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Necessary and sufficient conditions for robust reliable control in the presence of model uncertainties and system component failures☆

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ABSTRACT

This paper provides necessary and sufficient conditions for several forms of controlled system reliability. For comparison purposes, past results on the reliability analysis of controlled systems are reviewed and several of the past results are shown to be either conservative or have exponential complexity. For systems with real and complex uncertainties, conditions for *robust reliable stability and performance* are formulated in terms of the structured singular values of certain transfer functions. The conditions are necessary and sufficient for the controller to stabilize the closed-loop system while retaining a desirable level of the closed-loop performance in the presence of actuator/sensor faults or failures, as well as plant-model mismatches. The resulting conditions based on the structured singular value are applied to the decentralized control for a high-purity distillation column and singular value decomposition-based optimal control for a parallel reactor with combined precooling. Tight polynomial-time bounds for the conditions can be evaluated by using available off-the-shelf software.

1. Introduction

An inevitable consequence of industrial practice is that actuators and sensors can become faulty or fail, which motivates the development of methods to evaluate the reliability of the closed-loop system to such imperfect operations. A feedback-controlled system is said to be *reliable* if it is guaranteed to retain desired closed-loop system properties while tolerating faults or failures of actuators and/or sensors. Maximizing the reliability of a system concerns minimizing its potential performance degradation while retaining closed-loop stability when a fault or failure occurs in a control/measurement channel. In addition to the possibility of actuator/sensor faults or failures, plant-model mismatches are also inevitable, which motivates their incorporation into reliability and integrity analysis. This article is motivated by the need for nonconservative testing conditions to ensure closed-loop stability and to retain a satisfactory closed-loop performance in the presence of both plant-model mismatches and actuator/sensor faults or failures.

This paper primarily considers decentralized controlled systems and studies their *robust reliable stability and performance* in the presence of possible actuator/sensor faults or failures with consideration of the overall plant-model mismatches (i.e., model uncertainty) that are described in terms of bounded set-valued linear operators. The main purpose of this article is to present necessary and sufficient conditions for various types of *robust reliable stability and performance* of a set-valued plant model that is described by a linear fractional transformation (LFT) with structured uncertainties (Zhou et al., 1996). It is assumed that any failure of a local controller is detected and the controller is taken out of service whenever a failure occurs, so that any undesirable propagation of local failures to other parts of the system can be avoided. Although the main emphasis is on decentralized control systems, the proposed approach does not depend on the structure of the selected control schemes and can be applied to any type of linear controller and actuator–sensor selection.

Decentralized control depicted in Fig. 1a is ubiquitous in industrial applications, which is a special case of large-scale interconnected systems with interactions between subsystems and

☆ Part of the results of this article were presented in Braatz et al. (1994).

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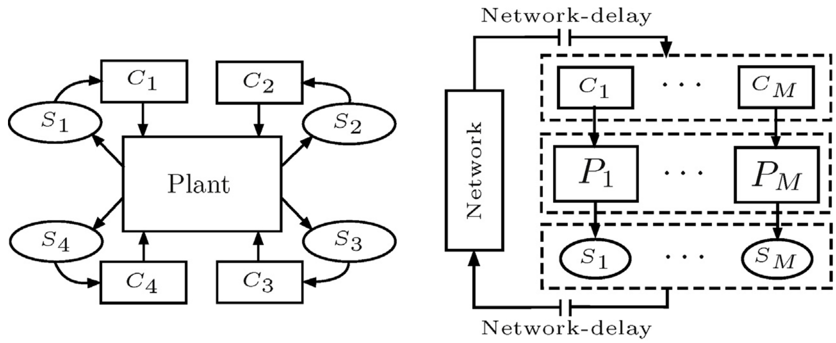

(a) Decentralized control systems (b) Networked decentralized control systems

Fig. 1. Large-scale interconnected systems.

constraints on information flows. Extensive overviews on decentralized control are available (Bakule, 2008; Siljak, 1996). For decentralized controlled systems, actuator/sensor faults or failures can occur and the selection of a reliable actuator/sensor structure is an important consideration (Braatz et al., 1996; Khaki-Sedigh and Moaveni, 2009; Lee et al., 1995). A resurgent topic in systems and control theory related to *reliable decentralized control* is the study of the effect and propagation of communication link failures between several components of a *networked control system* (NCS) depicted in Fig. 1b on the stability and performance of the overall system (Imer et al., 2006; Tipsuwan and Chow, 2003; Walsh et al., 2002; Zhang et al., 2001). Although studied for decades, NCSs have received a large surge of interest in recent years. As time delays and communication losses are inevitable in an NCS, reliability analysis in the presence of faults and failures in communication networks is also important.

