Special Issue on Cyber–Physical Systems

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This Special Issue presents papers that cover key features of CPS, including new research and technology advances, open problems, and technical challenges with the papers organized into three categories: theoretical foundations, small-scale applications, and large-scale applications.

Cyber–physical system (CPS) represents a new breed of emerging systems boldly transforming the way modern society perceives the physical world, lives, moves, and interacts in it. Internet virtually took us to a microscopic or remote place within a few seconds. In contrast, a goal of CPS is to "physically" take us to that place instantly, thereby attaching wings, wheels, and other modalities of locomotion to the Internet. If "cyber" prefix/term is synonymous with compositions of computing, storage, networking, and software, then conceptually CPS deeply and widely embeds cyber in a mix of humans, hardware, infrastructure, and natural elements to sense, control, and actuate physical world behavior. Cyberspace is scoped at macro as well as infinitesimal spatial and temporal scales to orchestrate extremely rich cyber–physical interactions. The resulting cyber–physical coupling is tightly controlled, tunable, precise, and predictable, offering tremendous growth opportunities and new services/applications for our society.

Vitality of the CPS vision is evident if you glance at worldwide

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infrastructure modernization plans, emerging smart technologies, national security strategies, and "green" initiatives. Critical infrastructures (e.g., electric grid, air, and ground transportation) lack necessary growth capacity to meet future demands, warranting cyber–physical technologies to refresh and modernize them. Platforms (e.g., medical devices, robots, unmanned ground, air, and space vehicles) are increasingly compact in physical dimensions, but depend on integration with cyber innovations for smart performance. Threats to humans (e.g., terrorism, extreme weather) and to nature (e.g., oil depletion, pollution, climate) are now greater, relying on cyber inventions to manage physical risks. CPS revolution promises system lifecycle paradigms and scientific and engineering breakthroughs to address such grand societal trends, challenges, and problems.

Primitive instances of CPS exist today. Research and technology advances have enabled implementation of the highly intangible cyber elements in hardware and infrastructures to control electrical, mechanical, structural, thermal, hydraulics, and biological components and processes. Some examples include flight control system in airplanes, smart adaptive cruise control in vehicles, advanced field devices in electrical grids, and artificial heart pacemakers. However, missing in such harbingers are the cyber advances such as in networking as well as the core focus on complex interdependencies and integration between cyberspace and physical world.

An intimate coupling of parallel cyber and physical worlds is an overwhelmingly complex task since fundamentally different design concerns intersect. Cyberspace designs, typically discrete time, logical, and asynchronous, must now handle contrasting properties such as inexorable nature of time, concurrent events, laws of physics, correctness, and human safety. New scientific models, cross-domain system design abstractions, analytical tools for multidimensional design space exploration, high confidence software development and verification tools, clear demarcation of boundaries for the cyber–physical interface, reinventing the interface functions including integration, monitoring, control and actuation, and digitization beyond nanoscales in hardware, are some of the major research urgently needed to streamline beneficial CPS applications.

Furthermore, deeper understanding of CPS inherently warrants the knowledge of multiple engineering disciplines and sciences. For instance, understanding the interactions and conflicts between mechanical, electrical, thermal, and network components is an essential ingredient for improved design of complex CPS such as aircraft, automobiles, and the smart grid. Additionally, it should be noted that the use of advanced networking, more intelligence in sensors/actuators, and more stringent performance constraints are some of the core features that differentiate CPS from traditional areas such as embedded control systems, robotics, and sensor networks. Another notable aspect is CPS research and technology advances that are mutually beneficial to several economic sectors.

Based on its paramount importance to societal and industrial growth, CPS was reported as a top-priority research area by the United States President's Council of Advisors on Science and Technology in 2007. The CPS area, spearheaded by Dr. H. Gill from the National Science Foundation (NSF), has received immense interest from various federal agencies in the United States such as the Air Force, National Institute of Standards and Technology, National Security Agency, National Aeronautics and Space Agency, Federal Aviation Authority, and National Transportation Safety Board. The National Coordination Office for the Networking and Information Technology Research & Development federal agency has organized several concerted efforts to rapidly form and progress the CPS community nationally and globally. A recent example of an international CPS community effort is the NSF–University of Washington–Boeing–Ford initiated transportation CPS workshop cosponsored by the NCO/NITRD.[1]

To streamline the community's effort to advance CPS, we bring forth this exciting special issue as a high-value compilation of 19 excellent research articles. Key features of CPS, new research and technology advances, and open problems and challenges are presented. The preface to this CPS special issue is available in the PROCEEDINGS OF THE IEEE, August 2010 issue. We have organized the papers into three categories: theoretical foundations of CPS, small-scale CPS applications, and large-scale CPS applications.

