

Cyber-physical Systems

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Introduction

The term *cyber-physical systems* (CPS) refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with, and expand the capabilities of, the physical world through computation, communication, and control is a key enabler for future technology developments. Opportunities and research challenges include the design and development of next-generation airplanes and space vehicles, hybrid gas-electric vehicles, fully autonomous urban driving, and prostheses that allow brain signals to control physical objects.

Over the years, systems and control researchers have pioneered the development of powerful system science and engineering methods and tools, such as time and frequency domain methods, state space analysis, system identification, filtering, prediction, optimization, robust control, and stochastic control. At the same time, computer science researchers have made major breakthroughs in new programming languages, real-time computing techniques, visualization methods, compiler designs, embedded systems architectures and systems software, and innovative approaches to ensure computer system reliability, cyber security, and fault tolerance. Computer science researchers have also developed a variety of powerful modeling formalisms and verification tools. Cyber-physical systems research aims to integrate knowledge and engineering principles across the computational and engineering disciplines (networking, control, software, human interaction, learning theory, as well as electrical, mechanical, chemical, biomedical, material science, and other engineering disciplines) to develop new CPS science and supporting technology.

In industrial practice, many engineering systems have been designed by decoupling the control system design from the hardware/software implementation details. After the control system is designed and verified by extensive simulation, ad hoc tuning methods have been used to address modeling uncertainty and random disturbances. However, the integration of various subsystems, while keeping the system functional and operational, has been time-consuming and costly. For example, in the automotive industry, a vehicle control system relies on system components manufactured by different vendors with their own software and hardware. A major challenge for original equipment manufacturers (OEMs) that provide parts to a supply chain is to hold down costs by developing components that can be integrated into different vehicles.

The increasing complexity of components and the use of more advanced technologies for sensors and actuators, wireless communication, and multicore processors pose a major challenge for building next-generation vehicle control systems. Both the supplier and integrator need new systems science that enables reliable and cost-effective integration of independently developed system components. In particular, theory and tools are needed for developing cost-effective methods to: (1) design, analyze, and verify components at various levels of abstraction, including the system and software architecture levels, subject to constraints from other levels; (2) analyze and understand interactions between the vehicle control systems and other subsystems (engine, transmission, steering, wheel, brake, and suspension); and (3) ensure safety, stability, and performance while minimizing vehicle cost to the

consumer. Increasingly, new functionality and the cost of vehicle control systems are major differentiating factors for business viability in automobile manufacturing.

Need for CPS Research

CPS research is still in its infancy. Professional and institutional barriers have resulted in narrowly defined, discipline-specific research and education venues in academia for the science and engineering disciplines. Research is partitioned into isolated subdisciplines such as sensors, communications and networking, control theory, mathematics, software engineering, and computer science. For example, systems are designed and analyzed using a variety of modeling formalisms and tools. Each representation highlights certain features and disregards others to make analysis tractable. Typically, a particular formalism represents either the cyber or the physical process well, but not both. Whereas differential equations are used for modeling physical processes, frameworks such as Petri nets and automata are used to represent discrete behavior and control flows. Workforce expertise is similarly partitioned, to the detriment of productivity, safety, and efficiency. Although this approach to modeling and formalisms may suffice to support a component-based “divide and conquer” approach to CPS development, it poses a serious problem for verifying the overall correctness and safety of designs at the system level and component-to-component physical and behavioral interactions [1]. In the following paragraphs, research needs in CPS are briefly discussed.

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Abstraction and Architectures

Innovative approaches to abstraction and architectures that enable seamless integration of control, communication, and computation must be developed for rapid design and deployment of CPS. For example, in communication networks, interfaces have been standardized between different layers. Once these interfaces have been established, the modularity allows specialized developments in each layer. The overall design allows heterogeneous systems to be composed in plug-and-play fashion, opening opportunities for innovation and massive proliferation of technology and the development of the Internet. However, the existing science and engineering base does not support routine, efficient, robust, modular design and development of CPS. Standardized abstractions and architectures are urgently needed to fully support integration and interoperability and spur similar innovations in cyber-physical systems [2].

Distributed Computations and Networked Control

The design and implementation of networked control systems pose several challenges related to time- and event-driven computing, software, variable time delays, failures, reconfiguration, and distributed decision support systems. Protocol design for real-time quality-of-service guarantees over wireless networks, tradeoffs between control law design and real-time-implementation complexity, bridging the gap between continuous and discrete-time systems, and robustness of large systems are some of the challenges for CPS research. Frameworks, algorithms, methods, and tools are needed to satisfy the high reliability and security requirements for heterogeneous cooperating components that interact through a complex, coupled physical environment operating over many spatial and temporal scales.

