Cyber Physical Systems:
A Review

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INTRODUCTION

The word "cyber physical system" (CPS) refers to those systems which feature tight integration of computation with physical processes. The example application areas of cyber-physical systems (CPSs) include automated medical devices, air traffic management, automotive systems, smart homes and building, hydro-electric dam controls, data centers, critical infrastructures, industrial control systems and environmental control. Modern CPSs range from small sized pace makers to large-scale national smart power grids. CPSs differ from conventional embedded systems in that CPSs are designed as a network of interacting elements which have physical input and output unlike embedded systems which typically act as standalone devices. An example of CPS is a body sensor network (BSN), which is a network of medical devices that can observe, react, and communicate with other BSNs or operators through a wireless network.

The confluence of the underlying CPS technologies offers new opportunities for the researchers. Further development of the field of CPS will require integration of techniques across various application areas. To provide a deep understanding of CPS field in a large spectrum of application areas, in this chapter, we review recent advances in the development and applications of CPSs. For sake of brevity, we discuss examples of only few research works, which helps in obtaining a broader picture of cyber physical systems. We especially focus on the applications of CPSs to give the reader an overview of the potential of CPSs.

BACKGROUND

A CPS is a "system of sub-systems" where heterogeneous sub-systems (e.g. cyber and physical) interact in a continuous manner. These sub-systems are functionally independent but operationally dependent on each other. Developing CPSs requires modeling the relationship between different sub-systems to effectively extract knowledge from underlying data, while ensuring quality of service and handling massive data (Gupta et al. 2008). Most CPSs have real-time constraints, and hence, it is important that they meet the demands of quality of service, while remaining secure from external attacks. These requirements make the development of CPSs challenging.

Several researchers have proposed approaches for development of CPSs. Martin et al. (2012) present design tools for translating high-level specification of CPS to actual implementation on physical devices. They formulate the specification of CPS in terms of motion description languages. This helps in bridging the gap between high-level specification and the actual implementation and breaking the control tasks into small-scale motion primitives which can be easily interpreted by the system.

Talcott (2008) develops an event-based semantics for cyber physical systems. The author classifies different events according to their characteristics e.g. punctual v/s durative and uses this semantics to provide a natural way to specify components of open systems in terms of interfaces and observable behavior. Roy et al. (2011)

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introduce a tool for synthesizing controllers for CPSs. This tool accepts a CPS represented in the form of automata and set of differential equations and produces a system controller that enforces the given specification up to an abstraction parameter.

Dabholkar et al. (2009) discuss a methodology for systematically specializing general-purpose middleware to meet the demands of cyber physical systems which are used in different application domains. Instead of focusing on source code-level details, they raise the level of abstraction to the features the middleware offers. This helps in specializing the general-purpose middleware to the needs of domain-specific CPS.

Balasubramanian et al. (2010) present a method for ensuring QoS in networked CPSs. For isolating an application developer from the complexities of lower-level programming and QoS mechanisms, they propose use of a middleware in the CPS.

Ou et al. (2011) present an algorithm to ensure quality of service in CPSs which works along with a feedback control framework. Their algorithm maximizes the system value under the thermal constraint and also guarantees task feasibility. Ahmadi et al. (2011) present a modeling technique for designing open CPSs. They use estimation and data mining techniques to capture complex system behavior at different levels of abstraction. They have applied their technique to promote green transportation and reduce vehicular fuel consumption and carbon footprint.

Hnat et al. (2008) present a macroprogramming framework, named MacroLab which is used for programming CPS. MacroLab accepts a single program for the entire CPS and decomposes the program into a set of microprograms which are loaded into each node. This facilitates easy development and small implementation overhead.

Huang and Tidwell et al. (2010) discuss the challenges in the design of cyber-physical instrument for real-time hybrid structural testing which include non-destructive testing of a system prior to its deployment. To address this, they propose a reusable middleware architecture within which both cyber and physical components can be integrated flexibly. Using this framework, a designer can get insights into real-time hybrid structural testing such as tolerance towards violations of small numbers of timing constraints.

MAIN FOCUS

Applications of Cyber Physical Systems

CPSs have been deployed in wide variety of application domains (e.g. Zhang et al. 2012). For example, in power systems, the motivation to use CPSs comes from the fact that the electricity demand is expected to increase more than 75% by 2030 and electricity generation contributes to more than 40% of greenhouse gas emissions. Use of cyber physical systems has enabled the power system operators to have enhanced control over power system operation using wide-area communications in smart grids. By promoting use of smart electrical meters for demand management and distribution automation and improving distribution efficiency, CPSs hold promise in this area.

A data center can be modeled as a CPS, where the cyber part is the online applications which ensure communication and computation and the physical component is the hardware and network which ensure correct functioning and continuous operation. In recent years, the power consumption of computing systems has greatly increased (Mittal et al. 2012, Mittal et al. 2013). The power consumption of typical data centers lies in range of 10GW which amounts to a cost of nearly $7 billion per year. At these levels of power usage, powering and cooling servers, racks, and the entire data center becomes a major challenge. Modern data centers are large CPSs which have hundreds of variables that can be measured and controlled. Further, their dynamics span over multiple scales; as an example the electricity costs can vary over a time scale of hours, temperatures evolve in the

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