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Event-based distributed recursive filtering for state-saturated systems with redundant channels

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ABSTRACT

In this paper, the event-based distributed recursive filtering problem is investigated for a class of discrete-time state-saturated systems subject to random occurring nonlinearities and measurement losses over the wireless sensor network. In the addressed measurement model, the sensors are assumed to have redundant communication channels that are helpful in increasing the probability of successfully delivering the measurements. At each intelligent node, the local estimation is obtained based on its own measurement and those transmitted from its neighbors according to the sensor topology. In order to reduce the bandwidth consumption and estimator update frequencies, an event-based signal transmission strategy is employed as opposed to the traditional time-based one. An upper bound for the estimation error covariance is constructed at each time step, which is shown to be the solution of a Riccati-like difference equation. Subsequently, the estimator parameter is designed to minimize such an upper bound. Moreover, the performance of the proposed estimator is analyzed by discussing how the packet losses of the measurements affect the obtained upper bound of the error covariance. Finally, a numerical simulation is exploited to show the effectiveness of the proposed distributed filter design algorithm.

1. Introduction

Over the past decades, the wireless sensor networks have attracted considerable attention due to their extensive applications in various fields such as multiple autonomous robot, target surveillance, air pollution monitoring, forest fire detection and so on [4,5]. A typical wireless sensor network usually consists of a large number of intelligent nodes geographically distributed in a large region, where each node is equipped with a radio transceiver, a sensor, a microprocessor and an energy source. Recently, a focus of research over such networks has been on the distributed estimator design problem. Compared with the traditional centralized filtering approach, the distributed filtering method has some advantages including better survivability and reliability, stronger fault-tolerance and lower communication and computation burdens, see e.g., [1,2,12,28] for more details. The essential idea of the distributed fusion estimation is to perform the local filters and weight the local state estimates to obtain a global optimal or suboptimal state estimate [11,15,17]. In sensor network environments, each local filter is executed by making use of the measurement data not only from its own node but also from its neighboring peers according to the topology of the network. As such, the key for designing an appropriate estimator lies in how to tackle the complex couplings between the nodes and also take the topology information into account [38].

State saturation, which is a typical nonlinear characteristic, occurs very often in a lot of practical dynamic systems where the states are constrained into a bounded set. If not adequately considered, the state saturation phenomenon may deteriorate the filter/controller performance or even lead to instability. Up to now, some research attention has been focused on the synthesis and analysis problems for the systems with state saturation, see, e.g., [7,8,19,31] and the references therein. For example, in [8], the finite-horizon H_∞ filtering problem for a class of state-saturated systems has been addressed by bounding the estimation error and solving a set of nonlinear matrix inequalities. In [7], by introducing a matrix whose infinity norm is not bigger than 1, a dissipative controller has been designed for the discrete time-varying state-saturated systems. In addition to the state saturation, the

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so-called random occurring nonlinearity (RON) is another major factor bringing a high-degree of complexity for dynamic system modeling [7,8]. In fact, the RONs are encountered frequently in engineering practice and caused by many factors including high maneuverability of the moving target, random system failures and sudden changes of the environment. Generally, the random nature of the RONs is related to the system states and therefore adds great challenges for the filter/controller design.

In many practical networked control systems, due to the limited bandwidth and fluctuation of the network conditions, the sensor outputs sometimes contain noises only because the data communication from the tracked plants to the sensor node experiences random faults or packet losses. To increase the probability of successful data communication, redundant communication channels have recently received particular research attention. It has been demonstrated that the performance of a controlled system with such channels is substantially better than that with the single channel. As such, the scheme of redundant transmission channels has been extensively investigated and a number of results have been reported in the literature, see e.g. [30,41]. For example, a communication protocol for transmitting the information through multiple paths has been proposed in [26] to handle the controller design problem for the networked control systems based on the average cost optimality criterion. Furthermore, in [32], a robust model predict control algorithm has been developed under redundant channel transmission with applications in direct current motor systems. In [27], a new hybrid adaptive modulation and a diversity scheme have been proposed for the systems with multiple faded channels to improve the signal-to-noise ratio and achieve a higher spectral efficiency. As for the state estimation problem, in spite of its advantages for improving the filter performance, the corresponding results have been very few. In [40], by using the scaled small gain theorem, a distributed H_∞ filter has been designed for fuzzy time-delay systems with two communication channels. It has been shown in [40] that, compared with the filter with single channel, the H_∞ performance has been much improved. So far, for the systems with more than two communication channels, to the best of the authors' knowledge, no available results have been reported due probably to the computational complexity.

