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Model-reduced fault detection for multi-rate sensor fusion with unknown inputs

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ABSTRACT

In multi-sensor fusion, it is hard to guarantee that all sensors work at the single sampling rate, especially in the distributive and/or heterogeneous case, and fault detection (FD) in multi-rate sensor fusion may face the existence of unknown inputs (UIs) in complex environment. Meanwhile, model reduction often refers to propose a possible lower-dimensional model to replace the original model without adding significant error in practical applications. By the fact that FD in dynamic systems should only focus on the fault-related controllability and observability characteristics, it is a good idea to obtain the fault-related controllable and observable subsystem via system decomposition (i.e., model reduction) for FD. Such a kind of model reduction not only guarantee the FD performance, but also reduce the system dimensions. To this end, we propose the model-reduced fault detection (MRFD) problem for multi-rate sensor fusion subject to UIs and faults imposed on the actuator and sensors. Our aim is to design a fast and computation-effective FD scheme based on the reduced model. We use the singular decomposition for UI decoupling, and then obtain the fault-related subsystem via controllability and observability decomposition. And then the multi-rate observer (MRO) with causality constraints is designed. Different from the traditional observer used for FD, the proposed MRO outputs the fault-related partial state estimate as soon as any a sensor measurement is received, resulting in fast and computation-effective FD. Furthermore, conditions for the existence of a stable MRO, fault-to-state controllability, and fault detectability are explored. A simulation example for simplified longitudinal flight control system and method comparison with the existing multi-rate FD algorithms show the effectiveness of the proposed MRFD method.

1. Introduction

In many complex systems such as the multi-sensor fusion system it is often unrealistic to guarantee all sensors operating at one common rate [1]. For example, for signals with different bandwidths, better trade-offs between performance and implementation cost can be obtained using A/D and D/A converters at different rates. On the other hand, for processed/estimated quantities, sometimes users may specify rates which are different from the sampling rates of sensors. Therefore the issue on multi-rate data fusion arises and has been paid much attention especially in the past decade [2–4].

The main challenge in conditioning monitoring systems of multi-sensor fusion is FD, which is the precondition of reliable multi-rate fusion. Generally speaking, a FD process consists of constructing a residual signal which can then be compared with a predefined threshold. When the residual signal exceeds the threshold, the fault is detected and an alarm is generated. However, most of the existing researches about FD for multi-rate sensor fusion systems with UIs use the entire state instead of the fault-related state for observer design and FD after UI decoupling, which has a large computation cost. In fact, we should only focus on the fault-related partial state since the remainder of the state is of no use in FD. Furthermore, conditions for a stable observer, fault-to-state controllability fault-to-measurement observability are quite important factors in FD and hence should be discussed. Motivated by the above observations, we investigate the problem of model-reduced FD of multi-rate sensor fusion with UIs and faults.

The purpose of model reduction is to obtain a lower-dimensional system which replaces a high-order system according to some given criterions [5–7]. Since for FD detection problems in multiple sensor systems with unknown inputs, the fault information can only be obtained from the fault-related subsystems. The model reduction here means to delete everything

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but the fault-to-state controllable, fault-to-measurement observable and UI-decoupled subsystems by singular value, controllability and observability canonical decompositions. The advantage of such a model reduction is that we can reduce the dimension of the system without influencing the FD performance, resulting in the simplification of the system model complexity though at the cost of extra decomposition computation. Fortunately, such extra computation is off-line. Furthermore, an MRO with causality constraint is designed for fast FD based on the reduced subsystem. The main contributions are listed as follows:

- the dimension of the subsystem after model reduction is smaller than the original multi-rate sensor system though at the cost of some extra computation. Fortunately, such extra computation brought by model reduction can be implemented off-line, and the online calculation only contains simple estimate update and residual evaluation;
- the developed MRO is UI-decoupled and fault-related. In other words, the decoupled UI has no effect on FD and only the fault-related partial state is used for FD, resulting in the accurate and computation-efficient FD;
- the existence conditions of the stable observer and fault controllability are explored, which are looser than the existing literature [34] and will supply the guidance of sensor type, sampling rate and sensor networking.

This paper is organized as follows. The related work is briefly reviewed in Section 2, the problem is formulated in Section 3 and then reformulated via model reduction in Section 4. Section 5 describes the scheme of the model-reduced FD. It includes the MRO design, residual generation and residual evaluation. Section 6 demonstrates the effectiveness of the proposed scheme via some numerical experiments, and some conclusions are drawn in Section 7.

