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Data-driven output-feedback fault-tolerant control for unknown dynamic systems with faults changing system dynamics

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ABSTRACT

This paper studies the data-driven output-feedback fault-tolerant control (FTC) problem for unknown dynamic systems with faults changing system dynamics. In a framework of active FTC, two basic issues are addressed: the fault detection employing only the measured input–output information; the controller reconfiguration to achieve optimal output-feedback control in the presence of multiple faults. To detect faults and write the system state via the input–output data, an approach to data-driven design of a residual generator with a full-rank transformation matrix is presented. An output-feedback approximate dynamic programming method is developed to solve the optimal control problem under the condition that the unknown linear time-invariant discrete-time plant has multiple outputs. According to the above results and the proposed input–output data-based value function approximation structure of time-varying plants, a model-free output-feedback FTC scheme considering optimal performance is given. Finally, two numerical examples and a practical example of a DC motor control system are used to demonstrate the effectiveness of the proposed methods.

1. Introduction

Because of the increasing requirements on high safety and reliability of digital or mixed analog-digital systems in key areas with regard to personal and property safety, and the development of data-driven fault detection and isolation (FDI) techniques [1–6], data-driven fault-tolerant control (FTC) techniques have gotten more attention in recent years [7–11]. Since the data-driven FTC techniques focus on the problem of the output-feedback stabilization of discrete-time systems with unknown dynamics when faults capable of changing system dynamics occur, achieving data-driven FTC is a challenging task in the research and application fields [1].

Until now, there exist two kinds of data-driven FTC methods. The first one is the subspace predictive control (SPC) scheme proposed in [7,8]. The SPC combined the model predictive control (MPC) and subspace identification methods (SIM) [12–14]. Through the use of Markov parameters updated recursively, SPC was able to be utilized for FTC. The second one takes advantage of a fault-tolerant control architecture (FTCA) [9–11]. The FTCA stems from the generalized internal model control (GIMC) [15], which is a realization of the well-known Youla parameterization of all controllers stabilizing feedback systems internally. In [16], GIMC evolved into the extended internal model control (EIMC), which could formulate all stabilization controllers in a residual generator form. Motivated by the above works, [11] presented a data-driven realization of EIMC, namely the FTCA. In the context of the FTCA, [10] gave feed-forward and feedback control approaches depending on the data-driven realizations of the introduced kernel and image representations, and verified the effectiveness of the proposed approaches on the continuous stirred tank heater (CSTH) system. All data-driven FTC schemes described above did not take into account the performance optimization in controller design. Nevertheless, to save energy and satisfy the prescribed performance, one usually wishes that a controller could not merely stabilize a plant in normal and faulty situations, but also achieve optimal control for the plant in the industrial field. Thus, based on the FTCA, a FTC scheme with performance optimization was proposed in [9], where by means of the iterative configuration of a post-filter with a fixed structure, the control law with the minimal performance index was found. However, the control policy given by [9] is not the optimal control policy corresponding to the dynamics of the plant because the optimal structure of the post-filter (such as its optimal order) is unknown. In addition, according to a power series expansion (PSE), some extremely valuable methods for solving problems

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under model parameter uncertainty have been recently presented in [17–22]. Furthermore, these approaches have the potential to address the FTC issue.

Approximate dynamic programming (ADP) is an effective and feasible method for solving optimal control problems [23,24]. ADP approaches are mainly divided into four schemes [25]: action dependent heuristic dynamic programming (ADHDP) (i.e. Q-learning), action dependent dual heuristic dynamic programming (ADDHP), dual heuristic dynamic programming (DHP), and heuristic dynamic programming (HDP). Due to the fact that Q-learning is a class of model-independent methods that can deal with linear quadratic regulation [26], optimal tracking control [27] and zero-sum games problems [23,28] for linear discrete-time systems, Q-learning has attracted much interest in the last two decades. Nevertheless, such methods require the information about the entire system state vector, which it may be very expensive and difficult to measure in practical implementations. To this end, the works [29,30] presented an output-feedback ADP algorithm, which gave optimal control laws for unknown plants, just as the Q-learning did, and moreover, made use of measured output data only. The above ADP approaches employed a fixed-structure value function approximation (VFA) scheme capable of approximating the prescribed performance index of a time-invariant system. However, when the plant under consideration is a time-varying system, the fixed-structure VFA scheme cannot approximate the given performance index due to changes over time in the dynamics of the plant. Therefore, these ADP approaches cannot solve optimal control issues for time-varying systems. To overcome this problem, by utilizing a self-organizing map (SOM) neural network applied widely in data mining and pattern recognition, Kiumarsi et al. in [31] proposed a time-varying VFA scheme consisting of several fixed-structure VFA schemes. According to the time-varying VFA scheme, [31] presented the novel ADP algorithms that could only tackle the FTC problem for partially-unknown dynamic systems and needed to measure the entire system state vector.

