ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Fault detection for piecewise affine systems with application to ship propulsion systems☆

Ying Yang [a], Li Linlin [b,*], Steven X. Ding [c], Jianbin Qiu [d], Kaixiang Peng [b]

[a] State Key Lab for Turbulence and Complex Systems, Department of Mechanics and Engineering Science, College of Engineering, Peking University, China
[b] Key Laboratory of Knowledge Automation for Industrial Processes of Ministry of Education, School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[c] Institute for Automatic Control and Complex Systems (AKS), University of Duisburg-Essen, Germany
[d] Research Institute of Intelligent Control and Systems, Harbin Institute of Technology, Harbin 150080, China

ARTICLE INFO

Article history:
Received 14 June 2017
Received in revised form
8 August 2017
Accepted 28 August 2017

Keywords:
Diagnostic observer
Fault detection (FD) systems
Piecewise affine systems
Continuous piecewise Lyapunov function

ABSTRACT

In this paper, the design approach of non-synchronized diagnostic observer-based fault detection (FD) systems is investigated for piecewise affine processes via continuous piecewise Lyapunov functions. Considering that the dynamics of piecewise affine systems in different regions can be considerably different, the weighting matrices are used to weight the residual of each region, so as to optimize the fault detectability. A numerical example and a case study on a ship propulsion system are presented in the end to demonstrate the effectiveness of the proposed results.

1. Introduction

Associated with the increasing reliability requirements from industrial processes, intensive attention has been drawn to the investigations on fault detection (FD) issues from both the research and application communities [1–6]. Over the past decades, observer-based FD approaches for linear time-invariant systems have been well developed. Among the involved studies, diagnostic observer-based FD schemes have been widely studied [6,7]. In recent years, the studies for more complex processes have become an important research subject in the control community [8–19]. This motivates the fault detection system design for complex industrial processes.

On another research frontier, the piecewise affine modelling technique has been shown as an effective way to approximate switched systems, hybrid systems, and general nonlinear systems with arbitrary accuracy [20]. A wide range of nonlinear elements in mechanical and electrical systems, such as relay action, saturation, stiction and backlash, can be well described by piecewise affine approximation [21]. In addition, considerable amount of practical control systems and chaotic circuits are embedded with piecewise components [22,23]. In recent years, the analysis and synthesis on the stabilization and filtering issues for piecewise affine systems have attracted increasing attention [24]. It has been shown that most of these approaches were developed via piecewise quadratic Lyapunov functions [25,26,22]. While most effort has been dedicated to control and filtering issues, up to now, limited research effort has been made on the FD issues for continuous piecewise affine systems.

In this paper, the optimization of diagnostic observer-based FD approach for continuous-time piecewise affine processes is investigated. Considering that the measurable signal is generally injected with noise or disturbances, the non-synchronized FD systems are studied based on continuous piecewise Lyapunov functions, which is applicable to the case that the process and the residual generator are not operating in the same region. The essential idea behind the optimization of the FD performance consists in weighting the residual signal of each region with different weighting matrices.

The rest of this paper is organized as follows. In Section 2, the preliminaries are given. The non-synchronized diagnostic observer-based FD approach is addressed in Section 3. In Section 4, a numerical example and a case study on a ship propulsion system are used to demonstrate the effectiveness of the proposed approach. It is followed by the conclusions and future works in Section 5.