I. THEORETICAL FOUNDATIONS OF CPS

This section consists of four papers that highlight the fundamental paradigm shifts in CPS, presenting some prominent challenges and advances in CPS design, development, testing, and validation. In the first paper, "Modeling cyber–physical systems," Derler *et al.* address the highly complex problem of developing CPS models, and present some open challenges and promising solutions. Recognizing heterogeneity, concurrency, and temporal sensitivity as core attributes of CPS, they provide a comprehensive insightful overview of the current state and future directions in the modeling of the joint dynamics in CPS and the impact of abstractions on the fidelity of models. Aircraft vehicle fuel management system is used to demonstrate challenges in modeling CPS.

In the second paper, "Toward a science of cyber–physical system integration," Sztipanovits *et al.* offer a science-based engineering approach

[1] http://www.ee.washington.edu/research/nsl/aar-cps

to the problematic area of system integration in CPS. They present challenges in constructing and verifying a complex CPS in the design phase of system lifecycle, focusing on composing a stable system from a heterogeneous interacting mix of cyber, electrical, and control components. Presenting cross-domain layered abstractions for design flows they propose a passivity-based design approach to decouple system stability from cyber timing uncertainties. Group coordination of networked unmanned aerial vehicles (UAVs) and quadrator UAV software design are two examples, i.e., integrating network with control design, and software design with hardware platform, respectively, used to demonstrate the proposed "horizontal" and "vertical" layer decoupling approaches.

Eidson *et al.*, in the third paper, "Distributed real-time software for cyber–physical systems," present new programming abstractions and modeling tools needed to capture the physical notion of time, more precisely in real-time embedded systems software for CPS. Their proposed programming model approach guarantees timing properties of interactions between control programs and the controlled physical processes, based on event timestamps. Data streams are ordered by timestamps and actuators apply commands at the time indicated on the command timestamp. Conditions are illustrated under which data streams from multiple sources can be correctly merged with respect to timestamp order. They also propose a modeling technique of timed mode transitions for system adaptation in the presence of unanticipated events. A power plant example is used to demonstrate the proposed techniques.

In the fourth paper, "Toward continuous state–space regulation of coupled cyber–physical systems," Bradley and Atkins focus on advancing CPS with a cyber–physical codesign approach, where the physics and the cyber component behaviors are simultaneously observed. They cast discrete cyber system properties into a continuous-time physical modeling paradigm to consider cyber effects on physics-based systems. Specifically, they abstract software execution rate of a controller program into a continuous state framework where linear systems analysis is traditionally applied. Their framework allows the application of modern control theory techniques to CPS as a whole, and enables optimal, simultaneous coregulation of both cyber and physical states.

II. SMALL-SCALE CPS APPLICATIONS: CURRENT AND FUTURE STATE

This section consists of seven papers on exciting CPS applications that impact human and robotic platforms. A spectrum of CPS instances are emerging in the medical sector enabling various wearable or implantable physiological sensors and actuators to be deployed on human body and used continuously to monitor patient health, enable fast detection of medical emergencies, and deliver suitable therapies. Hospitals are aligning towards such revolutionary transformations to efficiently and effectively enable patient-centric healthcare services in the future. In the first paper in this section, "Challenges and research directions in medical cyber–physical systems," Lee *et al.* give a broad overview of the emerging medical CPS applications. They present the different entities and stakeholders involved in medical CPS, along with the formidable challenges, promising solutions, and open problems in the high confidence development of cyber–physical medical devices that are smart, interoperable, highly assured, and certifiable. Calhoun *et al.*, in the second paper, "Body sensor networks: A holistic approach from silicon to users," survey the area of body sensor networks (BSNs) in medical CPS. They present a vision for BSNs that incorporates principles and novel ideas across all network layers, enabling adaptive operation in highly dynamic physical environments using miniaturized energy-constrained sensor devices. Their holistic cross-layer approach promises to simultaneously address various aspects of the system, from low-level hardware design to high-level communication and data fusion algorithms. In the third paper, "A mining technique using *n*-grams and motion transcripts for body sensor network data repository," Loseu *et al.* address the complex problem of efficient and intelligent utilization of a large volume of rich BSN data. They focus on efficiently representing human movement data from BSN nodes by using clustering techniques. They also propose efficient, intelligent mining of a large BSN database for analysis of a sensed physiological signal by leveraging structural patterns of human movement.

