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Retrofit control: Localization of controller design and implementation[☆]

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ABSTRACT

In this paper, we propose a retrofit control method for stable network systems. The proposed approach is a control method that, rather than an entire system model, requires a model of the subsystem of interest for controller design. To design the retrofit controller, we use a novel approach based on hierarchical state-space expansion that generates a higher-dimensional cascade realization of a given network system. The upstream dynamics of the cascade realization corresponds to an isolated model of the subsystem of interest, which is stabilized by a local controller. The downstream dynamics can be seen as a dynamical model representing the propagation of interference signals among subsystems, the stability of which is equivalent to that of the original system. This cascade structure enables a systematic analysis of both the stability and control performance of the resultant closed-loop system. The resultant retrofit controller is formed as a cascade interconnection of the local controller and an output rectifier that rectifies an output signal of the subsystem of interest so as to conform to an output signal of the isolated subsystem model while acquiring complementary signals neglected in the local controller design, such as interconnection signals from neighboring subsystems. Finally, the efficiency of the retrofit control method is demonstrated through numerical examples of power systems control and vehicle platoon control.

1. Introduction

Recent developments in computer networking technology have enabled large-scale systems to be operated in a spatially distributed fashion. For example, in power systems control (Kundur, 1994), a system operator manages distributed power plants with distributed measurement units to meet the demands of a number of consumers. Towards the systematic control of such large-scale network systems, decentralized and distributed control techniques have been studied over the past half century; see Šiljak (1991) and Šiljak and Zečević (2005) and the references therein. In this line of study, there are found several illustrative results that highlight the difficulty of controller design problems with structural constraints (Blondel & Tsitsiklis, 2000; Rotkowitz & Lall, 2006).

Starting from different perspectives, a number of decentralized and distributed control methods have been devised to overcome the difficulty of structured controller design. In this paper, we refer to structured control in which the subcontrollers have no direct communication among them as *decentralized control* and structured control in which subcontrollers have communication with neighboring subcontrollers as *distributed control*. For example, Šiljak (1972), Tan and Ikeda (1990) and Wang and Davison (1973) report decentralized control methods on the basis of connective stability or related coprime factorization. Furthermore, Wang, Xie, and de Souza (1995) introduces a decentralized control method based on small gain-type stability conditions or dissipation inequalities considering model uncertainty. Similar dissipativity-based approaches are used in Bamieh, Paganini, and Dahleh (2002), D'Andrea and Dullerud (2003) and Langbort, Chandra, and D'Andrea (2004) also for distributed control, and Rantzer (2015) introduces a distributed control method for positive systems that has good scalability. However, most existing decentralized and distributed control methods do not meet practical requirements, because they require an entire system model for controller design, and handle the design of all subcontrollers simultaneously. In fact, for large-scale systems control, it is not generally reasonable to assume the availability of an entire system model, because

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subsystem parameters and controller structures may not be fully known in the event of degradation, modification, and development of the subcontrollers and subsystems. From this viewpoint, such *centralized design* of decentralized and distributed controllers is impractical for large-scale systems, even though the resulting controller may be implemented in a distributed fashion.

To overcome this issue, the concept of *distributed design* has been introduced in Langbort and Delvenne (2010), where the authors discuss the performance limitations of linear quadratic regulators designed in a distributed manner. This result has been generalized to the case of networks composed of multi-dimensional subsystems, the states of which are fully controlled (Farokhi, Langbort, & Johansson, 2013). Furthermore, in Ebihara, Peaucelle, and Arzelier (2012), a distributed design method for decentralized control using the $\mathcal{L}_1$-norm has been developed for positive linear systems. Because each focuses on a particular class of systems, it is not simple to generalize their results to a broader class of systems. As a related work, Farokhi and Johansson (2015) discusses the distributed design of optimal state-feedback controllers for discrete-time linear systems with stochastically-varying model parameters. Even though the design of each subsystem controller is performed based on its local model information, the resultant optimal controller is a centralized controller in the sense that each subcontroller requires the feedback of full state information.

Another approach towards distributed design is control synthesis based on passivity, or, more generally, dissipativity and passivity shortage (Sepulchre, Jankovic, & Kokotovic, 2012; Willems, 1972a, b). It is known that appropriate interconnections of passive subsystems retain the passivity. This implies that the entire network system can be guaranteed to be stable provided that each subsystem is individually designed to be passive. However, in general, the design of subsystem interconnection structures is difficult to perform in a distributed manner. For example, the interconnection matrix for passive subsystems is required to be negative semidefinite (Hill & Moylan, 1978), and that for passivity-short subsystems is required to have a low-gain property in terms of eigenvalues in addition to negative semidefiniteness (Qu & Simaan, 2014). These characteristics are not fully determined by local interconnection structures.

