Automatica 85 (2017) 165–178

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

A data-driven approach to actuator and sensor fault detection, isolation and estimation in discrete-time linear systems☆

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ARTICLE INFO

Article history:
Received 21 May 2016
Received in revised form 29 April 2017
Accepted 3 July 2017

Keywords:
Data-driven methodology
Actuator and sensor fault diagnosis
Fault detection, isolation, and estimation
Linear discrete-time systems

ABSTRACT

In this work, we propose and develop data-driven explicit state-space based fault detection, isolation and estimation filters that are directly identified and constructed from only the available system input–output (I/O) measurements and through only the estimated system Markov parameters. The proposed methodology does not involve a reduction step and does not require identification of the system extended observability matrix or its left null space. The performance of our proposed filters is directly related to and linearly dependent on the Markov parameters identification errors. The estimation filters operate with a subset of the system I/O data that is selected by the designer. It is shown that our proposed filters provide an asymptotically unbiased estimate by invoking a low order filter as long as the selected subsystem has a stable inverse. We have derived the estimation error dynamics in terms of the Markov parameters identification errors and have shown that they can be directly synthesized from the healthy system I/O data. Consequently, our proposed methodology ensures that the estimation errors can be effectively compensated for. Finally, we have provided several illustrative case study simulations that demonstrate and confirm the merits of our proposed schemes as compared to methodologies that are available in the literature.

1. Introduction

Since the concept of autonomous fault diagnosis, also known as fault detection and isolation (FDI), has been introduced by Beard (1971), it has received a significant level of interest in the literature. Several excellent surveys have appeared that summarize the extensive literature on fault diagnosis of dynamical systems over the past decades (Gao, Cecati, & Ding, 2015a,b). The two main fault diagnosis categories are classified as model-based and data-driven approaches. The available model-based approaches have been reviewed and described in Hwang, Kim, Kim, and Seah (2010).

As engineering systems evolve and advance, it is becoming less likely that engineers have a detailed and accurate mathematical description of the dynamical system they work with. On the other hand, advances in sensing and data acquisition systems can generate and provide a large volume of raw data for most engineering applications. Consequently, one can find a significant interest and trend toward data-driven based approaches in various disciplines and problems, including the fault diagnosis domain.

The term "data-driven" covers a wide range of methodologies introduced in the literature. Some of the most important strategies are neural networks (Tayarani-Bathaie & Khorasani, 2015), fuzzy logic (Rodríguez Ramos, Domínguez Acosta, Rivera Torres, Serrano Mercado, Beauchamp Baez, Rifón, & Llanes-Santiago, 2016), and hybrid approaches (Sobhani-Tehrani, Talebi, & Khorasani, 2014). In addition to artificial intelligence-based methods, efforts have also been made that are aimed at extending the rich model-based fault diagnosis techniques to data-driven based approaches.

A simple solution will be the one where one can first identify a dynamical mathematical model of the system from the available data, and then use the resulting explicit model to implement and design conventional model-based FDI schemes. However, this approach would suffer from the resulting errors that are introduced in the system identification process and that could ultimately aggravate the FDI scheme design process errors, resulting in a totally unreliable fault diagnosis scheme.

In recent years, a new paradigm has emerged in the literature that aims at direct and explicit construction of the FDI schemes from only the available system input–output (I/O) data (Ding, Zhang, Naik, Ding, & Huang, 2009; Dong, Kulcsr, & Verhaegen, 2009; Wang, Ma, Ding, & Li, 2011). Subspace-based data-driven fault detection and isolation methods represent as one of the

☆ This research was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the Discovery Grants program. The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Michele Basseville under the direction of Editor Torsten Söderström.

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http://dx.doi.org/10.1016/j.automatica.2017.07.040
0005-1098/

main approaches that have been developed (Ding, 2014; Dong & Verhaegen, 2009). These methods require identifying the left null space of the system extended observability matrix using the I/O data. An estimate of the system order and an orthogonal basis for the system extended observability matrix – or its left null space – are obtained via the SVD decomposition of a particular data matrix that is constructed from the system I/O data. This process is known as the *reduction step*.

Essentially, in the reduction step it is assumed that the number of the first set of significantly nonzero singular values and the associated directions provide an estimate of the system order and a basis for the extended observability matrix. However, in most cases, this process leads to erroneous results due to the fact that the truncation point for neglecting "small" singular values, as being insignificant, is not always obvious or trivial and is a subjective and problem dependent process.

Consequently, an erroneous system order and basis for the extended observability matrix – or its left null space – can be obtained. This error manifests itself in the fault diagnosis scheme performance in a nonlinear manner. In other words, the performance characterization of the FDI scheme is not a linear function of the gap between the estimated system order and the system extended observability matrix and the actual ones. Due to these drawbacks, other works that have appeared in the literature are mainly concerned with only the fault estimation problem in which the main objective is to eliminate and remove the above reduction step.

