Cyber-physical Systems in Industrial Process Control

Yunbo Wang, Mehmet C. Vuran, Steve Goddard
Department of Computer Science and Engineering
University of Nebraska-Lincoln
Avery Hall, Lincoln, NE 68588-0115
{yunbow, mcvuran, goddard}@cse.unl.edu

Abstract

As a large-scale interconnected system of heterogeneous components integrating computation with physical processes, Cyber-Physical Systems (CPS) can greatly improve the efficiency of industrial process control systems. However, the inherent heterogeneity and the close integration of different components pose new challenges, which can only be solved by a new unifying network and control theory. This article investigates such challenges in industrial process control and proposes a CPS architecture for future research. Some open research issues are also suggested.

1 Introduction

Cyber-Physical Systems (CPS) are large-scale interconnected systems of heterogeneous components that are envisioned to provide integration of computation with physical processes [1]. The inherent heterogeneity and the close integration of different components pose new challenges to traditional control, communication, and software theory, and often make system design inefficient or even unfeasible with current technologies. Recently, several open research issues have been proposed in the definition and realization of CPS [1, 2, 3]. In this article, I investigate these challenges in the context of industrial process control and propose a CPS architecture for future research.

Industrial process control systems are widely used to provide autonomous control over production process through control loops. They monitor the production process through sensors deployed around the product line and interact with the process through actuators. The complexity of modern production processes is usually simplified by dividing the control load into subsystems containing separate control loops. Heavy control loop couplings among subsystems are avoided. When interactions between different subsystems are needed, usually trained technicians or simple communication methods, such as Controller Area Network (CAN), are exploited.

Such a design paradigm can improve the system modularity and help reduce the design cost. However, in many cases, creating a large control loop spanning over a number of subsystems or a long physical distance could greatly improve the efficiency, but the current design paradigm results in separated design and can not fully benefit from such inter-subsystem control loops. In addition, the simple communication methods used currently suffers from scalability problems. Consequently, an interconnected heterogeneous control network is clearly needed.

Cyber-Physical Systems can provide broad controls over complex and large industrial processes through a heterogeneous network architecture of sensors, actuators, and processors. In such a control network, a control loop often constitutes a large part of the network, where delay and reliability cannot be easily modeled for required real-time reliable communications. However, current control, communication, and software theory are insufficient to provide the necessary tools to analyze such a control network, especially on a large scale. This calls for a unifying theory of heterogeneous control and communication systems.

In this article, I aim to illustrate this necessity in industrial process control. The rest of the paper is organized as follows: Section 2 investigates the challenges in industrial process control systems. In Section 3, an example of a rice production control system is explained. Furthermore, to solve the problems in such a system, a CPS architecture is proposed. Finally, Section 4 suggests some open research issues in this area.

2 Challenges in industrial process control

The heterogeneity in cyber-physical systems exposes several problems that cannot be easily solved through current control, communications, and software theory. As an example, today's network research often deals with coverage and connectivity issues assuming homogeneous network components. However, coverage and connectivity should clearly be redefined in cyber-physical control network systems. Such systems will consist of wired and wireless networks with different capacities and reliability. To model such heterogeneous network systems, a rethinking of network technology is necessary.

Cyber-physical systems also put emphasis on real-time operations. Sensing, processing, communication and actuation in the control loops are handled by different components in the network. For example, a control loop can be easily designed for an optical quality monitoring system with bounded image processing time to determine if the product should be picked out due to optical defects. However, in large-scale control networks, handling the network events such as routing, verifying and retransmitting messages may consume unpredictable time if the network protocol is not designed with timing issues in mind.

To the best of our knowledge, there is not much work done towards a unifying theory for large-scale problems in industry process control. On the contrary, different subsystems of a production processing line are generally isolated. Moreover, traditional control theory lacks the necessary tools to analyze interconnected systems of heterogeneous components in large scale. Hence, it is difficult to provide real-time and reliability guarantees without revisiting communication and control theory.

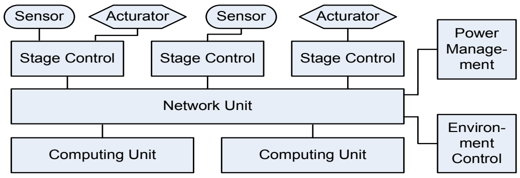

Figure 1. Proposed CPS architecture

3 CPS in Rice Production Lines

To illustrate some of the advantages of using CPS in the general context of industry process control, imagine a rice production control system that consists of several stages. The raw material is first cleaned, then fed into hulling machines to eliminate the hulls. Whitening and polishing are then performed to enhance the appearance and quality of the rice. Furthermore, the rice flows through an optical sorting machine to remove discolored rice. Finally the rice is packed and moved into storages. In each stage, control systems are embedded to make the control of the process autonomous.