☆This work has been supported by the National Natural Science Foundation of China under grants 61633001, 61603033, 61522306, 61473033 and 61210012, the Beijing Natural Science Foundation under grant 4174096, and the Fundamental Research Funds for the Central Universities under grant FRF-TP-16-084A1.
* Corresponding author.
E-mail addresses: yy@pku.edu.cn (Y. Yang), linlin.li@ustb.edu.cn, linlin.li@uni-due.de (L. Linlin), steven.ding@uni-due.de (S.X. Ding), jianbinqiu@gmail.com (J. Qiu), kaixiang@ustb.edu.cn (K. Peng).

http://dx.doi.org/10.1016/j.isatra.2017.08.016
0019-0578/

Please cite this article as: Yang Y, et al. Fault detection for piecewise affine systems with application to ship propulsion systems. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.08.016

Notations. The notations of this paper are fairly standard. $\star$ indicates the symmetric elements of a symmetric matrix. Sym$\{N\}$ represents $N + N^T$. $N_\perp$ represents the right null space of N. $\| d(t)\|$ denotes the Euclidean norm of the vector $d(t)$. $\| d \|_2 = \left(\int_{t=0}^{\infty} \| d(t)\|^2\right)^{1/2}$ represents $\mathcal{L}_2$-norm of $d(t)$. $\| d_\tau \|_2 = \left(\int_{t=0}^{\tau} \| d(t)\|^2\right)^{1/2}$ denotes $\mathcal{L}_{2,[0,\tau]}$-norm of $d(t)$.

2. Preliminaries and problem statement

Consider the following continuous-time piecewise affine system

$$\begin{cases} \dot{x}(t) = A_i x(t) + a_i + B_i u(t) + D_i d(t) \\ y(t) = Cx(t) + Gd(t), x(t) \in \Omega_i, i \in \{1, 2, \ldots, \nu\} \end{cases} \tag{1}$$

where $x(t) \in \mathcal{R}^{k_x}$, $u(t) \in \mathcal{R}^{k_u}$, $y(t) \in \mathcal{R}^{k_y}$ represent the state, input and output of the system, respectively; $d(t) \in \mathcal{R}^{k_d}$ denotes the disturbance; ν represents the number of the regions for the piecewise affine system; $\mathcal{Z} = \{1, 2, \ldots, \nu\}$ denotes the set of different regions; $\Omega_i \in \mathcal{R}^{k_x}, i \in \mathcal{Z}$ indicates the partition of the state space into a number of not necessarily polyhedral regions; $A_i, B_i, C, D_i, G, i \in \mathcal{Z}$ denote the system matrices; $a_i, i \in \mathcal{Z}$ denotes the additional offset.

It is important to mention that for the region that includes the origin, one has that $a_i = 0$. As a result, the regions $\mathcal{Z}$ can be further divided into two classes $\mathcal{Z} = \mathcal{Z}_0 \bigcup \mathcal{Z}_1$, where $\mathcal{Z}_1$ denotes the set of the region indices that do not contain the origin, and $\mathcal{Z}_0$ denotes the set of region indices that contain the origin. In other words, for all $i \in \mathcal{Z}_1$, $a_i \neq 0$.

It is noted that the piecewise affine system is divided into a set of regions based on the state space, which is generally not fully measurable. To deal with this issue, the estimation of the state $\hat{x}(t)$ is used instead for determining the region of the residual generator. As a result, the diagnostic observer and the plant might not be working in the same region, in particular for the initial stage of the process. Suppose that the dynamics of the process and the dynamics of the residual generator are in different regions as

$$x(t) \in \Omega_i, \quad \hat{x}(t) \in \Omega_j, \quad i, j \in \mathcal{Z} \tag{2}$$

then the non-synchronized residual generator can be governed by

$$\begin{cases} \dot{z}(t) = S_j z(t) + N_j a_j + M_j u(t) + L_j y(t) \\ \hat{x}(t) = z(t) - K_j y(t) \\ \hat{y}(t) = C\hat{x}(t) \\ r(t) = W_j(y(t) - \hat{y}(t)), \quad \hat{x}(t) \in \Omega_j, j \in \mathcal{Z} \end{cases} \tag{3}$$

where $S_j, M_j, N_j, L_j, K_j, j \in \mathcal{Z}$ represent the gain matrices of the diagnostic observer; $W_j, j \in \mathcal{Z}$ denote the weighting matrices; $z(t)$ indicates the auxiliary state of the diagnostic observer; $\hat{y}(t)$ indicates the estimation of $y(t)$; $r(t)$ represents the residual.

