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A generic approach to the design of decentralized linear output- feedback controllers☆

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Abstract

A sufficient condition for failure-tolerant performance stabilization in a desirable performance region under decentralized linear output-feedback is established. To exploit the flexibility in decentralized control beyond multivariable pole assignment, and to address the subsystem design objectives along with those of the overall system, a generic problem on decentralized linear output-feedback is then defined. The problem is reformulated in terms of a constrained nonlinear optimization problem. The proposed methodology results in the optimal reconciliation of failure-tolerant robust performance of the overall system, and (maximal) robustness, disturbance rejection, noninteractive performance, reliability and low actuator gains in the isolated subsystems in the face of unstructured perturbations in the controller and plant parameters. The effectiveness of the proposed approach is demonstrated by a numerical example.

Keywords: Decentralized linear output-feedback; Performance robustness; Failure tolerance; Minimal sensitivity; Disturbance rejection; Noninteractive performance; Optimization techniques

1. Introduction

In the broad sense, the existing results on large-scale systems appear in two main directions. On the one hand, some structural properties such as fixed modes, impulsive fixed modes, decentralized fixed modes, etc. (see [7,17,26,29] and the references therein) have been explored, and on the other hand, some stabilization methods have been developed (see [1–5,13,15–17,21,22,26,27,31,32] and the references therein). With reference to stabilization, the literature is teaming with algorithms. All the existing algorithms, however, suffer from some of the following defects: (a) dependence on full state information, and lack of: (b) performance robustness, (c) failure tolerance, (d) reliability, (e) disturbance rejection, (f) noninteractive performance, (g) low actuator gains, and (h) optimality. Moreover, the complex nature of the problem has encouraged the use of nonlinear control in many of the existing results. Nonlinear controllers, nonetheless, are more expensive and more difficult to implement than the linear ones. Thus, linear controllers are considered in this paper.

The first four of the above shortcomings are elaborated below.

(a) It is well-known that especially for large-scale systems state estimation is often infeasible and may even result in the curse of dimensionality [31]. Thus, output-feedback control is of special significance for high-order systems.

(b) A central issue in control systems design is that of robustness. Except few papers, e.g. [15,27], the existing decentralized robust control schemes address the problem of robust stabilization, not robust performance. The problem of robust stabilization as defined by disturbance attenuation has been considered in many works. In particular, in [32] a

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necessary and sufficient condition for the existence of a decentralized H_∞ controller was derived in terms of the feasibility problem of a bilinear matrix inequality (BMI). The paper presented a multistage design method; starting by a centralized H_∞ controller, they deformed the controller to a decentralized one in consecutive steps. At each step of the deformation, the BMI problem was solved as a linear matrix inequality (LMI) by suitably fixing one of the two matrix variables. A special restriction associated with this paper, and other robust H_∞-based controllers in general, is that it may be quite fragile, i.e., quite ill-conditioned in the face of uncertainties [19] in the controller parameters. A step towards performance robustness was taken in [24] by the introduction of the so-called guaranteed cost control. This, although being used in decentralized control methods, provides only an upper bound on a given performance index and does not address the uncertainties in the controller itself. It should also be emphasized that, in general, the robustness of the isolated subsystems (of a large-scale system) does not result in the robustness of the overall system and vice versa (Remark 4.1). Whilst the former is necessary for low sensitivity in each local subsystem, the latter is necessary for that in the overall system. Both of these issues are encapsulated in the proposed approach.

(c,d) A system is said to be reliable or failure/fault tolerant if it retains its nominal stability (and to some extent its nominal performance) despite the occurrence of fault in the components of its controllers/actuators/plant/sensors. Failure-tolerant control (FTC) methods fall in two main classes, passive FTC and active FTC, and a third class, passive and active integrated FTC. Decentralized FTC has been considered in many works, see e.g., [1,4,13,15] and the references therein. In this paper, actuator and/or sensor failures are addressed by robust controller design (passive FTC).

Very recently the first and second of the aforementioned defects, a and b, were partly rectified in [21]. In this paper, following the results of [2–5,15,16,20–22], the abovementioned shortcomings, a–h, are addressed. This work is organized as follows. In Section 2, the problem of finding suitable decentralized static output-feedback controllers for the subsystems of a large-scale system is formulated. The proposed formulation introduces some flexibility to the design procedure. In Section 3, a sufficient condition for failure-tolerant performance stabilization in a desirable performance region is established. In Section 4, in order to exploit the flexibility in decentralized control beyond multivariable pole placement, and to address the subsystem design objectives in addition to those of the overall system, a generic problem on decentralized linear output-feedback is defined. To solve this problem, its objectives are formulated separately. In particular, a new solution to the problem of minimal sensitivity design is presented. The above formulated objectives are then put back together in Section 5 where a restatement of the original problem is obtained in terms of a constrained nonlinear optimization problem. The proposed methodology results in the optimal reconciliation of failure-tolerant robust performance of the overall system, and (maximal) robustness, disturbance rejection, noninteractive performance, reliability and low actuator gains in the isolated subsystems in the face of unstructured perturbations in the controller and plant parameters. Finally, the effectiveness of the proposed approach is demonstrated by a numerical example.

Throughout the paper it is assumed that the desirable closed-loop eigenvalues are distinct, since they possess better robustness properties than the repeated ones. Also, since the design of a dynamic controller can be reduced to that of a static one [17,21], all the formulations are given for the static case. All the results are presented for output-feedback; state feedback thus follows directly. Besides, to distinguish between a large-scale system and its subsystems, the terms failure tolerance and reliability are used for them, respectively. For the sake of notational simplicity, it is assumed that the transfer functions of the actuators and sensors are one; an actuator/a sensor failure (i.e., a loop disconnection) is thus represented by the suppression of its controller gain to zero.

It should also be noted that in the literature (see e.g. [2,3,18,20,21,28]), by some misuse of the terminology, sometimes it is said that a matrix has (its eigenvalues have) low/minimal sensitivity to unstructured uncertainties in its elements if an upper bound (which is the condition number of its modal matrix) of the sensitivities of its eigenvalues is minimized/at its minimum. In other words, instead of minimizing the sensitivities themselves, an upper bound of the sensitivities is minimized. This terminology is used also in this paper. Moreover, since the derived condition for (failure-tolerant) performance stabilization has some inherent robustness to unstructured perturbations in the controller and plant parameters, the terminology (failure-tolerant) *performance robustness* of the overall system is used in this paper (see Section 4.5 for a precise explanation).

2. System description

Consider a large-scale system G with the state-space equations

$$\dot{x} = Ax + Bu,$$
$$y = Cx, \qquad (1)$$

where $A \in \mathbf{R}^{n\times n}$, $B \in \mathbf{R}^{n\times m}$ and $C \in \mathbf{R}^{p\times n}$ are the system state, input and output matrices, respectively, and B and C are block diagonal. Let the system be partitioned into N linear-time-invariant subsystems G_i described by

$$\dot{x}_i = A_{ii}x_i + \sum_{j=1}^{N} A_{ij}x_j + B_{ii}u_i, \quad j \neq i,$$
$$y_i = C_{ii}x_i, \qquad (2)$$