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Tradeoffs between quality-of-control and quality-of-service in large-scale nonlinear networked control systems[☆]

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ABSTRACT

In this paper we study input-to-state stability (ISS) of large-scale networked control systems (NCSs) in which sensors, controllers and actuators are connected via multiple (local) communication networks which operate asynchronously and independently of each other. We model the large-scale NCS as an interconnection of hybrid subsystems, and establish rather natural conditions which guarantee that all subsystems are ISS, and have an associated ISS Lyapunov function. An ISS Lyapunov function for the overall system is constructed based on the ISS Lyapunov functions of the subsystems and the interconnection gains. The control performance, or "*quality-of-control*", of the overall system is then viewed in terms of the convergence rate and ISS gain of the associated ISS Lyapunov function. Additionally, the "*quality-of-service*" of the communication networks is viewed in terms of the maximum allowable transmission interval (MATI) and the maximum allowable delay (MAD) of the network, and we show that the allowable quality-of-service of the communication networks is constrained by the required ISS gains and convergence rate of the hybrid subsystem corresponding to that network. Our results show that the quality-of-control of the overall system can be improved (or degraded) by improving (or relaxing) the quality-of-service of the communication networks. Alternatively, when relaxing the quality-of-service of one communication network, we can retain the quality-of-control of the overall system by improving the quality-of-service of one or more of the other communication networks. Our general framework will formally show these intuitive and insightful tradeoffs.

1. Introduction

In networked control systems (NCSs), sensor and actuator data is transmitted via shared (wired or wireless) communication networks. This offers several advantages over conventional control systems, in which sensor and actuation data is transmitted using dedicated point-to-point wired links, including reduced installation costs, better maintainability and greater flexibility. On the other hand, shared communication networks also introduce communication errors as a result of network imperfections such as varying transmission intervals and delays, and quantization errors. Additionally, since a network is usually shared by multiple sensor, controller and actuator nodes, there is a need for a medium access control

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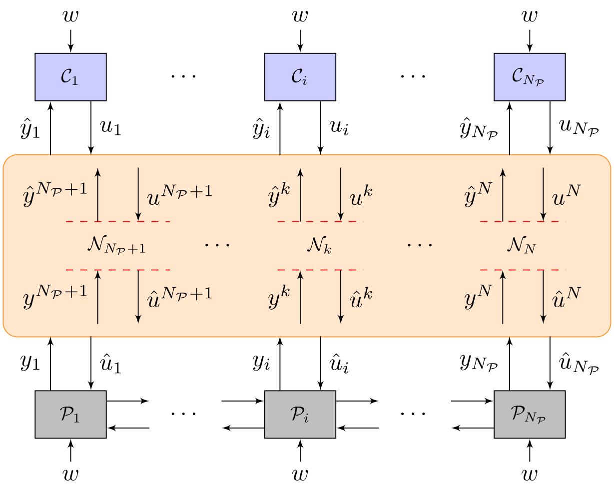

Fig. 1. The networked control setup considered in this paper, in which $N_{\mathcal{P}} \in \mathbb{N}$ (coupled) plants $\mathcal{P}_i$ and their controllers $\mathcal{C}_i$, $i \in \{1, 2, \ldots, N_{\mathcal{P}}\}$, are connected via $N_{\mathcal{N}} \in \mathbb{N}$ communication networks $\mathcal{N}_k$, $k \in \{N_{\mathcal{P}}+1, N_{\mathcal{P}}+2, \ldots, N_{\mathcal{P}}+N_{\mathcal{N}}\}$. The variable w denotes the disturbance acting on the plants.

(MAC) protocol that governs the access of the nodes to the network in order to prevent packet losses as much as possible. As a result, one needs to design the communication networks and controllers in such a way that the NCS displays desirable behavior in terms of stability and performance that is robust to these network-induced phenomena.

In most of the available literature on NCSs it is assumed that all sensor and actuation data is transmitted over *one* single communication network, see, e.g., [1–6]. These works provide insightful tradeoffs of the network performance ("*quality-of-service*", expressed in terms of, e.g., maximum allowable transmission interval (MATI), maximum allowable delay (MAD), network reliability, etc.) versus a certain control performance. However, it is not always reasonable to assume that there is one global communication network. For example, in the control of large-scale systems it is often more natural and cost-efficient to use a local controller for each subsystem than one global controller for the whole system. In such a system, it is much more reasonable to close the local control loops over several local communication networks, instead of (assuming the presence of only) one global communication network. This leads to large-scale NCSs with multiple local communication networks operating independently and asynchronously. Clearly, the required network parameters are to be formulated locally for each individual network, preferably based on local conditions involving only local dynamics of the subsystems and possibly a condition on the interconnection. The reason is that global conditions based on the dynamics of the complete large-scale system quickly become intractable when the overall system contains a large number of subsystems.

In this paper the objective is to provide a general framework for the stability analysis of large-scale networked control systems with multiple local communication networks, and to provide, based on local conditions, network parameters for each local communication network such that stability of the overall system is guaranteed. In particular, we focus on the general NCS setup shown in Fig. 1, which generalizes the setups considered in [1,7,8]. However, our results are also applicable to other NCS setups that are not captured by Fig. 1.

We are interested in input-to-state stability (ISS) [9] of the complete system of Fig. 1, which is a very useful concept of stability for nonlinear systems with inputs and interconnected systems, and has been studied in the context of NCSs in, e.g., [3]. The theory on interconnections of (hybrid) ISS systems is already well-developed (see, e.g., [10–18]) and seems well-suited for the stability analysis of large-scale networked control systems, as long as they can be modeled as an interconnection of ISS subsystems. This was already demonstrated in [19], which considers a (networked) interconnection of subsystems, and derives upper bounds on the gains for the communication links guaranteeing a small-gain condition of the overall network. Besides, in [19] extensions of the small-gain theorems of [11,13] are given that include subsystems that are only pre-globally stable (pre-GS) and not ISS. However, the paper does not connect local quality-of-service parameters such as MATI and MAD to the ISS gains (or pre-GS gains) of the communication links.

In this paper, we show that communication networks using a uniformly globally exponentially stable (UGES) [2] MAC protocol give rise to (hybrid) network-induced error systems that are ISS, and that the convergence rate and ISS gains of the network-induced error systems are related to the MATI and MAD of the corresponding communication network. By considering the MATI and MAD of the communication networks as design parameters, the convergence rate and ISS gains of the related hybrid network-induced error system can be scaled. Showing that the network-induced error systems are ISS enables us to model the large-scale NCS as an interconnection of hybrid ISS subsystems, and to extend the work in [7] to a more general networked control setup using the (hybrid) small-gain theory of [13,17]. Moreover, based on the ISS Lyapunov functions of the subsystems, we provide an ISS Lyapunov function for the overall system, an upper bound on its ISS gain, and a lower bound on its convergence rate. The control performance, or "*quality-of-control*" of the overall system is then viewed in terms of the convergence rate and ISS gain of the corresponding ISS Lyapunov function. As a result, the quality-of-control of the overall system can be tuned by varying the ISS gains and convergence rates of the network-induced error systems (which

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