Motivated by all the above-mentioned researches, this paper studies the model-free FTC problem considering optimal performance in a framework of output-feedback-based active FTC. This problem is more difficult to solve and, however more valuable than the state-feedback-based FTC issue on account of full information usually unavailable about the system internal states in practical situations. Compared with the existing works, this paper makes the following contributions:

- For an unknown linear time-invariant (LTI) discrete-time plant, the output-feedback ADP method reported in [29,30] cannot solve the optimal control problem under the condition that the plant has multiple outputs, while the ADP approach developed in the work can address this problem.
- By means of the aforementioned results, the fault detection mechanism and the proposed input–output data-based VFA structure, a model-free output-feedback FTC scheme considering optimal performance is designed and, from a control engineering perspective, is more feasible than the state-feedback-based FTC methodology presented in [31], where the input matrix of the controlled plant needs to be known.

The paper is organized as follows. The control objectives and basic assumptions of the paper are presented in Section 2. Section 3 describes a method for the data-driven design of a residual generator with a full-rank transformation matrix. In Section 4, an output-feedback ADP approach, together with a data-driven output-feedback FTC scheme for linear discrete-time systems with completely unknown system dynamics, is presented. Three simulation examples are given in Section 5 to show the effectiveness and the advantages of the proposed methods. Finally, in Section 6, some conclusions end the paper.

2. Problem statement

Suppose that the plant with faults changing system dynamics has a linear discrete-time model represented in the following state-space form

$$\begin{aligned} x_{k+1} &= (A+\triangle A)x_k + (B+\triangle B)u_k \\ y_k &= Cx_k \end{aligned} \tag{1}$$

where $x_k \in \mathcal{R}^n$, $u_k \in \mathcal{R}^l$ and $y_k \in \mathcal{R}^m$ are the system state, control input and system output vectors, respectively. ΔA denotes plant faults [8], such as the large variations in parameters caused by the aging of equipment. Similarly, ΔB is regarded as actuator faults (e.g. partial loss of effectiveness or outage of actuators). Moreover, A, B, C, ΔA and ΔB are unknown matrices with appropriate dimensions.

For the purpose of the fault detection, in the fault-free case, by (1), we give the I/O model

$$\mathcal{Y}_{k,f} = \Xi_f \mathcal{X}_k + \mathcal{H}_{f-1}\mathcal{U}_{k,f} \tag{2}$$

where the subscript $f > n$ and means the future horizon. Ξ_f stands for the extended observability matrix having the following form

$$\Xi_f = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{f-1} \end{bmatrix}. \tag{3}$$

$$\mathcal{H}_{f-1} = \begin{bmatrix} 0 & \cdots & \cdots & 0 \\ CB & \ddots & & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ CA^{f-2}B & \cdots & CB & 0 \end{bmatrix} \tag{4}$$

is a block Toeplitz matrix. $\mathcal{Y}_{k,f}$ is a Hankel matrix with the system output data, and is of the form

$$\mathcal{Y}_{k,f} = \begin{bmatrix} y_{k,k+f-1} & y_{k+1,k+f} & \cdots & y_{k+N-1,k+N+f-2} \end{bmatrix} \tag{5}$$

where

$$y_{k+i,k+i+f-1} = \begin{bmatrix} y_{k+i} \\ y_{k+i+1} \\ \vdots \\ y_{k+i+f-1} \end{bmatrix}, \quad i = 0, 1, \ldots, N-1.$$

In addition, $\mathcal{U}_{k,f}$ is also a Hankel matrix, which is composed of the system input data and has the same structure as $\mathcal{Y}_{k,f}$. $\mathcal{X}_k$ is the state sequences defined as:

$$\mathcal{X}_k = \begin{bmatrix} x_k & x_{k+1} & \cdots & x_{k+N-1} \end{bmatrix}. \tag{6}$$

For the research on the FTC problem, the following basic assumptions are required in this paper.

Assumption 1. The order n of the plant under consideration is known a priori.

Assumption 2. $(A+\Delta A, B+\Delta B)$ is controllable when any fault ΔA or ΔB occurs.

Assumption 3. $(A+\Delta A, C)$ is observable when any fault ΔA occurs.

Under Assumptions 1–3, and under the condition that the dynamics of (1) is completely unknown and it is not feasible to