CPS-IP: Cyber Physical Systems Interconnection Protocol

Shan Lin
Department of Computer Science
University of Virginia
shanlin@cs.virginia.edu

Tian He
Department of Computer Science and Engineering
University of Minnesota
tianhe@cs.umn.edu

John A. Stankovic
Department of Computer Science
University of Virginia
stankovic@virginia.edu

Abstract

As sensing, wireless communication, and embedded computing technologies evolve, more and more special-purpose cyber physical systems are emerging in our daily lives, such as mobile tracking and health care system, emplaced environmental monitoring systems, and building maintenance control systems. In these systems, heterogeneity is a fundamental research issue. To enable standard communication between these systems, we propose a new communication construct: CPS-IP and a framework combined with it. The goal is to facilitate the creation of systems of systems where there is an integration of myriads of physical data sources, actuators, and computing elements. Different from the Internet Protocol which is designed for a large scale, general-purpose systems, CPS-IP is designed for special- purpose CPS systems built on critical infrastructure which requires global regulation and performance assurance for cyber physical interaction. The novelty of our design is that we address heterogeneity of CPS systems at three different levels: function interoperability, policy regulation, and performance assurance.

1. Introduction

Cyber physical systems are created by synergizing technologies from several different areas: wireless sensor networks, embedded systems, control theory, and real-time systems. However, much of the key technologies in these areas are often, independent from one another. The lack of interaction support for systems of systems limits the explosion of research and technology. To enable cooperation among individual systems, it is essential to design a standard communication construct that addresses the key issues for cyber physical systems.

Emerging cyber physical systems have three special constraints that requires a redesign of interconnection protocols: first, resource constraints: many of the devices used in cyber physical system have very limited memory, computing capability and energy, which prevent the use of complex IP-type protocols. Second, special-purpose constraints: cyber physical systems are designed for critical applications that have tight coupling with physical phenomenon including mobility. Such applications require robust systems and real-time reactions. There are extra spatial-temporal constraints as well. IP as a general-purpose protocol doesn't address these issues. Third, function interaction constraints: there is a special two way information exchange in cyber physical systems: each subsystem provides data and control interfaces for cyber physical interaction. Decentralized and distributed control loops can be formed among different subsystems. Therefore, it is essential to have a special-purpose open design for interconnection of cyber physical systems.

In this paper, we propose CPS-IP, a data-oriented communication construct for cyber physical systems. The goal of CPS-IP is to interconnect heterogeneous CPS subsystems seamlessly. We note that CPS systems require different levels of special-purpose support other than mere interconnection, so we propose a framework combined with CPS-IP. The novelty of our approach lies in a three level design as shown in Figure 1.

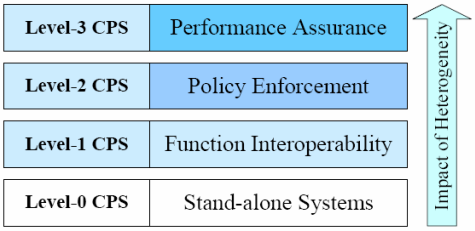

Figure 1. The Levels of Cyber Physical Systems

The first-level design goal, function interoperability, requires the flexible and seamless composition of heterogeneous components and subsystems together at the technical, syntactic and semantic level. The CPS-IP is designed to achieve this goal. It is a high-level construct, beyond mere connectivity, that enables a special-purpose open design for function interoperability among CPS subsystems. The second-level design goal, policy regulation, requires that certain rules are conformed at heterogeneous parts of CPS systems owned by different interest groups to ensure performance and resource sharing, privacy and security. The third-level design goal, performance assurance, requires uniform performance across different subsystems despite the heterogeneous physical and network environments they are located. Our first step to address this challenging issue is a unique framework, combining distributed feedback control and reflective interfaces.

2. Design of CPS-IP

CPS systems should have a special-purpose open system design for function interoperability with the emphasis on the cyber-physical interaction. To achieve this goal, we propose a distributed communication construct: CPS-IP, which flexibly interconnects heterogeneous CPS subsystems together. The existing solutions in the internet and in distributed system technology cannot be used directly. There are three major reasons:

First, the Internet is normally regarded as a general-purpose system of systems, in which IP is the single technology to integrate everything. Typically, general-purpose systems allow a high-degree of diversity and flexibility, which is exactly the design goal of the Internet. On the other hand, CPS systems are regarded as special-purpose systems of systems. Due to security, robustness and legal issues, it would bear significant risk to build national power grids and global gas pipeline systems on top of a general-purpose framework. This special-purpose feature challenges us to design a high-level abstraction above the mere connectivity as provided by IP technology.

Second, the traditional distributed sensing and control systems [1] [3] are closed system of systems with hierarchical ownerships, which allows vertical system integration through well-structured organization. Vertical integration has been shown very effective in the systems where centralized administration is possible. However, with increasing needs for highly reconfigurable systems with independent ownerships, it is critical to investigate how to build CPS systems in an open environment. For example, since federal mandates the deregulation of electric power transmission grid, it becomes very important to investigate how to build open systems of systems.

Third, the interoperability issues within CPS systems are different from other solutions such as Service Oriented Architecture (SOA) [2], component-based design such as JavaBeans [5] and CORBA [4]. All these solutions address mainly the interaction between the computing processes with no emphasis on cyber-physical interaction.

The key novelties of CPS-IP lie in (i) robust and secure CPS-IP control, (ii) transparency in information exchange and control loop formation, and (iii) evolvability in the CPS structure.

We identify that the one key for cyber physical interaction is the distributed/decentralized control loop formation [6]. The primary function of the directory service shall include a component library of sensors and actuators that can be used in the control loops. The programmer shall describe the structure of the control through the control description language. The advanced functions of the directory service shall assist the control loop formation by identifying or suggesting the appropriate components. We shall address the QoS guarantee by designing a distributed system identifier, which utilizes difference equation models for the specified controlled system, allowing automatic control parameter tuning and testing.

3. References

[1] T. F. Abdelzaher, J. A. Stankovic, C. Lu, R. Zhang, and Y. Lu. Feedback performance control in software services. IEEE Control Systems Magazine, 23(3), June 2003.

[2] Douglas K. Barry. Web Services and Service-Oriented Architectures: The Savvy Manager's Guide. Morgan Kaufmann Publishers, 2003.

[3] Boyer, Stuart A. SCADA: supervisory control and data acquisition, 3rd Edition. Research Triangle Park, 2004.

[4] O. GROUP. The common object request broker: Architecture and specification, 1995.

[5] Richard Monson-Haefel. Enterprise JavaBeans, 3rd Edition. O'Reilly, 2001.

[6] Ronghua Zhang, Chenyang Lu, Tarek F. Abdelzaher, and John A. Stankovic. Controlware: A middleware architecture for feedback control of software performance. In Proc. International Conference on Distributed Computing Systems (ICDCS 2002), pages 301-310, 2002.