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Performance assessment of decentralized control systems: An iterative approach

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ABSTRACT

In this work, an efficient approach for performance assessment of decentralized control systems based on a general quadratic performance index involving both system states and inputs is proposed. The performance assessment problem is formulated as an optimization problem subject to constraints in the form of linear/bilinear matrix inequalities which explicitly take the block-diagonal structural constraint on decentralized control systems into account. In order to solve the optimization problem efficiently, an iterative approach based on the original optimization problem and an equivalent transformation of the original one is proposed. Specifically, the proposed approach under the assumption that the full state feedback is available is first presented; and then the approach is extended to the case that only output feedback is available. The proposed approach solves for both the best achievable performance and the corresponding controller (and observer) gains. The application of the proposed approach to two examples including a reactor–separator chemical process example illustrates the applicability and effectiveness of the proposed approach.

1. Introduction

Large-scale complex systems are common occurrences in modern industry systems (e.g. chemical and petrochemical processes) which are composed of distributed interconnected subsystems that are tightly integrated through material, energy and information flows. Traditionally, control of large-scale systems has been studied primarily within the centralized or decentralized framework. While the centralized control framework is shown to provide the best performance, its high computational and organizational burden and fragile fault tolerance often make its implementation impractical. In a decentralized control framework, the overall system is divided into subsystems and the controller synthesis is carried out based on these subsystems (see, for example, Bakule, 2008; Sandell, Varajya, Athans, & Safonov, 1978 and references therein). Decentralized control in general has a reduced complexity in the control design and implementation. However, it may lead to deteriorated performance or even lost of closed-loop stability since in decentralized control the interconnections between the subsystems are totally neglected. These considerations motivate the recent research interests in distributed predictive control in which distributed local controllers communicate and exchange information with each other to coordinate their actions (Christofides, Liu, & Muñoz de la Peña, 2011; Christofides et al., in press; Liu, Chen, Muñoz de la Peña, & Christofides, 2010; Rawlings & Stewart, 2008; Scattolini, 2009) as well as research interests in coordination-based decentralized model predictive control (Cheng, Forbes, & Yip, 2007). Among different types of distributed predictive control systems, cooperative distributed predictive control has been proved to achieve the performance of corresponding centralized control systems in the context of linear systems (Christofides et al., 2011; Scattolini, 2009).

To select an appropriate control framework for an application, one important issue that one needs to consider is the achievable performance of the different control structures. Since early work on control performance assessment (Astrom, 1970; Harris, 1989), there are extensive studies on control performance assessment based on minimum variance control (MVC), linear quadratic Gaussian (LQG) control and other alternative benchmarks (see, for example, Harris, Boudreau, & MacGregor, 1996, 1999; Huang & Shah, 1999; Huang, Shah, & Kwok, 1997; Kadali & Huang, 2002; Qin & Yu, 2007 and references therein). It is also worth noting that in recent years, there are some efforts on assessing and tuning model predictive control (MPC) because of its wide applications in industries (Mayne, Rawlings, Rao, & Scokaert, 2000; Qin & Badgwell, 2003). These efforts aimed at optimally determining the MPC input and output variances based on MVC and LQG benchmarks (Xu, Huang, & Akande, 2007, 2011; Zhao, Su, Yong, & Chu, 2009, 2009). In another line of work (de Oliveira, Geromel, & Bernussou, 2002; Scherer, Gahinet, & Chilali, 1997), an H_2 controller parametrization method was proposed which provides an approach that can be applied to the performance assessment

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of centralized control systems. However, the direct application of these methods to the performance assessment of decentralized control systems may lead to unrealistic results because the interactions between the different subsystems and the inherent block-diagonal structure of decentralized control systems are not taken into account in the performance assessment.

The performance assessment of decentralized control has received less attention. There is a work that attempts to evaluate the best achievable decentralized control performance via parameterizing all decentralized stabilizing controllers which results in an infinite dimensional optimization problem (Sourlas & Manousiouthakis, 1995). However, most of the existing results try to characterize the upper or lower bounds on the performance of decentralized control. In Ko and Edgar (1998) and Jain and Lakshminarayanan (2007), approaches for finding upper bounds for decentralized control based on the MVC benchmark were developed. In Yuz and Goodwin (2003) and Kariwala, Forbes, and Meadows (2005), upper bounds were characterized by using the structure of the optimization problem. In Kariwala (2007), a lower bound on decentralized control performance was derived by considering impulse response coefficients of the closed-loop transfer function between disturbances and outputs. This approach was extended in Sendjaja and Kariwala (2012) by taking into account impulse response coefficients to reduce the conservativeness of the lower bound. Most of these results were based on the MVC benchmark. MVC, however, is not achievable or desirable in many practical applications since it is characterized by excessive control moves and has poor robustness (Huang & Shah, 1999).

