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Brief paper

Collaborative operational fault tolerant control for stochastic distribution control system ☆

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ABSTRACT

Based on a class of industrial processes, a new distributed fault diagnosis approach and a collaborative operational fault tolerant control law are proposed for an irreversible interconnected stochastic distribution control (SDC) system with boundary conditions. This control method is different from the existing collaborative fault tolerant controllers which enable the output probability density function (PDF) to track a desired PDF as close as possible. When fault occurs, a setpoint redesigned fault tolerant approach is adopted to accommodate the fault instead of reconstructing the controller. An augmented PID nominal controller and a setpoint compensation item with linear structure are used to obtain a collaborative operational fault tolerant controller via solution of linear matrix inequalities (LMIs). Simulations are included to show the effectiveness of the proposed algorithms where encouraging results have been obtained.

1. Introduction

During the last decades there has been considerable interest in the development of modeling and control for interconnected systems (Antonelli, 2013; Patton et al., 2007; Yang, Jiang, & Zhou, 2017). So far, there are mainly two types of couplings among subsystems for the interconnected systems: Physical couplings (He, Wang, Liu, Qin, & Zhou, 2017; Yang, Jiang, Staroswiecki, & Zhang, 2015) and Network connections (Ma & Yang, 2016; Zuo, Zhang, & Wang, 2015) . For the above interconnected systems, three main control frameworks have been considered in order to compensate the coupled-dynamics: (1) Centralized framework (Zhang, Liu, & Zhang, 2005) where the whole interconnected system is supervised by one controller; (2) Decentralized framework (Li & Tong, 2017; Panagi & Polycarpou, 2011) where the stability of the entire system is guaranteed by using only local information; and (3) Distributed framework (Keliris, Polycarpou, & Parisini, 2015; Panagi & Polycarpou, 2013) where multiple local controllers are designed for the exchange of information between subsystems.

Compared with the conventional control methods (Blanke, Kinnaert, Lunze, & Staroswiecki, 2006; Shen, Shi, & Jiang, 2017), the design and analysis of interconnected systems is more complicated since the stability and performance of individual subsystem need to be addressed, in the meantime the communication with delays and loss of data packets which can have impact on other subsystems should be considered. The collaborative controller design for such systems must insure the stability of the whole system, especially ensure the ability of operating within certain performance margins in the presence of faults.

Different from the prior fault tolerant controller, the impacts induced by the fault occurring in any of the subsystem or the communication channel are not only for the subsystem itself but also for the other subsystems due to the system coupling. Therefore, a collaborative fault tolerant control scheme needs to be developed in order to compensate the effects of fault on the local subsystems.

The existing results of fault tolerant control for interconnected systems are mainly based on the generalized models which are not suitable for some industrial processes, such as food particles processing procedure, molecular weight distribution control process and mineral froth flotation process. These systems contain N

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series connected subsystems in addition the operational process is irreversible. More specifically, the output of the previous subsystem may not act as the input of the next subsystem but as a boundary condition which causes the system parameter matrices to be influenced by the previous subsystems (Ren, Wang, & Wang, 2015).

Many stochastic control methods always assume that systems and variables subject to Gaussian distribution. In fact, many practical industrial processes do not meet this assumption. Motivated by this problem, Hong Wang proposed a novel approach for SDC systems which could directly control the shape of output PDF, i.e. the output SDC systems (Wang, 2000). Unlike the classical systems control problem, the objective concerned in the output SDC system is to achieve the tracking performance for the PDF of the system output, rather than the actual output values. On the basis of the SDC system, fault diagnosis and fault tolerant control methods were also developed besides a number of control algorithms. However, all the results were presented only for controlling the individual SDC system (Yao, Qin, Wang, & Jiang, 2012; Zhou, Li, & Wang, 2014). In fact, some problems are difficult or even impossible to solve by an individual system, such as multi-agent system(MAS) and the corresponding control method namely the cooperative (or collaborative) control. To address this issue, a number of profound results have been established for cooperative control of MAS (Ren & Beard, 2005). Furthermore, cooperative fault tolerant control, as an important part of cooperative control, should also be constructed when faults occur in interconnected system.

The conventional FTC for SDC systems focus on designing fault tolerant controllers after fault occurs so that the closed loop system is stable and the controlled output PDFs follow the designed PDFs as close as possible, under the assumption that the designed PDF is given. However, it is difficult to give an appropriate PDF to be tracked which can not only guarantee the stability of the whole system but also keep the system operating at optimal conditions.

The research on such FTC is still limited to a single control process, without considering the effect of the operational layer on the feedback control layer in case of failure. Moreover, the dynamics of fault operating conditions are different for industrial processes. It is difficult to use the existing methods for the diagnosis of fault caused by inappropriate setpoint and the self-recovery control in operational control for SDC systems. Inspired by Chai (Chai, Qin, & Wang, 2014), it is necessary to study a new diagnosis of fault operating condition as well as self-recovery control in collaborative SDC systems. In this paper, we tackle the operational fault tolerant tracking problem of collaborative SDC system with time-delays. To compensate actuator failure effects on the PDF tracking and maintain the system operation under an optimized status, an operational fault tolerant control algorithm is designed by estimating the faults and tuning the setpoint timely and appropriately. So that the overall system stability and acceptable performance can be maintained in the event of faults.

