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Resource aware quasi-decentralized control of networked process systems over wireless sensor networks

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ABSTRACT

This paper develops an integrated model-based networked control and scheduling framework for plants with interconnected units and distributed control systems that exchange information using a resource-constrained wireless sensor network (WSN). The framework aims to enforce closed-loop stability while simultaneously minimizing the rate at which each node in the WSN must collect and transmit measurements. Initially, the exchange of information between the local control systems is reduced by embedding, within each control system, dynamic models that provide forecasts of the evolution of the plant units when measurements are not transmitted through the WSN, and updating the state of each model when communication is re-established at discrete time instances. To further reduce WSN utilization, only a subset of the deployed sensor suites are allowed to transmit their data at any given time to provide updates to their target models according to a certain scheduling strategy. By formulating the networked closed-loop plant as a combined discrete-continuous system, explicit characterizations of both the stability and performance properties of the networked closed-loop system under state and output feedback control are obtained in terms of the communication rate, the sensor transmission schedule, the accuracy of the models, as well as the controller and observer design parameters. The results are illustrated using a chemical plant example where it is shown that by judicious management of the interplays between the control, communication and scheduling design parameters, it is possible to enhance the savings in WSN resource utilization beyond what is possible with concurrent transmission configurations.

1. Introduction

The convergence of recent advances in sensor manufacturing, wireless communications and digital electronics has produced low-cost wireless sensor networks (WSNs) that can be installed for a fraction of the cost of wired devices (e.g., see Kumar, 2001; Akyildiz et al., 2002; Herrera, 2004). WSNs offer unprecedented flexibility ranging from high density sensing capabilities to deployment in areas where wired devices may be difficult or impossible to deploy (such as inside waterways and high-temperature areas in oil refineries). Augmenting existing process control systems with additional WSNs has the potential to expand the capabilities of the existing control technology beyond what is feasible with the wired networked architectures alone. Specifically, deploying WSNs throughout the plant and interfacing those devices with the existing control systems permit collecting and broadly disseminating additional real-time information about the state of the plant units which in turn can be used to enhance the performance and robustness of the plant operations. The extra information, together with the increased levels of sensor redundancy achieved with WSNs, also enable achieving proactive fault-tolerance and real-time plant reconfiguration based on anticipated market demand changes. These are appealing goals that coincide with the growing calls (Ydstie, 2002; Christofides et al., 2007) over the last few years for expanding the traditional process control and operations paradigm in the direction of smart plant operations.

To harness the full potential of WSNs in process control, there is a need to address the fundamental challenges introduced by this technology from a control point of view. One of the main challenges to be addressed when deploying a low-cost WSN for control is that of handling the inherent constraints on network resources, including the limitations on the computation, processing and communication capabilities. Other constraints such as limited power (battery energy) are also important when the WSN is deployed in harsh or inaccessible environments where a continuous power supply is not feasible and the wireless devices have to rely on battery power instead (e.g., Song et al., 2006). These issues, together with many others that arise in the context of communication networks such as bandwidth limitations, network-induced delays, data losses and real-time scheduling constraints, have motivated a significant and growing body of research

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work in the area of control over networks (e.g., see Zhang et al., 2001; Tipsuwan and Chow, 2003; Hokayem and Abdallah, 2004; Antsaklis and Baillieul, 2004; Zhang et al., 2005; Yang, 2006; Hespanha et al., 2007; Heidarinejad et al., 2011 for some results and references in this area).

A tradeoff usually exists between the achievable control performance and the extent of network resource utilization. Specifically, maximizing the control performance requires continuous (or at least frequent) collection of data and disseminating it broadly to the target control systems. On the other hand, the limited resources of a WSN, together with the difficulty of frequent battery replacement in a plant environment, suggest that sensing and communication should be reduced in order to aggressively conserve resources and extend the lifetime of the network as much as possible. Realizing the potential of WSNs to improve plant-wide control requires proper characterization and management of this tradeoff.

An effort to address this problem in the context of plant-wide control was initiated in Sun and El-Farra (2008) where a quasi-decentralized networked control architecture was developed for plants with interconnected units that exchange information over a shared communication network. The main idea – inspired by the results in Montestruque and Antsaklis (2003) – was to reduce the rate at which the data are exchanged between the local control systems as much as possible (without sacrificing stability) by: (a) embedding in the local control system of each unit suitable models that provide estimates of the evolution of the neighboring units when measurements are not transmitted through the network and (b) updating the state of each model using the actual state of the corresponding unit provided by its sensor suite at discrete time instances to compensate for possible model uncertainty. Beyond generalizing the model-based networked control structure developed in Montestruque and Antsaklis (2003) to address the problem of networked control of distributed multi-unit plants, the results of this effort also led to an explicit characterization of the minimum allowable communication rate for the case when all sensor suites of the plant units communicate their measurements over the network concurrently and are given simultaneous access to the network.

