4-12-2011

Architecture for a Fully Distributed Wireless Control Network

Miroslav Pajic
University of Pennsylvania, pajic@seas.upenn.edu

Shreyas Sundaram
University of Waterloo

Mansimar Aneja
University of Pennsylvania, manismar@seas.upenn.edu

Srinivas Vemuri
University of Pennsylvania, svemuri@seas.upenn.edu

George Pappas
University of Pennsylvania, pappasg@cis.upenn.edu

See next page for additional authors

Recommended Citation

Miroslav Pajic, Shreyas Sundaram, Mansimar Aneja, Srinivas Vemuri, George Pappas, and Rahul Mangharam, "Architecture for a Fully Distributed Wireless Control Network", . April 2011.

@INPROCEEDINGS{wcndemo_ipsn11,
author={Pajic, M. and Sundaram, S. and Aneja, M. and Vemuri, S. and Mangharam, R. and Pappas, G.J.},
booktitle={Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on},
title={Architecture for a fully distributed Wireless Control Network},
year={2011},
pages={117-118},
keywords={distillation equipment;distributed parameter systems;networked control systems;process control;telecommunication control;wireless sensor networks;Simulink;distillation column control;distributed wireless control network;process control problem;process-in-the-loop simulation;wireless actuators;wireless networked control systems;wireless nodes;wireless sensors;Distillation equipment;Fires;Process control;Real

Architecture for a Fully Distributed Wireless Control Network

Abstract
We demonstrate a distributed scheme for control over wireless networks. In our previous work, we introduced the concept of a Wireless Control Network (WCN), where the network itself, with no centralized node, acts as the controller. In this demonstration, we show how the WCN can be utilized for distillation column control, a well-known process control problem. To illustrate the use of a WCN, we have utilized a process-in-the-loop simulation, where the behavior of a distillation column was simulated in Simulink and interfaced with an actual, physical network (used as the control network), which consists of several wireless nodes, sensors and actuators. The goal of this demonstration is to show the benefits of a fully-distributed robust wireless control/actuator network, which include simple scheduling, scalability and compositionality.

Keywords
Control over wireless networks, wireless sensor networks, control systems, cyber-physical systems

Disciplines
Computer Engineering | Electrical and Computer Engineering

Comments
@INPROCEEDINGS{wcndemo_ipsn11,
author={Pajic, M. and Sundaram, S. and Aneja, M. and Vemuri, S. and Mangharam, R. and Pappas, G.J.},
booktitle={Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on},
title={Architecture for a fully distributed Wireless Control Network},
year={2011},
pages={117-118},
keywords={distillation equipment;distributed parameter systems;networked control systems;process control;telecommunication control;wireless sensor networks;Simulink;distillation column control;distributed wireless control network;process control problem;process-in-the-loop simulation;wireless actuators;wireless networked control systems;wireless nodes;wireless sensors;Distillation equipment;Fires;Process control;Real time systems;Sensors;Wireless communication;Wireless sensor networks;Control over wireless networks;control systems;cyber-physical systems;wireless sensor networks}}

Author(s)
Miroslav Pajic, Shreyas Sundaram, Mansimar Aneja, Srinivas Vemuri, George Pappas, and Rahul Mangharam

Architecture for a Fully Distributed Wireless Control Network

[Demo Abstract] *

Miroslav Pajic[1] Shreyas Sundaram[2] Mansimar Aneja[1] Srinivas Vemuri[1]
George J. Pappas[1] Rahul Mangharam[1]

[1]Dept. Electrical & System Engineering
University of Pennsylvania
{pajic, mansimar, svemuri, pappasg, rahulm}@seas.upenn.edu

[2]Dept. of Electrical Engineering
University of Waterloo
ssundara@uwaterloo.ca

ABSTRACT

We demonstrate a distributed scheme for control over wireless networks. In our previous work, we introduced the concept of a Wireless Control Network (WCN), where the network itself, with no centralized node, acts as the controller. In this demonstration, we show how the WCN can be utilized for distillation column control, a well-known process control problem. To illustrate the use of a WCN, we have utilized a process-in-the-loop simulation, where the behavior of a distillation column was simulated in Simulink and interfaced with an actual, physical network (used as the control network), which consists of several wireless nodes, sensors and actuators. The goal of this demonstration is to show the benefits of a fully-distributed robust wireless control/actuator network, which include simple scheduling, scalability and compositionality.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*; C.3 [**Special-Purpose and Application-Based Systems**]: Process control systems

General Terms

Algorithms, Design

Keywords

Control over wireless networks, wireless sensor networks, control systems, cyber-physical systems

1. INTRODUCTION

In traditional wireless networked control systems, the network is used primarily as a communication medium. The nodes in the network simply route information to and from one or more *dedicated controllers*, which are usually specialized CPUs capable of performing computationally expensive procedures. The production of computationally more powerful wireless nodes has allowed the computation of the control algorithms to be migrated *into* the network, where a predefined node is assigned with the control algorithm execution. The use of wireless communication with such in-network computation requires runtime assignment of the control algorithm to any of the network nodes that satisfy the basic set of connectivity and computational requirements. The binding of the control algorithm to a specific controller (i.e., wireless node) makes the control infrastructure susceptible to failures of those (dedicated) nodes or any of the nodes used for data routing to and from the assigned controller. In these cases even a single-node failure might cause instability of the closed-loop system.

