Cyber-Physical Systems: The Next Computing Revolution

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Abstract

Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. Just as the internet transformed how humans interact with one another, cyber-physical systems will transform how we interact with the physical world around us. Many grand challenges await in the economically vital domains of transportation, health-care, manufacturing, agriculture, energy, defense, aerospace and buildings. The design, construction and verification of cyber-physical systems pose a multitude of technical challenges that must be addressed by a cross-disciplinary community of researchers and educators.

General Terms: Theory, Design, Reliability, Performance, Security, Human Factors, Verification, Languages.

Keywords: cyber-physical systems, engineering, computer science, grand challenges, new frontiers.

1. Introduction

Computing and communication capabilities will soon be embedded in all types of objects and structures in the physical environment. Applications with enormous societal impact and economic benefit will be created by harnessing these capabilities across both space and time. Such systems that bridge the cyber-world of computing and communications with the physical world are referred to as *cyber-physical systems*. Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. This intimate coupling between the cyber and physical will be manifested from the nano-world to large-scale wide-area systems of systems. The internet transformed how humans interact and communicate with one another, revolutionized how and where information is accessed, and even changed how people buy and sell products. Similarly, CPS will transform how humans interact with and control the physical world around us.

Examples of CPS include medical devices and systems, aerospace systems, transportation vehicles and intelligent highways, defense systems, robotic systems, process control, factory automation, building and environmental control and smart spaces. CPS interact with the physical world, and must operate dependably, safely, securely, and efficiently and in real-time.

The World-Wide Web can be considered to be a confluence of three core enabling technologies: hypertext, communication protocols like TCP/IP, and graphical interfaces. This integration enabled significant leaps in technology (e.g. graphics, networking, semantic webs, multimedia interfaces and languages), infrastructure (e.g. global connectivity with increasing bandwidth, PCs for every desktop and laptop) and applications (e.g. e-commerce, auctions, entertainment, digital libraries, social networks and online communities). Likewise, CPS can be considered to be a confluence of embedded systems, real-time systems, distributed sensor systems and controls.

The promise of CPS is *pushed* by several recent trends: the proliferation of low-cost and increased-capability sensors of increasingly smaller form factor; the availability of low-cost, low-power, high-capacity, small form-factor computing devices; the wireless communication revolution; abundant internet bandwidth; continuing improvements in energy capacity, alternative energy sources and energy harvesting. The need for CPS technologies is also being *pulled* by cyber-physical system vendors in sectors like aerospace, building and environmental control, critical infrastructure, process control, factory automation, and healthcare, who are increasingly finding that the technology base to build large-scale safety-critical CPS correctly, affordably, flexibly and on schedule is seriously lacking.

CPS bring together the discrete and powerful logic of computing to monitor and control the continuous dynamics of physical and engineered systems. The precision of computing must interface with the uncertainty and the noise in the physical environment. The lack of perfect synchrony across time and space must be dealt with. The failures of components in both the cyber and physical domains must be tolerated or contained. Security and privacy requirements must be enforced. System dynamics across multiple time-scales must be addressed. Scale and increasing complexity must be tamed. These needs call for the creation of innovative scientific foundations and engineering principles. Trial-and-error approaches to build computing-centric engineered systems must be replaced by rigorous methods, certified systems, and

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powerful tools. Analyses and mathematics must replace inefficient and testing-intensive techniques. Unexpected accidents and failures must fade, and robust system design must become an established domain. New sensors and sensor fusion technologies must be developed. Smaller and more powerful actuators must become available.

The confluence of the underlying CPS technologies enables new opportunities and poses new research challenges. CPS will be composed of interconnected clusters of processing elements and large-scale wired and wireless networks that connect a variety of smart sensors and actuators. The coupling between the cyber and physical contexts will be driven by new demands and applications. Innovative solutions will address unprecedented security and privacy needs. New spatial-temporal constraints will be satisfied. Novel interactions among communications, computing and control will be understood. CPS will also interface with many non-technical users. Integration and influence across administrative boundaries will be possible.

