ARTICLE IN PRESS

ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

A data-driven fault-tolerant control design of linear multivariable systems with performance optimization

Zhe Li [a], Guang-Hong Yang [a,b,*]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation of Process Industries, Northeastern University, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 12 December 2015
Received in revised form
18 May 2017
Accepted 18 July 2017

Keywords:
Residual generator
Fault-tolerant control (FTC)
Data-driven
Adaptive scheme.

ABSTRACT

In this paper, an integrated data-driven fault-tolerant control (FTC) design scheme is proposed under the configuration of the Youla parameterization for multiple-input multiple-output (MIMO) systems. With unknown system model parameters, the canonical form identification technique is first applied to design the residual observer in fault-free case. In faulty case, with online tuning of the Youla parameters based on the system data via the gradient-based algorithm, the fault influence is attenuated with system performance optimization. In addition, to improve the robustness of the residual generator to a class of system deviations, a novel adaptive scheme is proposed for the residual generator to prevent its over-activation. Simulation results of a two-tank flow system demonstrate the optimized performance and effect of the proposed FTC scheme.

1. Introduction

The complexity and automation degree of industrial processes are continually growing with the increasing demands for higher system performance and product quality. This development calls for more system safety and reliability. Today, one of the most critical issues on the automatic system design is the system reliability and dependability. Consequently, either fault detection and isolation (FDI) problem or fault-tolerant control (FTC) problem has become a necessary ingredient of modern automatic control system design.

Among various developed FDI and FTC techniques, the residual generator always plays an important role. The residual signal is crucial for FDI of the faulty systems. Moreover, in some control configurations, the filtered residual signal is applied as feedback to the faulty system to design the FTC systems. The core of a residual generator is an observer for faults, and its design strategies are first initiated as model- and observer-based residual generation schemes proposed by Beard and Jones in the early 1970s [1,2]. Thereafter, the Luenberger type residual generator is developed as a reduced-order fault observer in [3,4]. In the 1980 s, Chow and Willsky proposed the parity space approach in their pioneering work [5]. With a state space representation of the plant, the parity space technique selects a parity vector from the null-subspace of the observability matrix to generate the residual signal. In recent years, an approach of parameterization of residual generators for all types of LTI systems is proposed by S.T.Ding [6]. The key idea is to find the kernel representation from the input/output (I/O) data set, which in turn leads to the residual generator.

However, in modern industrial processes, there is often a certain amount of process data instead of an accurate process model available. Thus, the design of data-driven residual generator has become an unavoidable trend in both FDI and FTC problems. Qin and Li applied the subspace identification method (SIM) with the null-space of the observability matrix ($\Gamma_s^{\perp}$) to detect sensor faults in dynamic processes only based on the system data [7,8]. Motivated by the results, Ding further developed a data-driven Luenberger type residual generator based on SIM [9] as well as the data-driven kernel representation [6] for FDI and FTC purposes. Moreover, since a vector residual is necessary for a reliable FDI and FTC process, it is of more interest to develop the data-driven vector residual generator design schemes [10]. Thus, without the system order and Markov parameters of the plant model, the above data-driven methods can use the system I/O data to design the appropriate residual generators for FDI and FTC purposes.

Motivated by the above analysis, this paper proposes a data-driven FTC system design scheme under the Youla parameterization configuration. A data-driven residual generator is first designed via the canonical form identification [14,18,19]. Then the online FTC mechanism with tuning Youla parameters is implemented in the faulty case of the system. The FTC mechanism parameters are iteratively updated with system online data.

* Corresponding author at: College of Information Science and Engineering, Northeastern University, Shenyang 110819, China.
E-mail address: yangguanghong@ise.neu.edu.cn (G.-H. Yang).

http://dx.doi.org/10.1016/j.isatra.2017.07.021
0019-0578/

Please cite this article as: Li Z, Yang G-H. A data-driven fault-tolerant control design of linear multivariable systems with performance optimization. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.07.021

Finally, a novel adaptive residual generator design scheme is proposed to enhance the robustness to a class of system parameter deviations. It can prevent the over-activation of the FTC mechanism in practice.

The rest of the paper is organized as follows. In Section 2, preliminaries and problem formulation are presented. Section 3 addresses the integrated design of the data-driven observer-based FTC scheme, including the design of the adaptive scheme to deal with a class of system deviation. In Section 4, the performance of the proposed methods are illustrated by the simulation of a two-tank flow system.

2. Preliminaries and problem formulation

Consider the following discrete-time linear time-invariant (LTI) multivariable state-space plant model

$$x(k+1) = Ax(k) + Bu(k)$$
$$y(k) = Cx(k) + Du(k) \tag{1}$$

where $u(k) \in R^l$, $y(k) \in R^m$ and $x(k) \in R^n$ represent the input, the output and the system state respectively. (A, B, C, D) are the state-space matrices of the plant model and satisfy the following assumptions.

Assumptions:

1. (A, B, C, D) is a minimal realization, controllable and observable, the system order n of matrix A is a known priori, while all the parameters of (A, B, C, D) are unknown;
2. the plant system matrix A is stable or made to be;
3. the plant system matrix A is non-derogatory.

