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Wireless control system design and co-simulation

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ABSTRACT

This paper discusses the communication and control co-design and co-simulation of wireless networked control systems. The interactions between the network and the control system are considered, and general networking and control co-design solutions are proposed for wireless control applications. The PiccSIM simulator for wireless control system simulation is used to study the effects of specific network protocol and control algorithms in practice. Packet loss models based on measurements of real industrial radio environments are incorporated into the simulator. This allows the realistic evaluation of the suitability of the network protocols for wireless control applications. A network quality of service measure is introduced, which gives a direct relationship between the network and control performances. Two simulation cases show the capabilities of PiccSIM for wireless control application research and development, where the co-design issues and solutions are demonstrated in detail.

1. Introduction

Industry is currently investigating the use of networked wired and wireless technologies in monitoring, automation, and control (Neumann, 2007). The primary benefit of wireless technology is the reduced installation cost, both financially and in labor, as a considerable investment is made in the wiring of factories. The use of wireless technology is not only a replacement of cables, the benefits go beyond that. With wireless devices, increased flexibility is gained, as sensors can be placed more freely in a plug-and-play fashion, even on rotating machines. Cable failures are eliminated and wireless communication is robust, as it can be done over several paths in a mesh network. Finally, there are the opportunities for new applications that are enabled by wireless control. An example is an industrial wireless sensor network that provides additional real-time information of the system, allowing better control and enabling independent monitoring (Gungor & Hancke, 2009). Wireless communications can deliver the operator or maintenance man real-time access to process data on the factory floor, through a wireless handheld device. Some existing or emerging applications are remote control of devices, for example cranes, dexterous, and mobile robots, mobile applications, and wireless monitoring of large plants for fault detection, maintenance, production quality monitoring, and compliance to environmental regulations.

Today, wireless automation technology is mostly applied in monitoring applications, where the network requirements are low. Previously wireless solutions in the industrial setting have been based on expensive and inflexible proprietary protocols and devices. The introduction of commercial-off-the-shelf radios on the 2.4 GHz Industrial–Scientific–Medical (ISM) band, such as Bluetooth, WiFi, and IEEE 802.15.4 have dramatically reduced the cost of the radio based solutions, making their use more widespread. The IEEE 802.15.4 radio is used in several wireless sensor networks, including the ZigBee (Baronti et al., 2007), WirelessHART (Song et al., 2008), and the ISA100.11a standard. The latter two standards are designed for wireless automation systems, whereas ZigBee defines a protocol stack for short-range wireless networks, targeted at remote monitoring and control applications, such as home and building automation. In addition, the internet engineering task force IETF standardizes the use of IPv6 in wireless sensor networks (6LoWPAN, IPv6 over low power networks), which encourages the use of wireless technology in all kinds of applications.

The use of wireless technologies in automation introduces new challenges. The radio channel is a shared medium, subjected to interference and co-channel transmissions, and it is thus usually less reliable than wired solutions. Radio propagation in industrial setting can be harsh. Measurement results in factories indicate that the channel is subjected to frequency selective fading due to multipath propagation, because of the large amount of metal equipment in industrial environments. Furthermore, errors tend to appear in bursts in which several consecutive packets are lost (Willig & Mitschke, 2006), which is detrimental to the real-time

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operation requirement by closed-loop control. The unreliability problems of the wireless networks can be addressed on different protocol layers. These design choices have an impact on the used control methods, which needs to be redesigned to cope with the problems of wireless communication (Hespanha, Naghshtabrizi, & Xu, 2007; Lian, Moyne, & Tilbury, 2002; Liu & Goldsmith, 2005).

In this work, real-time control systems where the loop is closed over a shared wireless medium are mainly considered, because of the harder time-constraints imposed compared to sensor network based monitoring applications. The general design issues are discussed in several papers, for example communication issues in Baronti et al. (2007), and the control issues in Hespanha et al. (2007) and Willig (2008). In this paper, the focus is on relevant problems and solutions from the system design perspective. Particularly the interaction between the communication and control is pointed out and the co-design is examined in more detail in the next section and in the simulations in Section 5. The particular effect of the network on the control system is studied. Especially, a network cost for control measure is derived in Section 4.2, which gives a clear indication of the network impact on the control system and can aid in network protocol design.

