Automatica 53 (2015) 408–415

Contents lists available at ScienceDirect

Automatica

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

Brief paper

A robust nonlinear observer-based approach for distributed fault detection of input–output interconnected systems[☆]

Christodoulos Keliris[a], Marios M. Polycarpou[a], Thomas Parisini[b,c,1]

[a] KIOS Research Center for Intelligent Systems and Networks, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia 1678, Cyprus

[b] Department of Electrical and Electronic Engineering, Imperial College London, UK

[c] Department of Engineering and Architecture, University of Trieste, Italy

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form
15 October 2014
Accepted 19 January 2015

Keywords:
Fault detection
Nonlinear observers
Nonlinear uncertain systems
Filtering

ABSTRACT

This paper develops a nonlinear observer-based approach for distributed fault detection of a class of interconnected input–output nonlinear systems, which is robust to modeling uncertainty and measurement noise. First, a nonlinear observer design is used to generate the residual signals required for fault detection. Then, a distributed fault detection scheme and the corresponding adaptive thresholds are designed based on the observer characteristics and, at the same time, filtering is used in order to attenuate the effect of measurement noise, which facilitates less conservative thresholds and enhanced robustness. Finally, a fault detectability condition characterizing quantitatively the class of detectable faults is derived.

1. Introduction

Many of the vital services of everyday life depend on highly complex and interconnected engineering systems, where potential faults could lead to performance degradation, or even trigger a chain of failing subsystems, which may cause major catastrophes. The safe and reliable operation of such systems through the early detection of a "small" fault before it becomes a serious failure is a crucial component of the overall system performance and sustainability.

Over the last two decades the fault detection and isolation (FDI) problem has been examined intensively. In most real world applications the presence of modeling uncertainty and measurement noise may influence significantly the performance of fault detection schemes. In addition, recent advances in distributed sensing and communications motivated the investigation of not only centralized fault diagnosis approaches but also the development of hierarchical, decentralized and distributed schemes, most of which assume the availability of all state variables (Ferrari, Parisini, & Polycarpou, 2012; Keliris, Polycarpou, & Parisini, 2013a; Klinkhieo & Patton, 2009; Patton et al., 2007). In many cases, a distributed FDI framework is not an option but a necessity, since many factors contribute to this formulation such as the large scale nature of the system to be monitored, its spatial distribution, the inability to access certain parts of the system from a remote monitoring component and therefore local diagnosis should be performed.

In the case of input–output nonlinear systems, several papers dealing with the fault diagnosis problem have appeared but, as in the full-state measurement case, the vast majority of them address the problem in a centralized framework (De Persis & Isidori, 2001; Zhang, Basseville, & Benveniste, 1998; Zhang & Jaimoukha, 2009; Zhang, Polycarpou, & Parisini, 2001). Lately, special attention has been given to decentralized and distributed fault detection approaches (Boem, Ferrari, Parisini, & Polycarpou, 2012; Keliris et al., 2013a; Keliris, Polycarpou, & Parisini, 2013b; Wei, Gui, Xie, & Ding, 2009; Zhang & Zhang, 2012). One of the key methodologies for fault diagnosis of input–output systems is the observer-based approach. As pointed out in Frank and Ding (1997), the observers used in fault diagnosis are primarily output observers which simply reconstruct the measurable part of the state variables, rather than state observers which are required for control purposes. The use of state

[☆] This work was partially supported by funding from the European Research Council (ERC-AdG-291508) under the ERC Advanced Grant (FAULT-ADAPTIVE). The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Tongwen Chen under the direction of Editor Ian R. Petersen.

E-mail addresses: ckeliris@ucy.ac.cy (C. Keliris), mpolycar@ucy.ac.cy (M.M. Polycarpou), t.parisini@gmail.com (T. Parisini).