Throughout this paper, superscripts “-1”, “T” and “$*$” represent inverse, transpose, and conjugate transpose operations, respectively; “$I_{m\times n}$” and “$0_{m\times n}$” represent identity and zero matrices with $m\times n$ dimensions, respectively; $A_{i,j}$ presents (i, j)-th subblock of matrix A; subscript “j ” denotes matrix or variable related to the j-th sensor; diag{·} denotes diagonal matrix; rank{·} represents matrix rank; $\bigotimes$ stands for Kronecker product; $\mathbb{C}$ denotes set of complex numbers.

2. Related work

Multi-sensor data fusion is a method of integrating signals from multiple sources that allow for perception or measurement of the changing environment into a single signal or piece of information [8]. Definitely, the estimation and detection are the main topics of multi-sensor data fusion.

Regarding the multi-rate sensor fusion, much attention has been paid, especially in the last decade. State estimation approach based on dual-rate sensor measurements was proposed [9] and extended to deal with asynchronous multi-rate sensor measurements [10], where the ratio between the sampling rates of different sensors was allowed to be any positive integer. Accounting for out of sequence data and latent data, general asynchronous fusion estimation methods were put forward for multi-sensor systems [11,12]. Since different dynamic models always have different frequency properties in multiple model systems, the fast-rate sensor measurement was thus compressed to a slow-rate one with little or no accuracy degradation in low-frequency models, and hence results in multi-rate interacting multiple model estimators [13] and its target-tracking application to out-of-sequence GMTI data [14] or distributed fusion [15]. In the case that the updating rate of state estimates is different from the measurement sampling rate, the wavelet-transformation-based [16] and the optimal H_2/H_∞-based [17] estimation schemes were proposed. A linear minimum variance estimator was proposed for the four-rate estimation problem with the state updating rate, the measurement sampling rate, the estimate updating rate, and the estimate output rate [18]. For systems having measurement missing or packet losses, the multi-rate H_∞ filter method [19], its counterpart the linear minimum mean square error observer method [20], and the corresponding application to over-the-horizon radar target tracking [21] were developed, respectively. The optimal linear minimum variance estimators were designed for both centralized and decentralized fusion in the case of multi-rate packet dropouts [22] and stochastic correlated noises [23]. In addition, a two-stage distributed fusion estimation method was proposed for wireless sensor networks (WSNs) subject to data missing are presented, where the localized state estimates were obtained at a larger time scale and exchanged among neighboring nodes at a slower time scale for fast-rate data fusion [24]. For WSNs with nonuniform estimation rates, two fusion algorithms that can fuse available local estimates generated at different time scales were provided, allowing estimation rates at different sensors to be different from each other [25]. In general, the above researches are limited to the fault-free case.

Concerning the FD problem in multi-rate sensor systems subject to UIs , there are two commonly used strategies, i.e., decoupling the UI from the residual, or minimizing its influence on the residual while maximizing the influence of the fault on the residual. In the first strategy, the lifting technique is often used to convert the multi-rate system into a linear time-invariant (LTI) model with slow sampling rate, based on which a state observer was designed for residual generation [26,27] . However, the residual was updated at the same rate as the LTI model and the resultant FD was slow-rate. By adopting the left eigenvector assignment, a fast-rate residual generator based on multiple slow-rate sensors was designed [28]. In the second strategy, the parity-space based residual generator [29], the H_∞ optimal and causal residual generators [30] and the observer-based fault detection filter was presented where the residual was obtained by solving an H_∞/H_∞ or H_∞/H_- optimization problem [31]. A new form of multi-rate observer based FD scheme was presented for multi-sensor fusion subject to deterministic and stochastic uncertainties [32], and was extended to have the ability to tackle the problem of joint optimal state estimation and FD [33]. However, the fault controllability and detectability were not discussed. A bank of observers with different rates were designed where each observer was specialized for the corresponding sensor [34]. However, each observer just utilizes its corresponding sensor’s measurements, instead of all measurements from multi-rate sensors. It is not a good consideration for fast and reliable fault detection. For this reason, Nevertheless, the resultant fault-to-measurement observability and fault-to-state controllability conditions seems too stringent by the fact that FD of any a sensor is just based on measurements from itself, instead of all sensors’ measurements.

In addition, on another research front, with the rapid development of network technologies, more and more control systems are executed over communication networks. This kind of systems are called networked control systems (NCSs), which have many advantages such as low cost, reduced weight and power requirements, simple installation and maintenance, and high reliability [35]. In an NCS, data travel through the communication channels from sensors to the controller and/or from the controller to the actuators. However, since the network cable is of limited capacity, new interesting and challenging issues inevitably emerge for estimation and FD problem in NCSs, for example, the transmission delay, packet dropout, signal quantization, scheduling confusion, etc., giving rise to network-induced parameter uncertainties. Important progresses on dealing with these network-induced parameter uncertainties in estimation [36–45], FD [46–50] and the corresponding engineering