In this work, an efficient approach for performance assessment of decentralized control systems based on a general quadratic (LQG-type) performance index which can take both control actions and system states into account is proposed. Inspired by the results in de Oliveira et al. (2002) and Scherer et al. (1997) on H_2 controller parameterizations, the performance assessment problem is formulated as an optimization problem subject to constraints in the form of linear matrix inequalities (LMIs) or bilinear matrix inequalities (BMIs) which explicitly take the block-diagonal structural constraint on decentralized control systems into account. Specifically, the proposed approach under the assumption that the full state feedback is available is first presented. The decentralized control performance assessment problem is solved in an iterative fashion based on the original optimization problem and an equivalent transformation of the original problem. This iterative approach can handle the block-diagonal structural constraint very efficiently and solves for both the best achievable performance and the corresponding decentralized control gains. Subsequently, the approach is extended to the case in which only output feedback is available. In this case, separation principle is used to divide the overall problem into two independent problems: a decentralized state feedback control problem and a decentralized observer design problem. The evaluation of the optimal decentralized observer gains is formulated as an optimization problem subject to LMIs and BMIs as well and solved also in an iterative fashion. Based on the obtained optimal decentralized controllers and observers, the best achievable control performance is evaluated. The application of the proposed approach to two examples including a reactor–separator chemical process example illustrates its applicability and effectiveness.

2. Problem description and preliminaries

2.1. System description

This work considers a class of linear systems composed of m interconnected subsystems where each of the subsystem can be described by the following discrete-time state-space model:

$$x_i(k+1) = A_{ii}x_i(k) + B_{ii}u_i(k) + \sum_{j=1}^{m, j\neq i}(A_{ij}x_j(k) + B_{ij}u_j(k)) + M_i w_i(k)$$
$$y_i(k) = C_i x_i(k) + N_i w_i(k) \tag{1}$$

where k indicates the time instants with $k = 0, 1, \ldots$, $x_i \in R^{n_i}$ is the state vector of subsystem i with $i = 1, \ldots, m$, $u_i \in R^{l_i}$ is the control input vector of subsystem i, $y_i \in R^{p_i}$ is the output vector of subsystem i, $w_i \in R^{q_i}$ is the external disturbance vector associated with subsystem i, and A_{ii}, A_{ij}, B_{ii}, B_{ij}, M_i, C_i and N_i are matrices/vectors of appropriate dimensions. Denote $x \in R^n$ as the state of the entire system which is composed of the states of the m subsystems, that is $x = [x_1^T \ldots x_i^T \ldots x_m^T]^T \in R^n$. The dynamics of x can be described as follows:

$$x(k+1) = Ax(k) + Bu(k) + Mw(k)$$
$$y(k) = Cx(k) + Nw(k) \tag{2}$$

where $u = [u_1^T \ldots u_i^T \ldots u_m^T]^T \in R^l$ is the entire system control input vector, $y = [y_1^T \ldots y_i^T \ldots y_m^T]^T \in R^p$ is the entire system output vector, $w = [w_1^T \ldots w_i^T \ldots w_m^T]^T \in R^q$ is the external disturbance vector. The matrices A, B, M, C, and N are appropriate compositions of the matrices/vectors associated with the subsystems and zeros whose explicit description are omitted for brevity.

It is assumed that the pair (A,B) and pair (A,M) are controllable and the pair (A,C) is observable. It is also assumed that w consists of independent unit Gaussian noise sequences satisfying

$$E[w(k)] = 0, \quad E[w(k)w(k)^T] = I \tag{3}$$

where $E[\cdot]$ denotes the expectation of a random variable. Note that there is no loss of generality in assuming that the covariance of w is a unit matrix. If $E[w(k)w(k)^T] = \Omega$, where Ω is a diagonal matrix, one can always normalize it by a proper scaling of the system matrices M and N of Eq. (2) without affecting the overall dynamics of the system.

2.2. Centralized control system

Define a variable z which will be used in the evaluation of the control performance as follows:

$$z = C_z x + D_z u \tag{4}$$

where C_z and D_z are matrices with appropriate dimensions.

Suppose that the system of Eq. (2) is regulated by an LQG controller which is formulated as follows for a time instant k:

$$u^*(t|k) = \min_{u(t)} \quad J_c(\tilde{z}(t)) \tag{5a}$$

$$\text{s.t.} \quad \tilde{x}(t+1) = A\tilde{x}(t) + Bu(t) \tag{5b}$$

$$\tilde{z}(t) = C_z\tilde{x}(t) + D_z u(t) \tag{5c}$$

$$\tilde{x}(k) = x(k) \tag{5d}$$

where $t \geq k$, $u^*(t|k)$ indicates the optimal control input trajectory, the variables $\tilde{x}$ and $\tilde{z}$ are the predicted system state and output z, and $x(k)$ is the state measurement or estimation at time instant k.

The objective of the controller is to minimize a cost function J_c which is defined as follows:

$$J_c(z) = \lim_{N\to\infty} E\left[\frac{1}{N}\sum_{i=0}^{N} z(t)^T z(t)\right] \tag{6}$$

which is the H_2 norm of the transfer function matrix from w to z, that is, $\|H_{wz}\|_2^2$. The cost function of Eq. (6) is also equivalent to the