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# Quasi-decentralized model-based networked control of process systems

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ABSTRACT

This paper develops a quasi-decentralized control framework for plants with distributed, interconnected units that exchange information over a shared communication network. In this architecture, each unit in the plant has a local control system that communicates with the plant supervisor – and with other local control systems – through a shared communication medium. The objective is to design an integrated control and communication strategy that ensures the desired closed-loop stability and performance for the plant while minimizing network utilization and communication costs. The idea is to reduce the exchange of information between the local control systems as much as possible without sacrificing stability of the individual units and the overall plant. To this end, dynamic models of the interconnected units are embedded in the local control system of each unit to provide it with an estimate of the evolution of its neighbors when measurements are not transmitted through the network. The use of a model to recreate the interactions of a given unit with one of its neighbors allows the sensor suite of the neighboring unit to send its data in a discrete fashion since the model can provide an approximation of the unit's dynamics. The state of each model is then updated using the actual state of the corresponding unit provided by its sensors at discrete time instances to compensate for model uncertainty. By formulating the networked closed-loop plant as a hybrid system, an explicit characterization of the maximum allowable update period (i.e., minimum cross communication frequency) between each control system and the sensors of its neighboring units is obtained in terms of the degree of mismatch between the dynamics of the units and the models used to describe them. The developed control strategy is illustrated using a network of interconnected chemical reactors with recycle.



## 1. Introduction

Modern industrial and commercial systems, such as chemical plants and manufacturing processes are large-scale dynamical systems that involve complex, distributed arrangements of interconnected subsystems which are tightly integrated through mass, energy and information flows. Traditionally, control of plants with geographically distributed interconnected units has been studied within either the centralized or decentralized control frameworks. In the centralized setting, all measurements are collected and sent to a central unit for processing, and the resultant control commands are then sent back to the plant. While centralized control is known to provide the best performance – because it imposes the least constraints on the control structure – the computational and organizational complexity associated with centralized controllers often makes their implementation impractical, especially for plants with complex dynamics. Also, the consequences of failures in a centralized controller can be detrimental to the entire plant.

These considerations have motivated significant work on decentralized control. In this paradigm, the plant is decomposed into a number of simpler subsystems (typically based on functional and/or time-scale differences of the unit operations) with interconnections, and a number of local controllers are connected to each distributed subsystem with no signal transfer taking place between different local controllers. Decentralized control of multi-unit plants can reduce complexity in the controller design and implementation, and can also provide flexibility in dealing with local controller failures. However, since in this structure the interconnections between the constituent subsystems are totally neglected, the closed-loop performance of the plant may deteriorate, and in some cases stability may be lost. Significant research work has explored in depth the benefits and limitations of decentralized controllers as well as possible ways of overcoming some of their limitations (see for example, Baldea, Daoutidis, & Kumar, 2006; Cui & Jacobsen, 2002; Lunze, 1992; Price & Georgakis, 1993; Sandell, Varaiya, Athans, & Safonov, 1978; Siljak, 1991; Skogestad, 2004; Zheng, Mahajanam, & Douglas, 1999 and the references therein). In recent times, there also has been some interest in studying plant-wide control problems within the distributed model predictive control framework (see for example, Camponogara, Jia, Krogh,

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& Talukdar, 2002; Katebi & Johnson, 1997; Mercangoz & Doyle, 2006; Venkat, Rawlings, & Wright, 2004). Other examples of recent works on control of process networks include the development of a plant-wide control strategy based on the integration of linear and nonlinear model predictive control coupled with a plant decomposition procedure (Zhu & Henson, 2002), the development of a framework for the analysis and stabilization of process networks based on passivity and concepts from thermodynamics (Hangos, Alonso, Perkins, & Ydstie, 1999; Garcia-Onorio & Ydstie, 2004; Ydstie, 2002), the design of recycle systems using nonlinear analysis (Kiss, Bildea, Dimian, & Iedema, 2005), the development of agent-based systems to control reactor networks (Tatara, Birol, Teymor, & Cinar, 2005; Tetiker et al., 2006), and the analysis and control of integrated process networks using time-scale decomposition and singular perturbation techniques (Baldea, Daoutidis, & Kumar, 2006; Kumar & Daoutidis, 2002).