The network and control design can to some extent be done independently, but the ultimate goal is the performance of the whole application. The simulation of wireless control systems (WCSs) is important and necessary for several reasons. The current networked control system (NCS) research should be complemented by simulation based studies to assess the validity and practical benefits of the developed theory and algorithms. In practical case studies the critical properties and behavior of the network and the impact on the control system can be identified and analyzed. These issues, in particular the protocol specific ones and the problems that the network causes for the control system, are hard to approach analytically. Simulations are a feasible way to test and evaluate the network and control strategies. Simulation studies will, hopefully, unravel these matters and lead to a coherent theory, best practices knowledge, and design expertise of WCSs.

The currently available simulation tools for WCSs are few. Most of the simulators concentrate on either the network or control part. At the moment there exist only a couple of co-simulators, where both the network and control system are simulated simultaneously. The communication and control co-simulator PiccSIM is presented in Section 3 to study the coupling of communications and control in wireless control systems. Furthermore, measurements of real environments are made and a packet drop model is incorporated into the simulator in Section 4.1, to enable the realistic study of control in particular industrial environments. Simulation cases presented in Section 5 support the discussed design considerations.

2. Design of wireless control system

In this section, some wireless control system co-design choices are discussed. First the main network and control design choices for WCSs are discussed, and then the co-design issues are summarized. The co-design solutions are motivated and tested by the simulations in Section 5.

2.1. Network design

In order to achieve a wider acceptance of wireless technology in industrial control, various networking challenges are to be addressed. One main network design issue in WCSs is the medium access (MAC) protocol, as it determines the communication opportunities. The distribution and length of consecutive packet drops are significant from the control system point of view, because of the real-time requirements of control, as shown in Section 4.2.

MAC protocols can be categorized into deterministic and random access. In random access MACs, no guarantees to acquire access to the medium in a given time can, in general, be given. In deterministic MACs, a communication slot (either in frequency, time, with code division, or a combination of them) is assigned to each node or node-pair. This assignment has the advantage that the access to the medium can be guaranteed in a predetermined time. Deterministic MAC protocols are thus more desired in WCS, where real-time operation is required.

A network using a random access MAC protocol is obviously non-deterministic, but actually even a deterministic MAC protocol is somewhat stochastic due to interference or fading. In the case of packet loss, retransmission is needed, which results in variable response times, to avoid information loss. The use of frequency hopping and spread spectrum techniques makes the wireless network less vulnerable to these threats (Pickholtz, Milstein, & Schilling, 1991).

In current wireless automation standards, the trend is to use deterministic MAC protocols. The original IEEE 802.15.4 standard defines both beacon mode with reserved time slots, and contention based slots (random access). However, most of the shipped radios nowadays come only with CSMA random access MAC, which is due to the complexity of the beacon mode protocol and its known performance problems (Werb et al., 2005). In practical application, off-the-shelf radios can successfully be used, provided that controller co-design is done to compensate for the network uncertainties as discussed later on.

The WirelessHART protocol (Song et al., 2008) aimed at industrial applications uses a scheduled MAC. The protocol allows frequency/time slots to be dedicated to links. Some slots can also be reserved for contention based access using CSMA. The MAC is based on the Time Synchronized Mesh Protocol (TSMP) originally developed by Dust Networks (2006). The benefits of WirelessHART and how to accommodate the control system to the wireless network, and meet the required control performance, are discussed in Nixon, Chen, Blevins, and Mok (2008). Another emerging industrial standard is ISA100.11a, which uses a similar MAC protocol to TSMP.

2.2. Control design

The controller design in WCSs introduces the requirement of robustness against packet loss and delay jitter, which the network inherently induces. Single control-loop systems can be analyzed analytically and existing stability proofs take the network delay jitter into account. The case becomes difficult in large control systems with many control loops, or when specific network protocols are considered. In these cases, simulations are needed to investigate the effect of the network and the various protocols on the control system.

There are three main control system design architectures in NCS, depicted in Fig. 1. All architectures consider only wireless measurements, as the controller can in most cases be placed at the actuator, removing an unnecessary communication link between the controller and actuator. These cases can naturally be extended also to the case of wireless communication between the controller and actuator, but in those cases the design becomes more difficult.

The most laborious alternative is to design an optimal controller that can stabilize the plant with some given delay and packet loss specifications. In the literature, the controller is usually of state-feedback type, which might need a state observer at the sensor. The optimal controller is usually designed by an optimization problem of linear matrix inequalities (Hespanha et al., 2007; Zhang, Shi, Chen, & Huang, 2005).