The innovation and development of CPS will require computer scientists and network professionals to work with experts in various engineering disciplines including control engineering, signal processing, civil engineering, mechanical engineering and biology. This, in turn, will revolutionize how universities educate engineers and scientists. The size, composition and competencies of industry teams that design, develop and deploy CPS will also change dramatically. The global competitiveness of national economies that become technology leaders in CPS will improve significantly [16].

The rest of this paper is organized as follows. Section 2 presents a future vision for cyber-physical systems and identifies some specific grand challenges. Section 3 identifies research and educational challenges that must be addressed. Section 4 discusses the resulting societal and economic impact of such advances in CPS.

2. Grand Challenges and Vision

The core science and technology required to support the CPS vision are essential for future economic competitiveness. Creating the scientific and technological basis for CPS can pay dividends across a wide variety of application domains resulting in unprecedented breakthroughs in science and engineering. Groundbreaking innovations will occur because of the pervasive utility of the technology resulting in major societal and economic gains. Some grand challenges for CPS are as follows:

- Blackout-free electricity generation and distribution,
- Extreme-yield agriculture,
- Safe and rapid evacuation in response to natural or man-made disasters,
- Perpetual life assistants for busy, older or disabled people,
- Location-independent access to world-class medicine,
- Near-zero automotive traffic fatalities, minimal injuries, and significantly reduced traffic congestion and delays,
- Reduce testing and integration time and costs of complex CPS systems (e.g. avionics) by one to two orders of magnitude,
- Energy-aware buildings and cities,
- Physical critical infrastructure that calls for preventive maintenance, and
- Self-correcting cyber-physical systems for "one-off" applications.

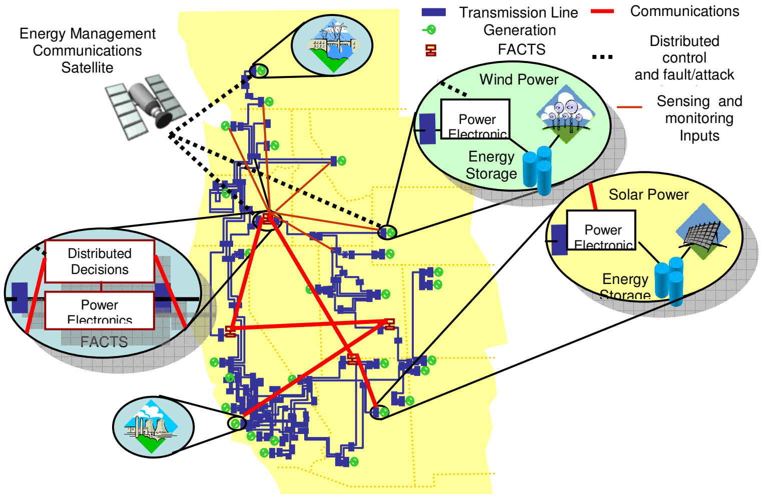
To illustrate the vision and challenges of CPS, several representative examples are presented next.

2.1. Advanced Electric Power Grid

Protecting critical infrastructure is vital to the health of an economy; one such infrastructure, the electric power transmission grid, forms one of the largest complex inter-connected networks ever built. Under normal operation, this web of interconnecting transmission lines makes the grid highly robust and reliable. However, during stressed conditions, a failure in one location can quickly propagate across the grid in complex ways leading to a cascading failure and wide-spread blackouts, such as the 2003 US Midwest blackout. Coordinated power electronics, such as Flexible AC Transmission Systems (FACTS), could help mitigate and protect against these failures.

An additional stress to the electric grid is the rapid growth of Distributed Energy Resource (DER) technologies. Wind power, the most rapidly growing technology in the US for renewable power generation, now provides more than 31,000 MW of power, a total that has grown rapidly and that keeps more than 200 million tons of carbon dioxide out of the atmosphere every year. However, wind power produces an irregular stream of electricity. New solutions including advanced power electronics and energy storage are available, but coordination and a science of interactions of these resources remains an open research challenge.