With this background, the present paper develops a distributed design method for decentralized control that does not require an entire system model. Instead, only a model of the subsystem of interest is needed for controller design, an approach that we call *retrofit control*. This retrofit control is based on the premise that a given network system, which can involve nonlinearity, is originally stable, and the interconnection signal flowing into the subsystem of interest is measurable. It is shown that the resultant closed-loop system remains stable and its control performance can be improved with respect to a suitable measure. This enables the scalable development of large-scale network systems because, towards further performance improvement, it is possible to consider the retrofit control of other subsystems while keeping the entire system stable.

To develop such a retrofit control method, we use a novel approach based on *hierarchical state-space expansion*, which generates a higher-dimensional cascade realization of the given network system, called a *hierarchical realization*. Its upstream dynamics corresponds to an isolated model of the subsystem of interest, decoupled from the other subsystems. A controller that stabilizes the isolated subsystem model is called a local controller. The downstream dynamics can be seen as a dynamical model that represents the propagation of interference signals among subsystems, the stability of which is equivalent to that of the original network system. It is shown that stabilization and improved control performance can be systematically realized. The resultant retrofit controller, which measures a local output signal and an interconnection signal from neighboring subsystems, is formed as a cascade interconnection of the local controller designed for the isolated subsystem model and a dynamical rectifier, which we call an *output rectifier*. As a generalization of this result, we further consider removing the assumption of the interconnection signal measurements. The resultant retrofit controller, which only measures the state of the subsystem of interest, also offers guaranteed stability and improved control performance.

The foundations of our contribution can be found in various previous studies. Based on the inclusion principle, relevant to state-space expansion, a distributed control method has been developed in İftar (1993) and Ikeda, Šiljak, and White (1984). Although some applications to vehicle control are described in Stipanović, Inalhan, Teo, and Tomlin (2004), this method does not necessarily produce a stabilizing controller for general systems. This limitation comes from the fact that a decentralized control design with an algebraic constraint is needed for an expanded system. Moreover, the controller is designed in a centralized fashion. This contrasts with the proposed retrofit control, which enables the systematic distributed design of decentralized control. This paper builds on preliminary versions, unifying the results of hierarchical distributed control in Sadamoto, Ishizaki, and Imura (2014) and nonlinear retrofit control (Sadamoto, Ishizaki, Imura, Sandberg, & Johansson, 2016) on the basis of the parameterized hierarchical state-space expansion. This paper also provides detailed mathematical proofs and extensive numerical examples to underline the significance of the retrofit control.

Finally, we make a comparison with robust control (Zhou, Doyle, & Glover, 1996). In fact, localized controller design may be performed by a standard robust control method if all of the neighboring subsystems other than the subsystem of interest are regarded as model uncertainty. However, this approach generally results in conservative consequences due to, e.g., the overestimation of uncertain system gains especially when available information on neighboring subsystems is limited. In contrast, the retrofit control is just reliant on the stability of a given network system. The retrofit controller guarantees robust stability in the sense that the entire closed-loop system is stable for any variations of neighboring subsystems other than the subsystem of interest, the norm bound of which is not assumed, as long as the given network system is originally stable.

The remainder of this paper is organized as follows. In Section 2.1, we formulate a fundamental problem of retrofit control. Then, in Section 2.2, hierarchical state-space expansion is introduced to solve it. Section 2.3 discusses the generalization of the proposed approach to nonlinear systems, amongst other remarks. In Section 3.1, we formulate a retrofit control problem without the assumption of interconnection signal measurements, and then we provide a solution in Section 3.2. Section 4 contains numerical examples of power systems and vehicle platoon control, demonstrating the results in Sections 2 and 3, respectively. Finally, concluding remarks are given in Section 5.

Notation We denote the set of real numbers by $\mathbb{R}$, the identity matrix by I, the transpose of a matrix M by M^{T}, the image of a matrix M by im M, the kernel by ker M, a left inverse of a left invertible matrix P by $P^{\dagger}$, the $\mathcal{L}_2$-norm of a square-integrable function f by $\|f\|_{\mathcal{L}_2}$, the $\mathcal{H}_2$-norm of a stable proper transfer matrix G by $\|G\|_{\mathcal{H}_2}$, and the $\mathcal{H}_\infty$-norm of a stable transfer matrix G by $\|G\|_{\mathcal{H}_\infty}$. A map $\mathcal{F}$ is said to be a dynamical map if the triplet (x, u, y) with $y = \mathcal{F}(u)$ solves a system of differential equations

$$\dot{x} = f(x, u) \quad y = g(x, u)$$

with some functions f and g, and an initial value $x(0)$.