Verification and Validation

Hardware and software components, middleware, and operating systems need to be developed that go beyond existing technologies. The hardware and software must be highly dependable, reconfigurable, and, where required, certifiable, from components to fully integrated systems. Such complex systems must possess a trustworthiness that is lacking in many of today's cyber infrastructures. For example, certification is estimated to consume more than 50% of the resources required to develop new, safety-critical systems in the aviation industry. Similar efforts are needed in the medical, automotive, energy systems, and other application domains. Overdesign is currently the only path to safe and successful system certification and deployment. Yet this approach is rapidly becoming intractable for complex designs and for systems where interoperability is needed. Testing "until the money runs out" is not a viable strategy, and science- and evidence-based methods are needed for reasoning about system reliability. New models, algorithms, methods, and tools are needed that will incorporate verification and validation of software and systems at the control design stage.

Challenges and Opportunities: Industry-Academia

Advances in CPS research can be accelerated by identifying needs, challenges, and opportunities in several industrial sectors and by encouraging multidisciplinary collaborative research between academia and industry. The objective is to develop new systems science and engineering methods for building high-confidence systems in which cyber and physical designs are compatible, synergistic, and integrated at all scales. Current and past industry investments in CPS technology research have been significant but focused on shorter-term, quicker-payoff proprietary technologies. Recently, governments and some industry sectors are investing in longer-term, precompetitive technologies and innovative testbeds. For example, the European Union has initiated a major joint technology initiative with public-private funding by European nations and industry called Advanced Research and Technology for Embedded Intelligence Systems (ARTEMIS). Similarly, based on recommendations in the August 2007 report of the U.S. President's Council of Advisors on Science and Technology (PCAST), the U.S. National Science Foundation has been funding fundamental CPS research and education [3]. Related initiatives are being pursued in other countries, including Japan, China, South Korea, and Germany.

CPS grand challenges are being articulated in many industry sectors. The U.S. National Academy of Engineering has listed 14 grand challenges that relate environmental, health, and societal issues; these issues will clearly benefit from advances achieved in cyber-physical systems. The control engineering research community can play a leading role in the development of cyber-physical systems. Some of the opportunities are described below.

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Biomedical and Healthcare Systems

CPS research is revealing numerous opportunities and challenges in medicine and biomedical engineering. These include intelligent operating rooms and hospitals, image-guided surgery and therapy, fluid flow control for medicine and biological assays, and the development of physical and neural prostheses. Healthcare increasingly relies on medical devices and systems that are networked and need to match the needs of patients with special circumstances. Thus, medical devices and systems will be

needed that are dynamically reconfigured, distributed, and can interact with patients and caregivers in complex environments. For example, devices such as infusion pumps for sedation, ventilators and oxygen delivery systems for respiration support, and a variety of sensors for monitoring patient condition are used in many operating rooms. Often, these devices must be assembled into a new system configuration to match specific patient or procedural needs. The challenge is to develop systems and control methodologies for designing and operating these systems that are certifiable, safe, secure, and reliable.

Research challenges in medical technology and healthcare were considered in a series of workshops that are summarized in a U.S. National Information Technology Research and Development (NITRD) report [4]. The report recommends research for new system science and engineering with the following goals:

- Interoperable and open medical systems;
- Distributed monitoring, distributed control, and real-time wireless networks for hospital intensive-care facilities;
- Certification methods for medical device software and systems and networked patient monitoring and assistance;
- Model-based frameworks that support component-based modeling, design, testing, and certification using patient-specific models.

Another challenging area for CPS research is cognition and neuroscience for understanding the fundamental principles of human motor functions and exploiting this understanding in engineered systems. Examples include brain-machine interfaces, therapeutic and entertainment robotics, orthotics and exoskeletons, and prosthetics. Humans and animals seamlessly integrate sensing, computing, and motor control functions. These highly coupled systems do not satisfy simple modularity principles, but are composed of multifunctional elements, computation, and feedback loops at different time and length scales, noisy signals, parallel processing, and redundant fault-tolerant architectures. Recent research has suggested that animals use some form of optimal filtering, stochastic control algorithms, and large-scale probabilistic computing structures in dealing with uncertainty. Control researchers working with biologists, neurophysiologists, and computer scientists may be able to make further progress.