To solve the problem where a decentralized control structure cannot provide the required stability and performance properties, and to avoid the complexity and lack of flexibility associated with traditional centralized control, a quasi-decentralized control strategy with cross communication between the plant units offers a suitable compromise. The term quasi-decentralized control refers to a situation in which most signals used for control are collected and processed locally—although some signals (the total number of which is kept to a minimum) still need to be transferred between local units and controllers to adequately account for the interactions between the different units and minimize the propagation of disturbances and process upsets from one unit to another. One of the key problems that need to be addressed in the design of quasi-decentralized control systems is how to coordinate the control and communication functions and how to account for possible limitations of the communication medium in the formulation and solution of the control problem. This is an important problem in view of the increased reliance in the process industries in recent years on sensor and control systems that are accessed over communication networks rather than hardwired (see for example, Christofides et al., 2007; Christofides & El-Farra, 2005; El-Farra, Gani, & Christofides, 2005). The traditional solution for exchanging information and control signals in an industrial plant is point-to-point communication, which involves a wire connecting the central control computer with each sensor or actuator point, and has been successfully implemented for decades. As the size and complexity of industrial systems continue to grow, however, the complexity and cost of installing and maintaining hard-wired control systems become significant. These considerations, coupled with the significant growth in computing and networking abilities in recent times, as well as the rapid advances in actuator and sensor technologies, have led to an increased reliance on distributed computing and process operations across computer networks.

Compared with dedicated, point-to-point cables, communication networks have many advantages, such as reduced installation and maintenance time and costs, flexibility and ease of diagnosis and reconfiguration, and enhanced fault-tolerance and supervisory control. Yet, control over networks also poses a number of fundamental issues that need to be addressed before plant operation can take full advantage of their potential. These issues, which stem from limitations on the information transmission and processing capabilities of the communication medium, challenge many of the assumptions in traditional process control theory dealing with the study of dynamical systems linked through ideal channels. While communication limitations have not been a major concern in traditional process control – due in part to the typically slow dynamics of chemical plants and the availability of reliable industry-standard dedicated communication networks with high communication rates – there are a number of factors that motivate re-examining this paradigm and incorporating communication issues explicitly in the controller design framework. For example, for fast-acting control loops, such as local regulatory control involving flows or gas pressure, communication disruptions and delays can degrade closed-loop performance and may even lead to instability. Also, as the shrinkage in process equipment size (e.g., micro-reactors) continues to make the time scales involved in chemical processing get progressively smaller, there will be a greater need to investigate the effect of communication delays on control system performance. Finally, as the trend towards augmenting dedicated control networks with low-cost wireless sensor and actuator networks in the process industry continues to take hold in order to achieve high-density sensing and actuation (e.g., Song, Mok, Chen, & Nixon, 2006), the need to account for communication costs in the controller design framework becomes increasingly apparent. In this context, communication limitations arise both from the disruptions caused by interference in the field, device failure, or environmental impact, as well as the inherent constraints on the power, computation and communication capabilities of the wireless devices.

The design of a quasi-decentralized control strategy that enforces the desired closed-loop objectives with minimal cross communication between the component subsystems is an appealing goal since it reduces reliance on the communication medium and helps save on communication costs. This is an important consideration particularly when the communication medium is a (potentially unreliable) wireless sensor network where conserving network resources is key to prolonging the service life of the network. Beyond saving on communication costs, the study of this problem provides an assessment of the robustness of a given networked control system, and allows designers to identify the fundamental limits on the tolerance of a given networked control system to communication suspension and thus helps determine a priori whether the desired control objectives can be met with a certain kind of network. This can be a major consideration that guides the design of the networked control system. While the emerging paradigm of control over networks (see for example, Hokayem & Abdallah, 2004; Mhaskar, Gani, McFall, Christofides, & Davis, 2007; Montestruque & Antsaklis, 2003; Munoz de la Pena & Christofides, 2007; Nesić & Teel, 2004; Tipsuwan & Chow, 2003; Xu & Hespanha, 2004; Walsh, Ye, & Bushnell, 2002; Zhang, Branicky, & Phillips, 2001 for some results and references in this area) provides a natural framework to address the issues of control and communication integration, the majority of research studies on networked control systems have focused mainly on single-unit processes using a centralized control architecture. As discussed earlier, a centralized control scheme implemented over a network is not always the best choice for the structure of the controller in a plant-wide setting. An additional drawback in the context of networked control systems is the reduced robustness against failures in the communication medium (El-Farra, 2005). By comparison, results on networked control of multi-unit plants with tightly interconnected units have been more limited.

Motivated by these considerations, we develop in this work a quasi-decentralized control framework for multi-unit plants with tightly interconnected units that exchange information over a shared communication network. In this architecture, each unit in the plant has a local control system that communicates with the plant supervisor – and with other local control systems – through a shared communication medium. We address the problem of designing an integrated control and communication policy that ensures the desired closed-loop stability and performance while keeping communication through the network to a minimum in order to save on communication costs. To this end, we embed in the local control system of each unit a set of dynamic models that pro-