The system can benefit from creating control loops spanning several stages. For example, parameters used in the hulling process can affect the optical sorting process, while the optical sorting results can be used to adjust the parameters of previous stages to maximize the yields. The interactions between different stages of the process control improves the efficiency and reliability significantly for large scale systems. If a stage in one line encounters fatal problems, the rice in that line can be routed around to other lines, rather than just bringing down the entire line. Through cyber-physical systems, such a large scale interactive control can be provided.

To address the problems introduced in Section 2, I propose a CPS architecture for the control network, as shown in Figure 1. The proposed heterogeneous CPS will consist of various interconnected CPS units including control units for the subsystems, sensors, cameras and actuators. There exist units with strong processors and that can communicate with different sensors and/or actuators to manage a control task. Some of the units do not communicate with any sensors or actuators but provide computing power to operate on requests. Some units are even as simple as sensors or actuators directly connected to the network. When the environment permits, wired network is used, otherwise wireless communication is exploited.

The key of this architecture is the *heterogeneous network unit*, which abstracts the timing and reliability issues of the heterogeneous CPS components. Other units are connected to the network unit through local on-board network adapters. The delay to the adapters is predictable and highly reliable. The adapters handle all the network events such as transceiving, routing and forwarding without interfering with the connected units. Therefore, the challenges are simplified to the design of the network unit that guarantees the timeliness and reliability of required communication.

Since current network and control technologies are insufficient to handle the problem, such a network unit can only be designed through the design of a unifying network control theory. In the following, I present the major research issues for the design of such a theory.

4 Open research issues

The heterogeneous architecture proposed in Section 3 is an example of a typical network structure for CPS. This inherent heterogeneity constitutes several open research issues for the realization of CPS as explained next:

1) Cyber-physical Architecture: As explained in Section 3, interaction with the environment necessitates different types of components in the CPS. Consequently, the cyber-physical architecture should be designed by considering the heterogeneity in communication, processing, and memory of each device to guarantee application requirements such as reliability and real-time communication. In the design of network architectures that interact with the environment, such as wireless sensor networks, *connectivity* and *coverage* are two major metrics to be considered. However, for CPS, new definitions of them are required to include the heterogeneous communication capabilities of each component, and real-time guarantees. Consequently, a generic framework for the design of CPS architecture can be developed through these new definitions of connectivity and coverage.

2) Real-time Operation: Providing real-time guarantees has been considered in many areas such as operating system, control theory, and communication. Although valuable solutions in each of these areas exist, a unified theory that addresses the heterogeneous challenges in CPS is missing. Since a real-time operation requires a combination of different operations such as sensing, processing, transmission, and actuation in CPS, providing real-time guarantees in such a heterogeneous system necessitates a unified theory of real-time operation that includes existing results and novel solutions from these research areas.

3) Cross-layer Design: Cross-layer design techniques have found significant attention in the design of communication protocols in wireless sensor networks. The close interactions between the wireless channel and the communication protocols necessitate such an approach. In CPS, however, a broader sense of cross-layer design needs to be employed. Each device should be designed based on hardware, operating system, middleware, sensing, actuation, as well as communication as a whole. To this end, the experience gained through cross-layer communication techniques in wireless sensor networks will be exploited for the design of *cross-layer cyber-physical systems*.

I believe with some of these issues being resolved, research in CPS can bring a positive impact to industrial control system design. Even on a large scale, the system can be made predictable and reliable while maintaining a relatively low design cost.

References

[1] Edward A. Lee. “Computing Foundations and Practice for Cyber-Physical Systems: A Preliminary Report”. Technical report UCB/EECS-2007-72, May 2007.

[2] Roy H Campbell, Guy Garnett and Robert E. McGrath. “CPS Environments”. NSF Workshop on Cyber-Physical Systems, Austin, TX, 2006.

[3] Brian D. Noble and Jason Flinn. “Wireless, Self-Organizing Cyber-Physical Systems”. NSF Workshop on Cyber-Physical Systems, Austin, TX, 2006.