The rest of this paper is organized as follows. The problem description is given in Section 2. In Section 3, fault diagnosis algorithm is proposed. Section 4 gives the design of operational fault tolerant controller for collaborative SDC system. Simulation results are included in Section 5, which is followed by some concluding remarks in Section 6.

2. System description

2.1. Preliminaries

Consider a directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ with a nonempty finite set of N nodes $\mathcal{V} = (v_1, v_2, \dots, v_N)$, a set of edges or arcs $\mathcal{E} \subset \mathcal{V}\times\mathcal{V}$, and the adjacency matrix $\mathcal{A} = [a_{ij}] \in \Re^{N\times N}$. An edge rooted at node v_j and ended at node v_i is denoted by (v_j, v_i), which means information can flow from node v_j to node v_i. a_{ij} is the weight of edge (v_j, v_i) and $a_{ij} = 1$ if $(v_j, v_i) \in \mathcal{E}$, otherwise $a_{ij} = 0$. Node v_j is called a neighbor of node v_i if $(v_j, v_i) \in \mathcal{E}$. The set of neighbors of node v_i is denoted as $N_i = \{j|(v_j, v_i) \in \mathcal{E}\}$. Define the in-degree matrix as $D = diag\{d_i\} \in \Re^{N\times N}$ with $d_i = \sum_{j\in N_i} a_{ij}$ and the Laplacian matrix as $L = D - \mathcal{A}$.

The edges in the form of (v_i, v_i) are called loops. $G = diag\{g_i\} \in \Re^{N\times N}$ is denoted as a loop matrix and has at least one diagonal item being 1. A graph with loops is called a multigraph, otherwise it is a simple graph.

2.2. System description

Consider the dynamic collaborative stochastic distribution system which consists of N subsystems connected in the way as shown in Fig. 1 with inputs $u_i(t) \in \Re^{m_i}, (i = 1, 2, \dots, N)$, respectively. Denote $z_i(t) \in [a_i, b_i]$ as the outputs of the concerned dynamic stochastic subsystems, respectively and assume that they are uniformly bounded.

In the future, $f_i(t)$ represents the unknown fault in the whole collaborative system. The output probability distribution functions of $z_i(t)$ are denoted by $\gamma_i(y, u_i)$ which can be obtained by calculating the following probability (Wang, 2000):

$$P\{a \le z_i(t) \le \xi_i|u_i(t)\} = \int_a^{\xi_i} \gamma_i(y, u_i(t))dy$$

where $P\{a \le z_i(t) \le \xi_i|u_i(t)\}$ is the probability of the output $z_i(t)$ lying inside the interval $[a, \xi_i]$ when $u_i(t)$ is applied to the system with $\xi_i(t) \in [a, b]$. As shown in Fig. 1, the considered subsystems are connected in series, the output PDF of the previous subsystem i affects the next $i + 1$ subsystem as a boundary condition. Denote

$$C(y) = [b_1(y) \quad b_2(y) \quad \cdots \quad b_{n-1}(y)]$$

$$V_i(t) = [v_{i1}(t) \quad v_{i2}(t) \quad \cdots \quad v_{i,n-1}(t)](V_i(t) \neq 0)$$

Based on the well-known B-spline neural networks, the following square-root B-spline model has been used to approximate the output PDFs $\gamma_i(y, u_i(t))$.

$$\begin{aligned}\sqrt{\gamma_i(y, u_i)} &= \sum_{j=1}^{n} v_{ij}(u_i)b_j(y) \\ &= C(y)V_i(t) + h(V_i(t))b_n(y) + \omega_i(y, u_i) \qquad (1)\end{aligned}$$

Different from the previous result for the square root B-spline models (Ren et al., 2015), model error $\omega_i(y, u_i)$ is also dealt with in this paper, which can obviously make the concerned model more feasibly. Furthermore, the model uncertainty $\omega_i(y, u_i)$ satisfy $|\omega_i(y, u_i)| \le \delta_{\omega_i}$ for all $\{y, u_i\}$ where δ_{ω_i} is a known positive constant. In Eq. (1), $b_j(y) \ge 0, (j = 1, 2, \dots, n)$ are pre-specified basis B-spline functions defined on $[a, b]$ respectively. $v_{ij}(u_i)$ (denoted as $v_{ij}(t)$ for simplicity) are the corresponding weights for all of the stochastic distribution subsystems. The output PDFs satisfy the condition $\int_a^b \gamma_i(y, u_i)dy = 1$. This means that only n-1 weights are independent for any of the subsystem. Denote $E_1 = \int_a^b C^T(y)C(y)dy$, $E_2 = \int_a^b C(y)b_n(y)dy$, $E_3 = \int_a^b b_n^2(y)dy$, then we have

$$h(V_i(t)) = \frac{1}{E_3}(-E_2V_i(t) \pm \sqrt{V_i^T(t)E_0V_i(t)})$$

where $E_0 = E_1E_3 - E_2^TE_2$ and $h(V_i(t))$ is a nonlinear function assumed to satisfy the following Lipschitz condition (Guo & Wang, 2005):

$$\|h_i(V_1) - h_i(V_2)\| \le \|U_i(V_1 - V_2)\| \qquad (2)$$

for any $V_1(t)$ and $V_2(t)$ where U_i is a known matrix. Actually, many nonlinearities satisfy the Lipschitz condition, at least locally.