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Fault detection filter design for data reconstruction-based continuous-time networked control systems

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ABSTRACT

This paper is concerned with observer-based fault detection filter design for a continuous-time networked control system (NCS) by taking packet dropouts and network-induced delays into account. An observer-based fault detection filter and a reference residual model are introduced to construct a novel model for the continuous-time NCS. To reduce the time for fault detection, a new data reconstruction scheme is proposed and the corresponding closed-loop model is established. Based on the established models, new fault detection filter design criteria are derived to asymptotically stabilize the residual system. The mutually exclusive distribution characteristic of interval time-varying delays is made full use to deal with integral inequalities for products of vectors. The designed fault detection filters can guarantee the sensitivity of the residual signal to faults. Simulation results illustrate the effectiveness of the proposed observer-based fault detection filter design.

1. Introduction

Networked control systems (NCSs) are spatially distributed systems in which sensors, actuators, and controllers are connected through a shared band-limited digital communication network. Introducing the communication network into control systems has several advantages, such as flexibility in communication architecture, plug and play devices, and ease of system diagnosis and maintenance, and so on. NCSs are the subject of intensive research and many results are available about stability analysis and/or stabilization [1,16,17,27,34,36,42], sampled-data control [4,5], sensors/actuators assignment [7,8,10], quantization [9,29], packet dropouts and network-induced delays [26,31,38,41,43–45], and the non-uniformly distributed interval time-varying delay [39,40].

For NCSs, the occurrence of the sensor fault or the actuator fault is usually unavoidable. Then, it is of paramount importance to study how to detect the occurrence of faults in time. The fault detection for traditional control systems has been paid much attention and some interesting results have been reported, see [14,18,20,30,46] and the references therein. On the other hand, some nice results dealing with fault detection for NCSs have been obtained. For example, Dong et al. [2] was concerned with the network-based robust fault detection problem for discrete-time Takagi–Sugeno fuzzy systems. He et al. [12] studied the problems of fault detection, isolation, and estimation for discrete time-varying networked sensing systems. Huang and Nguang [13] investigated robust fault estimation for NCSs with network-induced delays. Liu et al. [21] was devoted to the fault

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detection of linear systems over networks with bounded packet dropouts. Long and Yang [22,23] investigated the problem of fault detection in finite frequency domain for NCSs. Mao et al. [24] proposed a method for the fault detection of a nonlinear NCS. Wang et al. [32] was devoted to fault detection of NCSs subject to uncertain time-varying network-induced delays. Wang et al. [33] proposed a so-called packet-based periodic communication strategy to design optimal observer-based residual generators. It should be mentioned that discrete-time systems are considered in [2,12,22,24,33], while discretized NCSs are considered in [21,23,32]. Moreover, packet dropouts and/or network-induced delays are neglected in some of the above mentioned work. For continuous-time NCSs considering packet dropouts and network-induced delays simultaneously, how to propose an appropriate observer-based fault detection filter design scheme is interesting and practically valuable, which is the first motivation of this paper.

For NCSs with faults, the feasible fault signals are included in the measurement outputs $y(t_{k-1}),\ y(t_k), \ldots$, where k denotes a positive integer, and $y(t_{k-1}),\ y(t_k), \ldots$ are adopted by the fault detection filter (FDF) to detect the occurrence of faults. For a specific time interval $[t_k + \tau_k, t_{k+1} + \tau_{k+1})$, where t_k and τ_k denote the sampling instant and the length of the network-induced delays, respectively, if we combine the recently received measurement output $y(t_k)$ and the formerly received measurement output $y(t_{k-1})$ together, which is named as data reconstruction in this paper, and transmit the data reconstruction-based measurement outputs to the FDF, enlarged fault signals will be received by the FDF and the fault detection time will be reduced correspondingly. However, such a data reconstruction scheme has not been considered in the literature. To improve the fault detection performance of NCSs, one should take the data reconstruction scheme into account, which is the second and main motivation of this paper.

For continuous-time NCSs with $t \in [t_k + \tau_k, t_{k+1} + \tau_{k+1})$, the artificial delay $\tau(t) = t - t_k$, which is named as an interval time-varying delay, is usually introduced in the literature to study stability/stabilization of considered systems. Suppose that $\tau(t) \in [\tau_m, \eta)$, where τ_m and η denote known constants. Divide $[\tau_m, \eta)$ into ρ equidistant time intervals with ρ denoting a given positive integer. One can conclude that for a specific instant t, $\tau(t)$ can not be included simultaneously in two different time intervals derived above, in what follows, we refer to such a phenomenon as mutually exclusive distribution. When dealing with integral inequalities for products of vectors, how to make full use of the mutually exclusive distribution characteristic of interval time-varying delays to derive less conservative results is of paramount importance and still unsolved.

This paper is concerned with observer-based fault detection filter design for a continuous-time NCS under consideration of packet dropouts and network-induced delays. By introducing an observer-based fault detection filter, a reference residual model, and a new data reconstruction scheme, new closed-loop models for the considered NCS are established. Based on the established models, fault detection filter design criteria are proposed to asymptotically stabilize the residual systems.

The main contributions of this paper are summarized as follows:

- By taking packet dropouts and network-induced delays into consideration, and proposing a new data reconstruction scheme, closed-loop models for a continuous-time NCS with actuator faults are established.
- The mutually exclusive distribution characteristic, which introduces less conservatism, of interval time-varying delays is made full use to deal with integral inequalities for products of vectors.
- The observer-based fault detection filter design criteria are proposed. The designed fault detection filters can guarantee the sensitivity of the residual signal to faults.

The remainder of this paper is organized as follows. By introducing the data reconstruction scheme, Section 2 establishes new models for a continuous-time NCS considering faults, packet dropouts, and network-induced delays. Based on the established models, Section 3 is concerned with observer-based fault detection filter design. Section 4 is concerned with data reconstruction-based fault detection filter design. The results of numerical simulation are presented in Section 5. Conclusions are drawn in Section 6.

Notation. $\mathbb{R}^n$ denotes n-dimensional Euclidean space; $\mathbb{R}^{n\times m}$ is the set of all $n \times m$ real matrices. I and 0 represent an identity matrix and a zero matrix with appropriate dimensions, respectively. $*$ denotes the entries of a matrix implied by symmetry. Matrices, if not explicitly stated, are assumed to have appropriate dimensions.

2. Modeling for an NCS with faults and data reconstruction

Consider a continuous-time NCS, whose faults are to be detected, described by

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + D_1\omega(t) + E_1 f(t) \\ y(t) = Cx(t) \\ x(t_0) = x_0 \end{cases} \tag{1}$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $y(t) \in \mathbb{R}^s$, $\omega(t) \in \mathbb{R}^p$, $f(t) \in \mathbb{R}^q$ are the state vector, control input vector, measurement output, disturbance, and actuator fault signal, respectively; $\omega(t)$ is assumed to belong to $L_2[t_0, \infty)$; $x_0 \in \mathbb{R}^n$ denotes the initial condition; A, B, D_1, E_1, and C are known constant matrices of appropriate dimensions. C^T is assumed to be full column rank and (A, C) is detectable.

Throughout this paper, we introduce a buffer at the fault detection filter to store the outputs of the FDF and the recently received measurement outputs. Let $t_k,\ t_k + h,\ t_k + 2h,\ t_k + \cdots,\ t_{k+1},\ t_{k+1} + h,\ t_{k+1} + 2h,\ t_{k+1} + \cdots\ (k = 0, 1, 2, \ldots)$ denote the sampling instants, where h is the length of the sampling period. Suppose that the measurement outputs which are sampled at