Dong and his colleagues (Dong, Verhaegen, & Gustafsson, 2012a) have developed a fault detection scheme that can be directly synthesized from the system I/O data without involving the reduction step. The detection filter is in fact a high order FIR filter parameterized by the system Markov parameters. The extension of this work to the fault isolation task is not trivial and straightforward. It can be performed by obtaining a projection vector that is computed through the SVD decomposition of a transfer matrix parameterized by the Markov parameters estimation errors (Dong, Verhaegen, & Gustafsson, 2012b). However, the Markov parameters estimation errors are not generally available. Therefore, the authors in Dong et al. (2012b) have managed to synthesize this matrix from the I/O data. The order of the isolation filters can be as large as 30. Dong & Verhaegen (2012) used the same strategy for direct construction of the fault estimation filter. Their underlying assumption is that the system should have a stable inverse. It will provide an asymptotically unbiased estimate if the FIR filter order tends to *infinity*.

In this work, we have shown that our proposed data-driven FDI filters are conveniently configured for different fault isolation scenarios by only estimating the Markov parameters. In contrast, as pointed out above, the fault isolation scheme in Dong et al. (2012b) is significantly more complex due to the fact that it involves satisfying two additional steps namely, (i) obtaining a projection vector to be computed through the SVD decomposition of a transfer matrix parameterized by the Markov parameters estimation errors, and (ii) synthesizing the Markov parameters estimation errors from the I/O data.

Wan and his colleagues (Wan, Keviczky, Verhaegen, & Gustafsson, 2016) have reasoned in their recent work that the method of Dong and Verhaegen (2012) cannot be applied to certain open-loop systems. Moreover, it does not compensate for the estimation errors. Consequently, they have proposed off-line and online algorithms for compensating for the estimation errors. Yet, their approach suffers from *two* major drawbacks. First, the estimation is asymptotically unbiased if the filter order tends to infinity. Second, the computational time per sample for the online optimization algorithm – which is the one that yields an almost unbiased result among the others proposed – is significantly high as compared to the off-line methods in Wan et al. (2016).

In this work, to overcome the above drawbacks and limitations, we have proposed data-driven fault detection, isolation and estimation filters that are constructed directly in the state-space representation form and using *only* the available system I/O data. Our proposed schemes only require identification of the system Markov parameters that are accomplished by using conventional methods, such as correlation analysis (Ljung, 1998) or subspace methods (Chiuso, 2007; Huang & Kadali, 2008; Katayama, 2006; Van Overschee & De Moor, 1995) from the healthy I/O data.

Our proposed methodology does *not* involve and require the reduction step or equivalent forms of the extended observability matrix. Therefore, the estimation errors are linearly dependent on the Markov parameter estimation errors. This step is already addressed in the literature as reviewed above. However, it turns out that our state-space based approach can address several important challenges and difficulties that are associated with the currently available works in the literature.

First, our proposed identification and isolation filters are conveniently configured for the isolation task of both single *as well as* concurrent faults through constructing a bank of filters. Second, an important feature of our proposed state-space based method is that the estimation will be achieved asymptotically unbiased by a filter order *as low as* the maximum of the system relative degree and the system observability index. Both of these parameters are bounded by the system order. Moreover, it does not necessarily require the condition of having an entire stable inverse system. Our proposed scheme's flexibility allows arbitrary selection of the subsystems for achieving the fault isolation or for performing the fault estimation tasks.

In other words, one can select a different subsystem if an actuator fault estimation is blocked due to unstable inversion of a specific subsystem. Finally, our state-space based approach allows one to implement a simple and yet effective procedure for compensating for the estimation errors. Towards this end, in this work we derive the estimation error dynamics and show that it can be directly identified from the healthy system I/O data. We will demonstrate through comprehensive simulation case studies the effectiveness and capabilities of our proposed error compensating procedure.

In view of the above discussion, the *contributions* of this paper can now be summarized as follows:

(1) A general fault detection and isolation filter for both actuator and sensor faults is developed and directly constructed from only the available system I/O data in the state-space form in a manner that does not involve a reduction step. Moreover, our approach does not require an *a priori* knowledge of the system order. The proposed fault detection and isolation filters can be conveniently configured for both single and concurrent fault detection and isolation tasks by using a subset of the I/O data.
(2) A fault estimation scheme for both actuator and sensor faults (single and concurrent) is developed and directly constructed from the available system I/O data in the state-space form in a manner that does not involve a reduction step. The proposed estimation filter is asymptotically unbiased having an order as small as the maximum order of the observability index and the system relative degree.
(3) A new offline procedure for *tuning* the estimation filters are proposed to compensate for errors that are caused by the Markov parameters estimation process and uncertainties.

The outline of the remainder of this paper is as follow. The preliminaries, problem definition and assumptions are provided in Section 2. In Section 3, we discuss the theoretical aspects of our proposed fault estimation scheme. We present the development and design of data-driven fault detection and isolation filters in