In addition to controlling the transmission rates of individual sensors in the network, another important way of conserving the WSN resources is to select and activate only a subset of the deployed sensor suites at any given time to communicate with the rest of the plant. Under this restriction, the stability and performance characteristics of each unit in the plant become dependent not only on the controller design but also on the selection of the scheduling strategy that, at any time, determines the order in which the sensor suites of the neighboring units transmit their information. Forcing the different subsystems to transmit their data at different times (rather than simultaneously) creates opportunities for providing a more selective and targeted correction to the models' estimation errors, such that the models with the largest uncertainties can receive more timely updates than is feasible under the simultaneous transmissions configuration where all models in all units are updated simultaneously. By careful selection of the transmission schedule, it may therefore be possible to further reduce the rate at which the WSN nodes transmit their data. The extra savings in communication costs help prolong the service life of the network.

Motivated by these considerations, we present in this work a model-based sensor scheduling approach for enhancing power management in WSNs deployed within a large-scale distributed plant with interconnected processing units. The objective is to find an optimal strategy for establishing and terminating communication between the sensors suites (or nodes) of the WSN and the target controllers that minimizes the rate at which each node in the WSN must collect and disseminate data to the rest of the plant without jeopardizing closed-loop stability. To address this problem, we initially design a quasi-decentralized control structure in which a family of local control systems (that rely each on a dedicated communication network) communicate with one another through a plant-wide WSN to account for the interactions between the units and minimize disturbance propagation. Embedded in each control system is a set of models that provide an approximation of the interactions between each unit and its neighbors when measurements are not transmitted through the WSN. The state of each model is updated using actual measurements from the corresponding unit when communication is re-established. Since the wireless sensor suites of the different units are forced to transmit their data at different times, the models within each control system will be updated at different times according to the chosen transmission schedule.

The rest of the paper is organized as follows. Following some preliminaries in Section 2, the networked control and scheduling problem is formulated. Sections 3 and 4 then present the quasi-decentralized control structure and describe its implementation using the WSN with the aid of process models and sensor transmission scheduling under both full-state and output feedback control formulations, respectively. The networked scheduled closed-loop system is formulated and analyzed, and precise conditions for closed-loop stability are provided in terms of the update period between the wireless sensor suite of each unit and its neighboring subsystems, the scheduling strategy for sensor transmissions, as well as the accuracy of the models and the choice of controller and observer designs. The performance properties of the scheduled closed-loop system are then analyzed in Section 5 and used to further aid in selecting the optimal transmission schedule. We show how the stability and performance criteria provide systematic tools that can guide the search for optimal transmission schedules that achieve the biggest savings in WSN resource utilization. The results are illustrated in Section 6 using a chemical plant example, and concluding remarks are given in Section 7.

2. Preliminaries

2.1. Plant description

We consider a large-scale distributed plant composed of n interconnected processing units, represented by the following state-space description:

$$\dot{x}_1 = A_1 x_1 + B_1 u_1 + \sum_{j=2}^{n} A_{1j} x_j, \quad y_1 = C_1 x_1$$

$$\dot{x}_2 = A_2 x_2 + B_2 u_2 + \sum_{j=1, j\neq 2}^{n} A_{2j} x_j, \quad y_2 = C_2 x_2$$

$$\vdots$$

$$\dot{x}_n = A_n x_n + B_n u_n + \sum_{j=1}^{n-1} A_{nj} x_j, \quad y_n = C_n x_n \tag{1}$$

where $x_i := [x_i^{(1)}\ x_i^{(2)}\ \cdots\ x_i^{(p_i)}]^T \in \mathbb{R}^{p_i}$ denotes the vector of process state variables associated with the i-th processing unit, p_i is the number of state variables in the i-th unit, $y_i := [y_i^{(1)}\ y_i^{(2)} \cdots y_i^{(q_i)}]^T \in \mathbb{R}^{q_i}$ and $u_i := [u_i^{(1)}\ u_i^{(2)}\ \cdots\ u_i^{(r_i)}]^T \in \mathrm{I\,R}^{r_i}$ denote the vector of measured outputs and manipulated inputs associated with the i-th processing unit, respectively. x^T denotes the transpose of a column vector x, A_i, B_i, A_{ij} and C_i are constant matrices. The interconnection term $A_{ij}x_j$, where $i \neq j$, describes how the dynamics of the i-th unit are influenced by the j-th unit in the plant. Note from the summation notation in (1) that each processing unit can in general be connected to all the other units in the plant.