In Siljak (1978, 1980), multi-controller systems were introduced for reliable control and since then reliable stabilization problems under various failure and fault scenarios have been studied using decentralized configurations (Campo and Morari, 1994; Gündes, 1998; Morari, 1985; Morari and Zafiriou, 1989; Skogestad and Morari, 1992; Tan et al., 1992). In particular, the reliability of decentralized control with integral action was investigated in terms of steady-state gain matrices (Campo and Morari, 1994; Grosdidier et al., 1985; Morari, 1985) and existence conditions for a reliably stabilizing decentralized integral controller were derived in terms of the Niederlinski index (NI) and block relative gain (BRG) (Kariwala et al., 2005, 2006). Explicit conditions for reliable decentralized control of linear systems were derived for a two-channel decentralized feedback control configuration (Gündes, 1998), and coprime factorization methods and a design method for such controllers were proposed (Gündes and Kabuli, 2001).

In addition to the aforementioned frequency-domain approaches, some researchers have proposed design methods for reliable controllers in terms of state-space realizations of the plant and controller. Centralized reliable state feedback controllers have been investigated (Joshi, 1986; Mariton and Bertrand, 1986) and design methods for decentralized reliable observer-based output-feedback controllers were developed (Date and Chow, 1989; Veillette et al., 1992). Robust pole placement was used to design state feedback controllers for dynamical systems in the presence of actuator failures (Zhao and Jiang, 1998) while requiring redundant actuators to recover the normal level of operation. The design method of Zhao and Jiang (1998) was only applicable to state feedback control problems without any plant-model mismatch, so that the proposed design methods may perform poorly in the presence of model uncertainties. In Seo and Kim (1996), a simple high-gain state feedback control based on a Riccati-type equation was proposed with actuator redundancy for systems for some form of time-varying model uncertainties, but not fully structured and with no uncertainty allowed in the input channel matrices. The passivity theorem has been used to design a decentralized controller with some form of H_2 performance while maintaining stability when each control loop is detuned (Bao et al., 2002; Zhang et al., 2002).

The approaches described in this article are based on the structured singular value (μ) and a standard representation of uncertain systems known as the linear fractional transformation (LFT). Robust reliable control problems for large-scale systems with decentralized control are reformulated in terms of robustness analysis based on μ to model the effects of faults. The structures of interconnected sensors and actuators as well as the structure of the model uncertainties can be fully exploited to perform nonconservative or less conservative analysis. Some of the results in this article were presented in Braatz et al. (1994) and subsequently there were many research efforts such as the aforementioned works to develop robust reliable controllers. The main objective of this article is to provide an efficient framework for the analysis and synthesis of robust reliability. Faults and failures in process components are treated as parametric uncertainties that are compatible with μ. In response to the resurgence of research interest in robust reliable control for systems with integral action, this article extends and expands our past results (Braatz et al., 1994) to derive conditions for robust reliable stability of decentralized systems with integral action. Although the main focus of this article is on decentralized control problems, the methodology is not restricted to decentralized control and the results can be extended to general control structures in a straightforward manner.

1.1. Mathematical notation

The notation used in this paper is standard. $\|\cdot\|$ is the Euclidean norm for vectors or the corresponding induced matrix norm for matrices. $\mathbf{0}$ and $\mathbf{I}$ denote the null matrix whose components are all zeros and the identity matrix of compatible dimension, respectively. $\mathbb{C}_+$ denotes the open right-half plane, i.e., $\mathbb{C}_+ \triangleq \{s \in \mathbb{C} : s = \alpha + j\beta,\ \alpha > 0,\ \beta \in \mathbb{R} \cup \{\infty\}\}$. The set of eigenvalues is denoted by $\sigma(A) \triangleq \{\lambda \in \mathbb{C} : \det(\lambda \mathbf{I} - A) = 0\}$ and $\rho(A)$ refers to the spectral radius of A, i.e., $\rho(A) = \max_{\lambda \in \sigma(A)} |\lambda|$. The vector whose entries are all ones is represented by $1_m \triangleq [1, \ldots, 1]^T \in \mathbb{R}^m$. diag($A$, B) denotes a block-diagonal matrix whose diagonal entries are A and B. The argument s for a transfer function may be omitted for notational convenience, but will appear whenever required to avoid confusion. The standard LFT (or M–Δ configuration), uses the notation $\mathcal{F}_\ell(M, \Delta) \triangleq M_{11}(s) + M_{12}(s)\Delta(\mathbf{I} - M_{22}(s)\Delta)^{-1}M_{21}(s)$