhang, Zhuang, & Shi, 2015), and non-Gaussian filtering (Einicke, 2015). To be more specific, the celebrated Kalman filtering algorithm has been proposed in Kalman (1960) for linear stochastic systems with Gaussian noises. Based on polynomial observations, the mean-square filters have been designed in Basin, Loukianov, and Hernandez-Gonzalez (2013) and Basin, Maldonado, and Karimi (2011) for nonlinear polynomial systems with, respectively, white Poisson processes and Wiener processes. In Wang et al. (2009), the extended Kalman filtering approach has been developed for nonlinear dynamic gene regulatory networks to identify the model parameters and the actual value of gene expression levels. The stochastic stability of the extended Kalman filter

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has been discussed in Reif et al. (1999) for nonlinear stochastic systems, and the corresponding results have then been extended to the case where the measurement outputs suffer from intermittent observations. Recently, the H_∞ filter has been constructed in Zhang et al. (2015) for a class of discrete-time linear switched systems with the persistent dwell-time switching signals.

On another research frontier, sensors may not always be capable of providing signals with unlimited amplitudes due to physical/technological restrictions. The occurrence of the sensor saturations could impose severe degradations on the system performance if not handled properly (Dong, Wang, & Gao, 2012; Wang et al., 2012). Consequently, the filtering problems with sensor saturations have been gaining some initial research attention and some preliminary results have appeared in the recent literature (Niu, Ho, & Li, 2010; Wang et al., 2012). The main challenge with this topic is how to design a filtering algorithm by making full use of the available information about the sensor saturations (e.g. types, intensities and distributions) subject to specified performance requirements (e.g. minimized variance and guaranteed H_∞ constraints). For example, in Dong et al. (2012), the fault detection filter has been designed for discrete-time Markovian jump systems with sensor saturations, incomplete knowledge of transition probabilities and randomly varying nonlinearities. The state estimation problem has been considered in Hu, Chen, and Du (2014) for a class of time-invariant systems with distributed sensor delays by using a linear matrix inequality (LMI) approach, where the performance specification (i.e. variance) and sensor saturations have not been considered. Recently, an effective H_∞ filtering algorithm has been developed in Wang et al. (2012) to address the phenomena of the randomly occurring sensor saturations and missing measurements in a unified framework. It is worth mentioning that, so far, most reported results have been concerned with *time-invariant systems* only and the corresponding filter design issue for *time-varying* systems with variance constraints has not been paid adequate research attention despite the fact that almost all real-world systems have certain structures/parameters that are time-varying.

Apart from the sensor saturations, component faults constitute another common cause for performance deteriorations or even instability of the engineering systems (Gao & Ho, 2006; Hamouda, Ayadi, & Langlois, 2016; Shi, Shi, & Zhang, 2015; Yao, Wu, & Zheng, 2011; Yaramasu, Cao, Liu, & Wu, 2015). Therefore, in the past decade, considerable research effort has been devoted to the fault detection and estimation (FDE) problems, see e.g. Jiang, Zhang, and Shi (2011), Karimi (2010), Karimi (2011), Yin, Zhu, and Kaynak (2015) and the references therein. Among others, a new estimation algorithm based on augmented approach has been presented in Gao and Ho (2006) for descriptor nonlinear systems with sensor fault and efficient fault-tolerant control approach with compensation mechanism has been developed in Zuo, Ho, and Wang (2010) for singular systems with actuator saturation and nonlinear perturbation. The sensor fault-tolerant speed tracking control scheme has been given in Kommuri, Defoort, Karimi, and Veluvolu (2016) for an electric vehicle powered by a permanent-magnet synchronous motor and novel estimation method has been proposed in Youssef, Chadli, Karimi, and Wang (2017) for Takagi–Sugeno fuzzy model with time-varying sensor fault. Moreover, in Karimi (2010) and Karimi (2011), the fault detect filters have been designed for uncertain systems with mixed time-varying delays and nonlinear perturbations by using LMI method. Recently, the FDE problems for *time-varying* systems have stirred much research interest owing to the increasing importance of the time-varying behaviors in practical system modeling. Up to now, a few efficient FDE schemes have been proposed for linear/nonlinear time-varying systems. For example, the finite-horizon H_∞ fault estimation problems have been studied in Shen, Ding, and Wang (2013) and Zhong, Zhou, and Ding (2010) for linear discrete time-varying stochastic systems by using the Krein-space theory.