In [4, 5] we have recently introduced the Wireless Control Network (WCN), a fundamentally different concept where the network *itself* acts as the controller. This is achieved by having each node in the network maintain a (possible vector) state, and utilizing a time-triggered architecture (TTA). At each time-step, each node in the network updates its state to be a linear combination of its previous state value and the state values of its neighbors. In addition, as described in [4], the update procedure includes a linear combination of the sensor measurements (i.e., plant outputs) from all sensors in the node's neighborhood. Denoting node v_i's state at time step k by $z_i[k]$, the update procedure can be described as:

$$z_i[k+1] = w_{ii}z_i[k] + \sum_{v_j \in \mathcal{N}_{v_i}} w_{ij}z_j[k] + \sum_{s_j \in \mathcal{N}_{v_i}} h_{ij}y_j[k], \quad (1)$$

where $\mathcal{N}_{v_i}$ denotes all nodes in the neighborhood of node v_i. Here, $y_j[k]$ is the measurement provided by sensor s_j that is installed on the plant that we are controlling. Finally, each plant input $u_i[k]$ is computed as a linear combination of states from the nodes in the neighborhood of the actuator a_i:

$$u_i[k] = \sum_{j \in \mathcal{N}_{a_i}} g_{ij}z_j[k]. \quad (2)$$

In [4, 5] it has been shown that the WCN scheme causes the network to essentially act as a linear dynamical system with sparsity constraints on the system matrices imposed by the underlying network topology. In addition, in [4, 5] we have described a procedure that can be used to extract a stabilizing configuration (i.e., link weights - coefficients in Eq. (1), (2) that guarantee that the closed-loop system is stable) even in scenarios with random link failures.

The WCN uses a simple linear iterative scheme and thus, it introduces a very low implementation overhead. Also, since the WCN requires each node to transmit exactly once in each step (i.e., communication frame) it is not necessary to try to decrease end-to-end delay, which simplifies extraction of a communication schedule. In addition, from the communication schedule it is simple to determine a computation schedule for each node in the network, since each node needs to execute its procedure between the last transmission of its neighbors and its next transmission. Finally, the WCN enables compositional design (and analysis) meaning that an existing design can be easily extended to accommodate new subsystems

---

[*] This work has been partially supported by NSF-CNS 0931239 Grant.

IPSN'11, April 12–14, 2011, Chicago, Illinois.

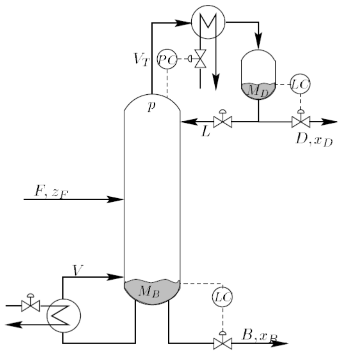

Figure 1: A distillation column structure. The column design and diagram are taken from [7].

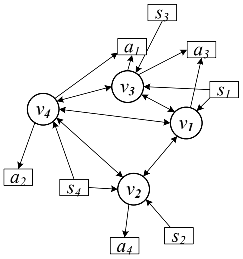

Figure 2: Structure of the WCN. The network topology corresponds to sensor and actuator positions in Fig. 1.

added to the plant, along with other tasks that are assigned to the network (such as transmitting data from one point to another).

We demonstrate here how the WCN is used in a real world process control application. Using a combination of process-in-the-loop simulation with an actual physical network, we present the use of the WCN for closed-loop system control.

2. PROCESS CONTROL CASE STUDY

To illustrate the use of the WCN we consider a well-known process control problem, the distillation column control described in [7] and shown in Fig. 1. Four inputs are available for the column control. These are flows: reflux (L), boilup (V), distillate (D) and bottom flow (B). The goal is to control 4 outputs: x_D - top composition, x_B - bottom composition, M_D - liquid levels in condenser, and M_B - liquid levels in the reboiler.