Remark 1. It is noteworthy the weighting matrices W_i in (3) can be considered as the post-filter, which are used to improve the fault detectability.

In general, an observer-based FD system consists of an observer-based residual generator, a residual evaluator, a threshold setting unit and a decision logic. In this paper, the residual evaluator $J(r)$ is the $\mathcal{L}_2$-norm of $r(t)$, that is, $J(r) = \| r_\tau \|_2^2$. In the norm-based FD context, the threshold J_{th} is generally set as the maximal value of $J(r)$ in the fault-free case. Then the following detection logic leads to an effective observer-based FD approach

$$\begin{cases} J(r) > J_{\text{th}} \Longrightarrow \text{faulty} \\ J(r) \le J_{\text{th}} \Longrightarrow \text{fault-free.} \end{cases} \tag{4}$$

The main objective of this paper is to develop a non-synchronized diagnostic observer-based FD approach for continuous piecewise affine processes (1) such that the residual is robustness against unknown and known inputs. Meanwhile, the fault detectability is improved by optimizing the design of the weighting matrices W_i.

3. Fault detection system design

In this section, the non-synchronized FD design approach for piecewise affine systems is addressed.

To deal with the non-synchronized FD system design, system (1) is first recast as

$$\begin{aligned} \dot{x}(t) = {} & A_j x(t) + a_j + B_j u(t) + D_j d(t) + (A_i - A_j)x(t) \\ & +(B_i - B_j)u(t) + (D_i - D_j)d(t) + a_i - a_j \\ y(t) = {} & Cx(t) + Gd(t), \quad i, j \in \mathcal{Z}. \end{aligned} \tag{5}$$

By defining $e(t) = x(t) - \hat{x}(t)$, we have

$$\begin{cases} e(t) = x(t) - z(t) + K_j y(t) \\ r(t) = W_j\left(y(t) - \hat{y}(t)\right) \end{cases} \tag{6}$$

which yields

$$\begin{aligned} \dot{e}(t) = {} & S_j e(t) + \left(T_j A_j - S_j T_j - L_j C\right)x(t) + \left(T_j - N_j\right)a_j \\ & +\left(T_j B_j - M_j\right)u(t) + (T_j D_j - L_j G - S_j K_j G)d(t) \\ & +T_j\left((A_i - A_j)x(t) + (B_i - B_j)u(t) + (D_i - D_j)d(t) + a_i - a_j\right) \\ r(t) = {} & W_j\left(Ce(t) + Gd(t)\right)x(t), \quad x(t) \in \Omega_i, \hat{x}(t) \in \Omega_j, i, j \in \mathcal{Z} \end{aligned} \tag{7}$$

where

$$T_j = I + K_j C. \tag{8}$$

Suppose that

$$T_j A_j - S_j T_j - L_j C = 0 \tag{9}$$

$$T_j B_j - M_j = 0 \tag{10}$$

$$T_j - N_j = 0 \tag{11}$$

$$K_j G = 0 \tag{12}$$

hold, by defining

$$\begin{aligned} \xi(t) &= \left[e^T(t) \quad x^T(t)\right]^T \\ \eta(t) &= \left[u^T(t) \quad d^T(t)\right]^T \end{aligned} \tag{13}$$

we have

$$\begin{aligned} \dot{\xi}(t) &= \bar{A}_{ij}\xi(t) + \mathrm{a}_{ij} + \bar{B}_{ij}\eta(t) \\ r(t) &= W_j\bar{C}\xi(t) + W_j\bar{G}\eta(t) \\ & \qquad x(t) \in \Omega_i, \hat{x}(t) \in \Omega_j, i, j \in \mathcal{Z} \end{aligned} \tag{14}$$

where

Please cite this article as: Yang Y, et al. Fault detection for piecewise affine systems with application to ship propulsion systems. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.08.016