Heart failure is a terminal disease with a very poor prognosis and one of the greatest areas of healthcare spending, hence presenting a significant societal impact opportunity for medical CPS. However, in using implantable cardiac devices, such as heart pacemakers, two prominent challenges are posed to the medical CPS community. First, the devices must be tested and verified to behave safely and predictably in their operational configuration and environment with the patient in the loop. In the fourth paper of this section, "Cyber–physical modeling of implantable cardiac medical devices," Jiang *et al.* present a formal-methods-based approach towards such verification and validation for heart pacemaker device software. They develop an electrophysiological model of the heart integrating it with timing properties of an implantable pacemaker device model for simulating the closed-loop organ–device interactions. The resulting timed-automata model is demonstrated to be effective for a clinical case where pacemaker drives the heart into a harmful condition. Second, the power wiring for implantable cardiac devices must be eliminated. As a result of their extended lifetime of implantable cardiac devices, these wirings pose an increasing risk to the patient and degrade the patient's quality of life. Hence, Waters *et al.*, in the fifth paper, "Powering a ventricular assist device (VAD) with the free-range resonant electrical energy delivery (FREE-D) system," study the challenging problem of delivering power wirelessly to an implanted cardiac device of a patient. Their proposed technology can unobtrusively recharge implanted battery in the pacemaker using magnetically coupled resonators. The resulting efficient wireless transfer of power across a distance to the implanted device is shown to be robust to any geometric changes due to patient mobility.

A cornerstone of robotic CPS applications is the problem of managing in real time the mobility of unmanned autonomous platforms for an intended mission. Two papers address this concern. Swain *et al.*, in the paper "Real-time feedback-controlled robotic fish for behavioral experiments with fish schools," present an interesting investigation of robotic platforms in the behavioral study of fish schools. They propose the cyber–physical implementation of robotic fish that move with respect to neighboring live fish and other objects. Each robotic fish receives processed video-based feedback from the fish group and their surrounding environment. The mobility of each robotic fish is controlled to resemble that of the same species or of a predator, enabling various behavioral experiments on the fish schools. Furthermore, in the paper "Robust control for mobility and wireless communication in cyber–physical systems with application to robot teams," Fink *et al.* address the joint control of mobility and wireless networking for an autonomous networked robot team on terrains. Their goal is to optimize wireless network performance under safe trajectory constraints and communication channel uncertainties. They design a cyber–physical controller that can jointly optimize end-to-end reliable network routes and spatial configurations of a team of robots, ultimately determining trajectories that ensure availability of communication resources.

III. LARGE-SCALE CPS APPLICATIONS: CURRENT AND FUTURE STATE

This section consists of eight papers that exposition the magnificent scales at which CPS applications must perform. An interesting breed of large-scale CPS applications is emerging in the next-generation air and road transportation systems around the world. Information exchanges between vehicles and between vehicle and off-board infrastructure present tremendous opportunities to enhance safety, throughput, efficiency, and comfort in transportation. Several CPS challenges in both aviation and automobile sectors are discussed in the Transportation CPS workshop.[2] In the paper "A hierarchical flight planning framework for air traffic management," Zhang *et al.* provide a glimpse of some of the CPS complexities in air transportation. They focus on the problem of leveraging information exchange capability of NextGen for decentralized control of a large volume of air traffic routes in high-altitude airspace. Their approach is to manage 4-D (time and 3-D waypoints) air traffic flows in high-altitude airspace by incorporating each flight operator's preferences and aircraft type. They propose a hierarchical two-layered architecture which can design the entire 4-D path plans according to users' preferred cost metrics with systematical considerations of weather risks and airspace capacity constraints. In combination with the above papers on mobility, this paper highlights the complex scopes and contexts in which platform mobility must be addressed in CPS.

