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Distributed data-based fault identification and accommodation in networked process systems

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HIGHLIGHTS

- A methodology for the design and analysis of networked plant-wide fault–tolerant control systems for large-scale process systems is presented.
- Resource-aware quasi-decentralized networked control balances the tradeoff between the stability and communication requirements.
- Distributed optimization-based fault identification using sampled data allows timely on-line estimation of the fault magnitude and its location.
- A fault accommodation algorithm that determines the appropriate fault compensation measure based on the plant's stability region is presented.
- The results are applied via simulations to a reactor–separator process network.

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ABSTRACT

This paper presents a data-based framework for distributed actuator fault identification and accommodation in networked process systems controlled over a resource-constrained communication medium. Initially, a quasi-decentralized networked control structure is designed to stabilize the plant in the absence of faults. The structure consists of a set of local model-based control systems that communicate with one another at discrete times. An explicit characterization of the networked closed-loop stability region is obtained in terms of the update period, the accuracy of the models, and the choice of controller design parameters. To address the actuator fault identification problem, a set of local fault diagnosis agents are designed and embedded within the various subsystems. Each agent uses a moving-horizon parameter estimation scheme to estimate on-line the size and location of the local faults using the locally sampled states and the model state estimates for the interconnected units. Potential discrepancies or ambiguities in the local fault diagnosis results, which may be caused by the strong dynamic coupling between the individual subsystems and the presence of plant-model mismatch, are reconciled by means of a fault estimation confidence interval which is obtained by analyzing the networked closed-loop dynamics at update times. Once the locations and magnitudes of the actuator faults are identified, the resulting estimates are transmitted to a higher-level supervisor to select and implement a suitable fault accommodation strategy. A number of stability-preserving fault accommodation strategies are devised, including updating the post-fault models, adjusting the controllers' parameters, or a combination of both. The selection of the appropriate fault accommodation strategy is made on the basis of the estimated fault magnitude and the characterization of the networked closed-loop stability region. Finally, the developed methodology is illustrated using a reactor–separator process example subject to both sudden and incipient control actuator faults.

1. Introduction

Chemical plants are large-scale dynamical systems that typically involve a large number of distributed interconnected subsystems that are tightly integrated through material, energy and information flows and recycle. Control and supervision of such large-scale systems are fundamental problems that encompass a host of theoretical and practical challenges. These problems have received significant attention in process control over the past few decades and have motivated many research studies on the analysis and design of distributed and supervisory control systems for process networks (see, for example, Lunze, 1992; Cui, 2002; Jillson and Ydsite, 2007; Tetiker et al., 2008; Jogwar et al., 2009; Stewart et al., 2011; Christofides et al., 2011 for some results and references

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in this area). In addition to these advances, research efforts within process control have recently begun to address the new challenges emerging from the integration of networked control systems in process operations. These efforts have been motivated by a number of recent developments in the field, including the shift in industrial operation towards sensor and distributed control systems that are accessed over shared communication links (Tipsuwan and Chow, 2003; Hespanha et al., 2007; Gupta, 2010); as well as the drive towards expanding the traditional process control an operations paradigm in the direction of smart plant operations (Christofides et al., 2007).

A key feature of smart plant operations is the use of advanced cyber-infrastructure and communication technologies (such as wireless sensor networks) to achieve tight real-time integration of control, computing and communication at different levels of the plant, in order to realize the desired environmental, health and safety targets. In this context, efforts to address problems such as network resource utilization and real-time scheduling constraints were initiated in a number of studies which led to the design of resource-aware networked plant-wide control (Sun and El-Farra, 2008), state estimation (Sun and El-Farra, 2010) and communication scheduling methods (Sun and El-Farra, 2012) that enforce the desired stability and performance properties with minimal communication requirements. A central aim of these methods is to balance the tradeoff that exists between the achievable control quality on the one hand, and the extent of network utilization by the units sharing the communication medium, on the other. To keep the necessary information transfer to a minimum, a model-based quasi-decentralized control structure is used, whereby a set of dynamic models are included within each local control system to provide estimates of the states of the interconnected units. These estimates, which are used to generate the local control action when communication is suspended, are then corrected or updated using the actual state measurements whenever communication between the different subsystems is restored.