In a traditional sensor network, each local estimator needs the data from its neighbors, and such data is transmitted based on a given transmission logic. Up to now, there have been mainly two different transmission strategies adopted in data communication: time-based transmission strategy and event-based transmission strategy [34]. The time-based strategy means that the data sending action is determined by a predefined time schedule. If neither the communication bandwidth nor the power storage is the major concern, this scheme is useful in practice for its some advantages such as quasi-deterministic behavior and easy implementation. However, to reduce manufacturing costs, the node involved in a wireless sensor network usually has limited communication capability, computation capability and battery life. Therefore, time-based communication strategy becomes less useful because it could lead to excessively unnecessary data transmissions and numerical computations that would add extra burdens to the systems [6,14]. Event-based strategy, on the other hand, provides an alternative communication logic where the transmission action will be invoked if and only if the current signal deviates from the previous transmitted value by a given level. Since the event-based scheme can reduce communication bandwidth usages and estimator update frequencies, in the past decade, a growing number of results about the applications of the event-based schedules have been available in the literature [23,36].

Summarizing the above discussions, although the control problem for the system with redundant communication channels has gained initial research interest, the corresponding filtering problem for state-saturated systems over wireless sensor network has not been adequately investigated yet, not to mention the consideration of the event-based mechanism. Moreover, the nonlinearities caused by the state saturation add substantial difficulties to the distributed estimator design, which are further complicated by the challenges brought from the even-based transmission strategy as well as RONs. Therefore, in this paper, we endeavour to look into the distributed filtering problem for the state-saturated systems with redundant channels according to the event-based mechanism. Note that, in [10], the event-triggered distributed state estimation problem has been considered for a class of time-varying systems with redundant channels, where the state saturation has not been considered and the minimum variance constraints on the estimation errors have not been discussed.

The main contributions of this paper can be summarized as follows: (1) the sensors measuring the tracked plant contain redundant communication channels, and sets of Bernoulli random variables are used to describe the random packet losses in each channel; (2) the distributed filtering algorithm for the state-saturated system is developed and an upper bound for the filtering error covariance is presented by solving a set of Riccati-like difference equations; (3) the relationship between the performance of the proposed distributed estimator and the probability of successfully delivering the measurements for each sensor is analytically evaluated.

Notation. The notations used in this paper are standard. $\mathbb{R}^n$ and $\mathbb{R}^{m\times n}$ denote, respectively, the n-dimensional Euclidean space and the set of all $m \times n$ real matrices. For a matrix A, A^T, A^{-1}, $\rho(A)$, $\sigma_{\max}(A)$, $\|A\|$ and $\text{tr}\{A\}$ denote the transpose, the inverse, the spectral radius, the largest singular value, the spectral norm and the trace, respectively. The notation $A > B$ (respectively, $A \geq B$), where A and B are symmetric matrices, means that $A - B$ is positive definite (respectively, positive semidefinite). $\circ$ stands for the Hadamard product with definition $[A\circ B]_{ij} = A_{ij}B_{ij}$. I and 0 are the identity matrix and zero matrix with compatible dimensions, respectively. $\mathbb{E}\{x\}$ stands for the expectation of the random variable x. $\|x\|$ refers to the Euclidean norm of vector x. $\|A\|$ denotes the spectral norm of matrix A, and $\|x\|$ refers to the Euclidean norm of vector x. The notation $\text{diag}\{X_1, X_2, \cdots, X_N\}$ stands for a block-diagonal matrix with matrices $\{X_1, X_2, \cdots, X_N\}$ on the diagonal.

2. Problem formulation and preliminaries

Consider the following discrete time-varying state-saturated system:

$$x_{k+1} = \sigma(A_k x_k + f(x_k, \xi_k)) + \Gamma_k w_k \tag{1}$$

where $x_k \in \mathbb{R}^n$ is the system state to be estimated, $\xi_k \in \mathbb{R}^n$ is a zero mean noise sequence, and $w_k \in \mathbb{R}^p$ is a zero mean additive noise with covariance $Q_k \geq 0$. A_k and Γ_k are known system matrices of appropriate dimensions. The random nonlinearity $f(x_k, \xi_k)$: $\mathbb{R}^n \times \mathbb{R}^n \mapsto \mathbb{R}^n$ satisfies $f(0, \xi_k) = 0$ and has the following first moment for all x_k:

$$\mathbb{E}\{f(x_k, \xi_k)|x_k\} = 0 \tag{2}$$

with the covariance given by

$$\mathbb{E}\left\{f(x_k, \xi_k)f^T(x_k, \xi_k)|x_k\right\} = \sum_{i=1}^{r} \Pi_{i,k} x_k^T \Omega_{i,k} x_k \tag{3}$$

where r is a known positive integer, $\Pi_{i,k}$ and $\Omega_{i,k}$ $(i = 1, 2, \cdots, r)$ are known positive semidefinite matrices of appropriate dimensions. The saturation function $\sigma(\cdot)$: $\mathbb{R}^n \mapsto \mathbb{R}^n$ is defined as

$$\sigma(s) \triangleq [\sigma_1(s_1) \quad \sigma_2(s_2) \quad \cdots \quad \sigma_n(s_n)]^T \tag{4}$$

where

$$\sigma_i(s_i) = \text{sign}(s_i)\min\{s_{i,\max}, |s_i|\} \tag{5}$$