[1] Tel.: +44 0 20 75946240.

http://dx.doi.org/10.1016/j.automatica.2015.01.042
0005-1098/

observers for nonlinear systems has not been extensive for the FDI problem, even though analytical results regarding the stability of the nonlinear observers and design procedures have been established (Besançon, 2007; Gauthier & Kupka, 1994; Rajamani, 1998; Thau, 1973; Zhu & Han, 2002). The main issue with the observer approach is that the design of observers for nonlinear systems with asymptotically stable error dynamics is not an easy task even when the nonlinearities are fully known. As a result, the research in fault diagnosis for nonlinear systems utilizing state observers is more limited (Adjallah, Maquin, & Ragot, 1994; Garcia & Frank, 1997; Hammouri, Kinnaert, & El Yaagoubi, 1999; Zhang & Zhang, 2012).

In this paper, we propose a nonlinear observer-based approach for distributed fault detection of a class of interconnected input–output nonlinear systems, which is robust to modeling uncertainty and measurement noise. The use of nonlinear observer design allows for a particular class of input–output systems to be considered. Specifically, in order to deal with the fault detection task, a nonlinear observer is designed for each subsystem that guarantees that the state estimation error, for the nominal nonlinear system, converges to zero. Then, the designed observer is combined with filtering for attenuating measurement noise and is used in a novel way for the derivation of suitable adaptive thresholds for the filtered state estimation error of the uncertain system, which guarantee no false alarms. Therefore, the fault detection scheme is inherently tied with the nonlinear observer design. In addition, a general class of filters is integrated in the design for the purpose of attenuating the measurement noise and hence it facilitates the design of tight, adaptive detection thresholds. This filtering approach for nonlinear fault diagnosis was first developed in Keliris et al. (2013a) where the case of full-state measurement was considered and a rigorous investigation of the filtering impact (according to the poles' location and filters' order) on the detection time was presented. In this work, we extend significantly the approach given in Keliris et al. (2013a) by relaxing the assumption of the availability of all the state measurements (through the design of a nonlinear observer) whilst maintaining the use of filters for dampening the uncertainty effects. Due to the lack of full-state measurement, the analytical treatment of the filtering design in this paper is different than the one in Keliris et al. (2013a). The novelty in the filtering approach in this work stems from its treatment as a linear state transformation, which allows a more general class of filters to be considered. It must be pointed out, that this paper extends significantly the work by the same authors in Keliris et al. (2013b), where a simplified problem formulation for the input–output case is investigated in which the nonlinear observer design is not needed for fault detection purposes, since the nonlinearity term in Keliris et al. (2013b) contains only terms that can be measured with some uncertainty. The nonlinear observer design was also not required in Ferrari et al. (2012) and Keliris et al. (2013a) since full state measurement was considered. Finally, the distributed fault detection scheme is based on local fault filtering schemes with each one assigned to monitor one subsystem and provide a decision regarding its health.

The paper is organized as follows: in Section 2, the problem formulation for distributed fault detection of a class of input–output nonlinear dynamical systems with modeling uncertainty and measurement noise is presented and in Section 3, details regarding the nonlinear observer design are given. In Section 4, the design of the distributed fault detection scheme based on Lyapunov analysis combined with a filtering approach is presented in detail and, in Section 5, a fault detectability condition is derived. In Section 6, a simulation example illustrates the concepts presented and finally, Section 7 provides some concluding remarks.

2. Problem formulation

Consider a large-scale distributed nonlinear dynamic system, which is comprised of N subsystems $\Sigma_I, I \in \{1, \ldots, N\}$, described by:

$$\Sigma_I : \begin{cases} \dot{x}_I(t) = A_I x_I(t) + f_I\big(x_I(t), \bar{C}_I \bar{x}_I(t), u_I(t)\big) \\ \qquad + \eta_I\big(x_I(t), \bar{x}_I(t), u_I(t), t\big) \\ \qquad + \beta_I(t - T_0)\phi_I\big(x(t), u_I(t)\big) \quad \text{(a)} \\ y_I(t) = C_I x_I(t) + \xi_I(t) \quad \text{(b)}, \end{cases} \tag{1}$$