Remark 1. Similar to the assumption in [11,12], Assumption 1 is typical in the parameter identification methods; In Assumption 2, a stable A matrix is for data-based identification procedure, for diverged data may generate a biased identified result. If A is unstable, some known simple open-loop implementation should be added first to make it stable; Assumption 3 of the non-derogatory property can be referred to [13,14].

Let $G_0(z)$ denote the nominal system transfer function matrix. To build the residual observer of the Youla parameterization configuration, the coprime factorization of the nominal system $G_0(z) = N(z)M^{-1}(z) = \hat{M}^{-1}\hat{N}(z)$ and the nominal feedback controller $K_0(z) = U(z)V^{-1}(z) = \hat{V}^{-1}(z)\hat{U}(z)$ are given as:

$$\begin{bmatrix} M(z) & U(z) \\ N(z) & V(z) \end{bmatrix} = \left[\begin{array}{c|cc} A+BF & B & L \\ \hline F & I & 0 \\ C+DF & D & I \end{array}\right] \tag{2}$$

$$\begin{bmatrix} \hat{V}(z) & \hat{U}(z) \\ \hat{N}(z) & \hat{M}(z) \end{bmatrix} = \left[\begin{array}{c|cc} A-LC & -B+LD & -L \\ \hline F & I & 0 \\ C & D & I \end{array}\right] \tag{3}$$

where $A - LC$, $A + BF$ are stable and all the relevant transfer functions belongs to RH_∞.

Then all the stabilizing controllers for the nominal plant are denoted in a class of double factored form with a stable parameter $Q(z) \in RH_\infty$:

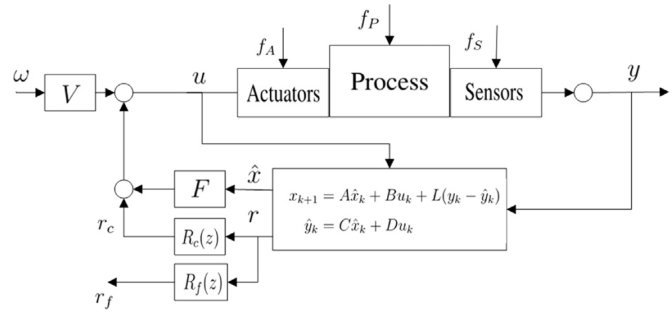

Fig. 1. The closed-loop fault-tolerant control configuration based on Youla parameterization.

$$\begin{aligned} K(Q(z)) &= (U(z) + M(z)Q(z))(V(z) - N(z)Q(z))^{-1} \\ &= (\hat{V}(z) - Q(z)\hat{N}(z))^{-1}(\hat{U}(z) + Q(z)\hat{M}(z)) \end{aligned} \tag{4}$$

where $Q(z) \in RH_\infty$ is the parameter matrix. Thus a fundamental property of the left-coprime factorization in fault- and noise-free case is

$$\begin{bmatrix} -\hat{N}(z) & \hat{M}(z) \end{bmatrix} \begin{bmatrix} u(k) \\ y(k) \end{bmatrix} = 0, \quad \forall\, u(k). \tag{5}$$

Therefore, the left-coprime factorization can be used for the parameterization of the residual generation.

Reference [16] proposed the observer-based realization of the Youla parameterization as in Fig. 1. According to the Youla parameterization, all stabilizing controllers with plant model (1) can be modified into the fault-tolerant architecture with a state-observer

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(y(k) - \hat{y}(k))$$
$$\hat{y}(k) = C\hat{x}(k) + Du(k) \tag{6}$$

The closed-loop feedback control law in faulty case and the residual generation are given by

$$u(k) = F\hat{x}(k) + r_c(k) + Vw(k) \tag{7}$$

$$r_c(k) = R_c(z)r(k) \tag{8}$$

$$r_f(k) = R_f(z)r(k) \tag{9}$$

$$r(k) = y(k) - \hat{y}(k) \tag{10}$$

where $w(k)$ denotes the output reference signal. F represents the feedback gain to achieve the closed-loop performance. V denotes the pre-filter to eliminate the output tracking errors. $R_c(z) = -Q(z) \in RH_\infty$ is the parameter matrix. f_A, f_P and f_S represent actuator faults, process faults and sensor faults respectively [15,16]. In the above control structure, $r_f(k)$ is usually obtained as a scalar signal for FDI with a post-filter $R_f(z)$, whose details can be referred to [4]. $r_c(k)$ is the FTC feedback signal with a stable post-filter $R_c(z)$ to deal with the faulty case of the system. The post-filter $R_c(z)$ and the pre-filter $V(z)$ are related to the FTC performance, which is one of the main topics of this paper.

As a result, under the condition that the parameters of the system plant model are unknown, this paper proposes an integrated FTC scheme to achieve the optimized performance in the system faulty case. The proposed FTC scheme is formulated as follows: First, the canonical form identification technology is applied to build the data-