The quasi-decentralized control structure offers a compromise between the complexity and lack of flexibility associated with centralized control structures on the one hand, and the performance limitations of purely decentralized schemes, on the other. However, the problems of fault diagnosis and handling were not explicitly addressed in the networked control system design. These are important problems that require special attention in the context of large-scale process networks. Specifically, due to the interconnections between the plant units through mass and energy flows and recycle, and the resulting dynamic coupling between the various component subsystems, the adverse effects of local faults in a given subsystem may propagate to the rest of the plant and potentially cause failure at the plant level, if not explicitly accounted for. Timely identification and handling of faults are therefore essential capabilities that the networked plant-wide control system needs to have.

Fault diagnosis and fault–tolerant control are fundamental problems at the interface of process control and operations, which are motivated by the need to develop autonomous and intelligent process control and monitoring systems that operate reliably in the presence of faults. Faults in dynamic processes are characterized by critical and unpredictable changes in the process dynamics resulting possibly from malfunctions in the control actuators, the measurement sensors, and/or the process equipment. Within the context of smart plant operations, fault detection and accommodation are essential tools for realizing the goal of zero-incident plant operations. While the literature on these problems is quite extensive (see, for example, Frank and Ding, 1997; Venkatsubramanian et al., 2003; Blanke et al., 2003; Isermann, 2005; Steffen, 2005; Zhang and Jiang, 2008; Jiang and Yu, 2012, for some results and references in this area), systematic methods for the design of fault–tolerant control systems for integrated process networks are limited at present. Notable exceptions within process control include control approaches based on distributed model predictive control formulations (Chilin et al., 2012) and safe-parking frameworks (Gandhi and Mhaskar, 2009). These approaches, however, do not explicitly account for communication constraints in the control system design. Outside of process control research, fault detection of distributed multi-agent systems has also received some attention, including, for example, efforts to develop algorithms for distributed fault diagnosis in discrete event systems (Baroni et al., 1999), design of sensor networks for fault–tolerant estimation (Staroswiecki et al., 2004), strategies for fault–tolerance in distributed systems (Patton et al., 2007), decentralized fault detection (Patton et al., 2007) and decomposition-based distributed fault detection and isolation using adaptive approximations (Ferrari et al., 2014). The focus of these studies, however, has been primarily on the fault diagnosis task. Also, networked communication issues between the component subsystems were not explicitly considered in the problem formulation.

Motivated by these considerations, we present in this work an approach that combines process data and process models to achieve distributed identification and accommodation of control actuator faults in networked process systems controlled over a resource-constrained communication medium. A model-based quasi-decentralized networked control structure containing a set of local model-based control systems that communicate with each other at discrete times is initially designed. By analyzing the behavior of the networked closed-loop system, an explicit characterization of the closed-loop stability region is obtained in terms of the network update period, the model uncertainty, the magnitudes of the faults and the controller design parameters. The fault identification mechanism involves the use of a set of local fault diagnosis agents, which are embedded in the various subsystems. A moving-horizon optimization problem is solved by each agent at each sampling time to determine on-line the size and location of the local faults using the past sampled state data and the states of the locally embedded models describing the dynamics of the interconnected units. An estimation confidence interval of the actual fault parameter is obtained to resolve the ambiguities introduced by the strong dynamic coupling between the individual subsystems and the presence of plant-model mismatch. Once the faults are identified, the estimated magnitudes of the faults are sent to a higher-level supervisor, which uses this information, together with the characterization of the networked closed-loop stability region, to determine the appropriate fault accommodation strategy. The fault accommodation strategies include updating the post-fault models in the plant subsystems and/or switching to a new set of stabilizing controller parameters.

The rest of the paper is organized as follows. In Section 2, mathematical preliminaries describing the class of networked process systems considered and an overview of the problem formulation are presented. Section 3 then focuses on the design of the model-based quasi-decentralized networked controller and presents an analysis of the networked closed-loop stability properties. The fault identification and fault accommodation strategies are presented next in Section 4. Finally, the proposed framework is illustrated in Section 5 using a networked reactor–separator process example, and conclusions are given in Section 6.

2. Preliminaries

2.1. Class of process networks

In this study, we focus on large-scale networked process systems composed of n interconnected subsystems or units, where each subsystem is modeled by a continuous-time linear system,