Next-Generation Air Transportation Systems (NextGen)

Cyber-physical systems research is likely to have an impact on the design of future aircraft and air traffic management systems, as well as on aviation safety. Specific research areas include (1) new functionality to achieve higher capacity, greater safety, and more efficiency, as well as the interplay and tradeoffs among these performance goals; (2) integrated flight deck systems, moving from displays and concepts for pilots to future (semi)autonomous systems; (3) vehicle health monitoring and vehicle health management; and (4) safety research relative to aircraft control systems. One of the key technical challenges to realizing NextGen involves verification and validation of complex flight-critical systems with a focus on promoting reliable, secure, and safe use for NextGen operations. As the complexity of systems increases, costs related to verification and validation and safety assurance will likely increase the cost of designing and building next-generation vehicles. The broader aeronautics community has identified verification and validation methodologies and concepts as a critical research area [5].

The goals of research in verification and validation of aviation flight-critical systems include providing methods for rigorous and systematic high-level validation of system safety properties and requirements, from initial design through implementation, maintenance, and modification, as well as understanding tradeoffs between complexity and verification methods for supporting robustness and fault tolerance. Some of the control engineering challenges include:

- Large-scale, real-time, deterministic robust or stochastic optimization algorithms;
- Multiple-objective, multiple-stakeholder optimization frameworks;
- Design of automation with graceful degradation modes;
- Safety diagnosis/health monitoring methods;
- System architectures that facilitate distributed decision making;
- Data fusion from heterogeneous sensors and assessment of the value of the derived information.

Smart Grid and Renewable Energy

Smart grid and renewable energy research and development has been in the forefront of public interest and is therefore a high priority for policy makers. The goal is to improve energy efficiency by investing in modernization of the energy infrastructure. The geopolitical drivers for renewable energy and smart grids are that (1) electricity demand is expected to increase more than 75% by 2030; (2) generation of electricity contributes to more than 40% of greenhouse gas emissions; (3) the cost of generating 1 KWh is four times greater than the cost of saving 1 KWh. Government funding agencies have partnered with industry, utilities, and local government in technology development and demonstration projects dealing with smart grids. For example, “Energy Smart Florida” is a groundbreaking public/private alliance of the City of Miami, Florida Power and Light, General Electric, Silver Spring Networks, and Cisco. This project is using federal economic stimulus funds as part of an \$800 million investment in smart grid technology and renewable energy over the next two years. An estimated 4.5 million smart meters will be installed in U.S. homes and businesses to develop and demonstrate technology for demand management, distribution automation, substation intelligence, distributed generation, and information technology. The goal is to demonstrate the increase in energy efficiency through demand optimization and distributed automation by significantly reducing peak load.

Advances in flexible AC transmission devices (FACTS) and phasor measurement units (PMUs) have opened new opportunities for wide-area control of smart grids. The U.S. Department of Energy-sponsored North American SynchroPhasor Initiative (NASPI) has been heavily investing in PMU hardware. Future efforts will be needed to focus on data fusion and analysis for real-time dynamics monitoring, prediction, and system control. With increased reliance on wide-area communications and control to improve system operation, tight coupling is needed between cyber systems and the components of physical systems in smart grids. Critical gaps and shared challenges pertain to advances in system science, particularly hybrid digital-analog systems, complex emergent systems, and advanced software systems for large-scale, time-varying, geographically distributed systems. Advances in optimization of multiscale stochastic dynamic systems as well as in distributed control are necessary to improve smart grid performance with respect to security, efficiency, reliability, and economics. These issues have been identified by the research community in several workshops dealing with information technology and smart grids.

Conclusions

Cyber-physical systems are expected to play a major role in the design and development of future engineering systems with new capabilities that far exceed today's levels of autonomy, functionality, usability, reliability, and cyber security. Advances in CPS research can be accelerated by close collaborations between academic disciplines in computation, communication, control, and other engineering and computer science disciplines, coupled with grand challenge applications.

Selected recommendations for research in cyber-physical systems:

- Standardized abstractions and architectures that permit modular design and development of cyber-physical systems are urgently needed.
- CPS applications involve components that interact through a complex, coupled physical environment. Reliability and security pose particular challenges in this context—new frameworks, algorithms, and tools are required.
- Future cyber-physical systems will require hardware and software components that are highly dependable, reconfigurable, and in many applications, certifiable . . . and trustworthiness must also extend to the system level.

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