where $x_I \in \mathbb{R}^{n_I}$, $u_I \in \mathbb{R}^{m_I}$ and $y_I \in \mathbb{R}^{p_I}$ are the state, input and measured output vectors of the Ith subsystem respectively and $x \triangleq \left[x_1^\top, x_2^\top, \ldots, x_N^\top\right]^\top \in \mathbb{R}^n$ is the state vector of the overall system. The vectors $\bar{x}_I \in \mathbb{R}^{\bar{n}_I}$ and $\bar{C}_I \bar{x}_I \in \mathbb{R}^{\bar{p}_I}$ denote the state variables and the corresponding output variables, respectively, of neighboring subsystems that affect the Ith subsystem. Specifically, the interconnection variables $\bar{C}_I \bar{x}_I$ are a subset of noiseless output variables of neighboring subsystems and, this special form is required for the design of the nonlinear observer. The matrix $A_I \in \mathbb{R}^{n_I} \times \mathbb{R}^{n_I}$ and the function $f_I : \mathbb{R}^{p_I} \times \mathbb{R}^{\bar{p}_I} \times \mathbb{R}^{m_I} \mapsto \mathbb{R}^{n_I}$ characterize the known nominal function dynamics of the Ith subsystem and, are derived from the linearization at the origin of the Ith nominal nonlinear subsystem. Note that the function f_I, which contains only terms strictly higher than a linear function with respect to x_I (Thau, 1973), contains also the known part of the interconnection function between the Ith and its neighboring subsystems, and moreover, note that the influence of the interconnected subsystems is known with some uncertainty (measurement noise). The matrix $C_I \in \mathbb{R}^{p_I} \times \mathbb{R}^{n_I}$ is the known nominal output matrix of the Ith subsystem. The vector function $\eta_I : \mathbb{R}^{n_I} \times \mathbb{R}^{\bar{n}_I} \times \mathbb{R}^{m_I} \times \mathbb{R}^+ \mapsto \mathbb{R}^{n_I}$ denotes the modeling uncertainty associated with the nominal dynamics and $\xi_I \in \mathcal{D}_{\xi_I} \subset \mathbb{R}^{p_I}$ ($\mathcal{D}_{\xi_I}$ is a known compact set) represents the measurement noise. The term $\beta_I(t - T_0)\phi_I(x, u_I)$ characterizes the time-varying fault function dynamics affecting the Ith subsystem. More specifically, the term $\phi_I : \mathbb{R}^n \times \mathbb{R}^{m_I} \mapsto \mathbb{R}^{n_I}$ represents the unknown fault function and the term $\beta_I(t - T_0) : \mathbb{R} \mapsto \mathbb{R}^+$ models the time evolution of the fault, where T_0 is the unknown time of the fault occurrence. Note that the fault function ϕ_I may depend on the global state variable vector x and not only on the local state vector x_I. From a practical perspective, this allows for propagative fault effects to be transferred across neighboring subsystems (as it is the case in real networks such as electric power systems, and transportation systems). In this work, no particular modeling is considered for the time profile $\beta_I(t - T_0)$ which can be used to model both abrupt and incipient faults. Instead, we simply consider it to be zero prior to the fault occurrence, i.e. $\beta_I(t - T_0) = 0$, for all $t < T_0$.

In this paper, we do not deal explicitly with the control problem. Therefore, it is assumed that there exist feedback controllers for selecting u_I such that some desired control objectives are achieved.

The notation $\|\cdot\|$ used in this paper denotes the Euclidean 2-norm for vectors and, the matrix norm induced by the 2-norm for matrices. The following assumptions are used throughout the paper:

Assumption 1. For each subsystem $\Sigma_I, I \in \{1, \ldots, N\}$, the pair (A_I, C_I) is observable.

Assumption 2. For each subsystem $\Sigma_I, I \in \{1, \ldots, N\}$ the local state variables $x_I(t)$ and the local inputs $u_I(t)$ remain bounded before and after the occurrence of a fault (well-posedness).

Assumption 3. The modeling uncertainty η_I in each subsystem is an unstructured and possibly unknown nonlinear function of