In parallel to the recent development of the networked control systems (Gao & Chen, 2008), some initiatives have been made on the network-induced nature of the fault signals. Recently, it has been shown in Dong, Wang, Ding, and Gao (2014) that the occurrence of the faults could be intermittent or even random especially in networked environments due to unpredictable parameter fluctuations or structural changes over the networks. In Dong et al. (2014), the effects from the randomly occurring faults (ROFs) onto the estimation performance have been examined by proposing an H_∞ fault estimation algorithm over a finite horizon, where a backward recursive Riccati difference equation approach has been employed. So far, to the best of the authors' knowledge, the problem of *joint* state and fault estimation problem for *time-varying* systems with *ROFs* has not been addressed yet, not to mention the case when the underlying system is also subject to sensor saturations, parameter uncertainties as well as nonlinearities. Besides, it should be mentioned that most of existing methods fail to provide the performance analysis of estimation algorithm for addressed time-varying nonlinear systems with certain complexities. As such, the purpose of this paper is to shorten such a gap by developing a design scheme for effective estimators capable of jointly estimating system states and fault signals with help from the difference equation method and presenting a performance analysis criterion.

Motivated by the above discussions, in this paper, we aim to investigate the problem of joint state and fault estimation for a class of uncertain time-varying nonlinear systems with ROFs and sensor saturations. The phenomenon of randomly occurring fault is characterized by using a Bernoulli random variable with known occurrence probability. The focus is on designing a recursive estimator to simultaneously estimate the system states and fault signals such that, for all admissible parameter uncertainties, nonlinearities, ROFs and sensor saturations, an upper bound of the estimation error covariance is guaranteed and then minimized at each time step by properly choosing the estimator gain. The main novelties of this paper are highlighted as follows: (1) the addressed model is comprehensive which accounts for several well-known phenomena (i.e. parameter uncertainties, nonlinearities, ROFs and sensor saturations) contributing to system complexities in a unified framework; (2) a new compensation scheme is proposed to attenuate the effects from both the ROFs and the sensor saturations onto the estimation performance; (3) a sufficient criterion is given to quantify the boundedness analysis of the estimation error in the mean square sense and an upper bound of the bias of developed estimation is presented; and (4) the designed estimation algorithm is of a recursive feature suitable for online computations. Finally, simulations are provided to demonstrate the usefulness of proposed estimation method.

Notations. The notations used throughout this paper are standard. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. $\|\cdot\|$ is the Euclidean norm of real vectors or the spectral norm of real matrices. For a matrix P, P^T and P^{-1} represent its transpose and inverse, respectively. $\mathbb{E}\{x\}$ is the mathematical expectation of the stochastic variable x and $\mathbb{E}\{x|y\}$ is the mathematical expectation of the stochastic variable x conditional on y. I and 0 stand for the identity matrix and the zero matrix with appropriate dimensions, respectively. $\mathrm{tr}(P)$ represents the trace of matrix P. $\mathrm{diag}\{P_1, P_2, \ldots, P_N\}$ represents a block-diagonal matrix with matrices $P_1, P_2, \ldots, P_N$ on the diagonal. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. Problem formulation and preliminaries

In this paper, we consider the following class of discrete uncertain time-varying nonlinear systems:

$$\vec{x}_{k+1} = (\vec{A}_k + \Delta\vec{A}_k)\vec{x}_k + \vec{g}(\vec{x}_k) + \alpha_k\vec{F}_k f_k + \vec{B}_k\omega_k \tag{1}$$

$$\vec{y}_k = \sigma(\vec{C}_k\vec{x}_k) + \nu_k \tag{2}$$