As a successor to one of the greatest engineering feats of our lifetime, the smart grid is today investigated as the most prominent large-scale CPS. With enormous challenges such as keeping the nation "powered on," affordably and with zero CO_2 emissions footprint, the smart grid performance is extremely critical to society. CPS advances in the aging electrical grid enable benefits to "green" power generators to smart meter-enabled service enhancements for utilities to smart appliances and dynamic pricing for consumers. However, as the smart grid evolves, several existing and cyber–physical issues need to be addressed.

Operation of the electricity grid must be ensured to be safe, secure, stable, deterministic, and predictable, under both normal and failure conditions. Three papers in this section address this issue. In the first paper, "Cyber–physical security of a smart grid infrastructure," Mo *et al.* overview the smart grid and its security requirements, classifying attacks, and discussing limitations of cyber security advances and control-theoretic measures to securing the smart grid. They propose combining control systems theory and cyber security for smart grid cyber–physical security, illustrating their approach in assuring continuous power flows and dynamic power pricing. Sridhar *et al.*, in the second paper, "Cyber–physical system security for the electric power grid," present an in-depth survey of control in power systems that may be vulnerable to potential security attacks. They discuss various control loops in the electric grid, classify their vulnerabilities and the potential impact of disturbing the control loops, and overview several mitigations. In the third paper, "A hybrid system approach to the analysis and design of power grid dynamic performance," Susuki *et al.* develop a hybrid-model-based theory and methods for managing the joint dynamics of cyber elements and physical processes in the smart grid and ensuring grid stability.

Another significant issue in the smart grid is improving energy efficiency at the end users. Major contributors to energy consumption are buildings with electromechanical

[2]http://www.ee.washington.edu/research/nsl/aar-cps/NCO_June_2009.pdf

cooling systems such as heating, ventilation, and air conditioning (HVAC) and Internet data center (IDC) with racks of servers and networking hardware. Electrical load of HVAC is for maintaining comfortable temperature ranges for humans and physical equipment, while the electrical load for IDC is due to both cooling of operating equipment and quality of service to data users. Three papers in this section aim to reduce energy footprint of buildings. In the first paper, "Reducing transient and steady state electricity consumption in HVAC using learning-based model-predictive control," Aswani, *et al.* investigate energy efficiency improvement from retrofitting a single-stage heat pump air conditioner. They study the electrical characteristics of the pump and the temperature dynamics of the space impacted by the pump to precisely model the physics and dynamics in the pump controller software. A model-predictive control strategy is proposed to maintain a comfortable temperature, carefully balancing between transient and steady state of the pump in the presence of occupancy dynamics. A two-position control strategy is used as a benchmark to demonstrate energy savings. Parolini *et al.*, in the paper "A cyber–physical systems approach to data center modeling and control for energy efficiency," investigate the interplay between information technology, power, and cooling systems in an IDC. For an IDC, they develop a cyber–physical control strategy to efficiently coordinate the electrical load on the smart grid and quality of service for cyber users, and minimize the integrated weight sum of energy consumption and computational performance. They propose a metric to quantify the cyber–physical control impact in the IDC. In the third paper, "Distributed coordination of Internet data centers under multiregional electricity markets," Rao *et al.* consider only the power consumption of cyber elements in an IDC and study the problem of minimizing the total energy costs for a collection of IDCs in the presence of a multielectricity market environment. Accounting for the spatial and temporal dynamics of energy pricing and quality-of-service constraints, they propose a control strategy to balance computational load and power consumption in the collection of IDCs.

Finally, after presenting CPS theoretical foundations, different types of systems/applications, and their engineering, this special issue concludes with some insight into advances in ensuring quality of systems in the presence of expected and unanticipated cyber and physical world anomalies. A foremost concern in CPS is to provide critical assertions for applications performance because human lives and society's wellbeing depend on them. In the paper "Ensuring safety, security, and sustainability of mission-critical cyber–physical systems," Banerjee *et al.* offer some insights into the complex challenge of ensuring some critical performance properties of CPS applications in the presence of physical dynamics. They propose a framework to study the cyber–physical interactions of several small- and large-scale CPS applications and the design of solutions that assure some critical properties. They employ BSNs, smart grid, IDCs, and UAVs as case studies to demonstrate their framework. ■

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