In our experiments, the distillation column inputs and outputs are monitored/controlled with 4 sensors and 4 actuators positioned according to the distillation column structure (Fig. 1). In addition, 4 nodes ($v_1 - v_4$) have been added, resulting in the network topology from Fig. 2. To demonstrate the performance of the WCN when used for the distillation column control we utilize the continuous-time Linear Time Invariant (LTI) model of the plant from [7]. The state-space model contains 8 states and the aforementioned 4 inputs and 4 outputs. Assigning each node to maintain a scalar state, using an extension of the procedure from [4, 5] we obtained a stabilizing configuration for the topology presented in Fig. 2 and a discretized LTI model of the distillation column. The stabilizing configuration is able to guarantee mean square stability of the closed-loop system with uncorrelated random link failures and single node failures.

3. WCN EXPERIMENTAL PLATFORM

The WCN scheme is implemented using FireFly embedded wireless nodes [3]. FireFly is a low-cost, low-power platform based on Atmel ATmega1281 8-bit microcontroller with 8KB of RAM and 128KB of ROM along with a Chipcon CC2420 IEEE 802.15.4 standard-compliant radio transceiver. FireFly nodes can be used for real-time TDMA-based communication with the RT-Link protocol [6]. RT-Link on FireFly nodes supports both tight global, hardware-based, out-of-band time synchronization and in-band synchronization provided as a part of the TDMA-based link protocol.

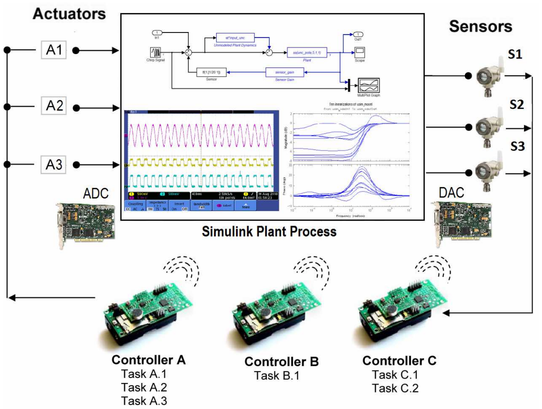

Figure 3: Process-in-the-loop simulation of the distillation column control; The plant model is simulated in Simulink, while the Wireless Control Network is implemented on FireFly nodes.

The linear iterative procedure on each wireless node is implemented as a simple task executed on top of the nano-RK RTOS [1]. On FireFlies, nano-RK operates with a 1ms OS tick. The WCN task was assigned a period equal to the RT-Link frame size. Since RT-Link was configured to use sixteen 5ms slots, the period of the WCN task is 80ms. In addition, since nano-RK and RT-Link provide support for Rx and Tx slot allocation at each node, scheduling the computations (of the WCN procedure) and transmission slots was straightforward. Also, since the WCN requires TTA, nano-RK has been modified to enable scheduling of sensing and actuation at the beginning of the desired slots. This guarantees loosely synchronized sampling/actuation at all sensors and actuators, respectively.

The column, modeled as a continuous-time LTI system along with disturbances and measurement noise, is run in Simulink in real-time using Real-Time Windows Target [2]. The interface between the Simulink model and the real hardware are two National Instruments PCI-6229 boards which provide analog outputs that correspond to the Simulink model's outputs (see Fig. 3). The boards also sample the analog input signals generated by the actuator nodes at a rate of 1 kHz to provide inputs to the Simulink model. Finally, Simulink input and output signals are processed by the WCN with the topology from Fig. 2. Using the aforementioned setup, we have been able to demonstrate that the WCN is able to maintain stability of the distillation column, while maintaining only a scalar state at each of the four wireless nodes.

4. REFERENCES

[1] nano-RK Sensor RTOS. http://nanork.org.

[2] Real-Time Windows Target - Run Simulink models on a PC in real time. http://www.mathworks.com/products/rtwt/.

[3] R. Mangharam, A. Rowe, and R. Rajkumar. FireFly: A Cross-layer Platform for Real-time Embedded Wireless Networks. *Real-Time System Journal*, 37(3):183–231, 2007.

[4] M. Pajic, S. Sundaram, J. Le Ny, G. J. Pappas, and R. Mangharam. The Wireless Control Network: Synthesis and Robustness. In *Proceedings of the 49th IEEE Conference on Decision and Control*, 2010.

[5] M. Pajic, S. Sundaram, R. Mangharam, and G. J. Pappas. The Wireless Control Network. Technical Report, 2010.

[6] A. Rowe, R. Mangharam, and R. Rajkumar. RT-Link: A global time-synchronized link protocol for sensor networks. *Ad Hoc Networks*, 6(8):1201–1220, 2008.

[7] S. Skogestad and I. Postlethwaite. *Multivariable Feedback Control: Analysis and Design*. Wiley, 1996.