Shown below is an example of the Advanced Electric Power Grid based on the WECC power grid which consists of the Electric Power Transmission Grid, Distributed



Energy Resources (insets), and Cyber Coordination and Protection, which uses distributed decisions to coordinate control and system sensing and monitoring to maintain correct operation, and to detect and react to faults and attacks.

The challenge is to develop a fully integrated robust, stable, failure-free advanced power network with interacting distributed, intelligent real-time control through the *composition* of cyber and physical resources. Specific operational aspects must include

(1) Multiple time scales of interacting, distributed, control must embrace the capabilities and failures of distributed elements such as power generation and transmission technology. Power electronics and their cyber control must be modeled for correctness in a uniform way. Bridge theories may also be necessary to accommodate multiple models.

(2) Resilience is needed to maintain correctness in the context of improperly coordinated control of cyber and physical resources.

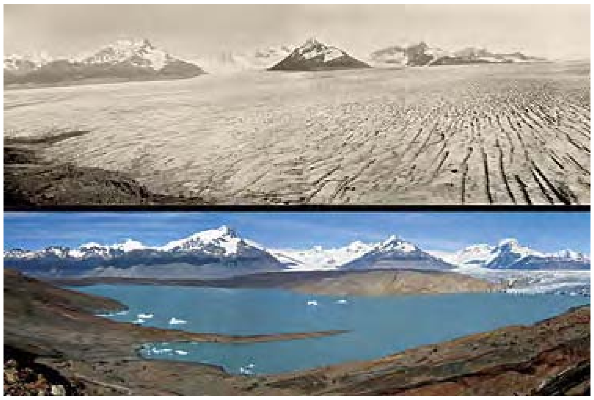
(3) Security policy development and intrusion detection and mitigation must counter possible attacks.

(4) The existing power grid system must transition to the advanced power network.

(5) To have a reliable, secure and economically sustainable power system, a fair financial arrangement must exist for buyers and sellers in the electricity market to maximize total social welfare.

(6) Multidisciplinary educational paradigms for *Power Informatics* must be developed.

2.2 Symbiotic Cyber-Physical Networks at Scale: New Paradigms for Scientific Discovery



Natural resources in our environment are some of our most fundamental national assets that must be cared for sustained economic prosperity. Urbanization, deforestation, and common agricultural practices (exemplified, for instance, in the Midwestern landscape) severely diminish natural ecological diversity, introducing accumulative side-effects that are not sustainable in the long term. To give one example of unsustainable trends, observations show that global warming has resulted in the melting of polar ice-caps at the astonishing rate of roughly 8% per decade in the recent past. The picture above illustrates the Uppsala Glacier in 1928 (top) and today (bottom) [15]. If not corrected, such side-effects may lead to mega-catastrophes that significantly affect life on the planet.

In 20 years, the accumulative effects will be much more pronounced, producing a significantly higher awareness of the necessity of fundamental long-term solutions to avert a global crisis. This awareness will result in significant investment in a new critical infrastructure for ecological, urban, and industrial monitoring that observes and models natural resource use, extrapolates global effects on various natural cycles, and provides basis for correction, including the use of legislative action designed to avert or postpone encroaching environmental mega-catastrophes. Pervasive networks of sensors and actuators will offer access to large expanses of the environment at an unprecedented spatial and temporal resolution. Such fine-grained real-time data will revolutionize how science is conducted. Also, this type of CPS infrastructure is an essential counter-measure against encroaching environmental mega-catastrophes.

A significant cyber-physical challenge is, therefore, to enable planetary-scale deployment of sensors and actuators to measure key environmental parameters and make local corrections. Such sensors must be networked for data collection, aggregation, and response. They must be environmentally friendly and self-sustaining (e.g., do not contain non-self-regenerative resources such as non-rechargeable batteries). They should be easy to program in bulk, yet resist malicious attacks, failures, and false data feeds. To be sustainable without a significant maintenance cost, these networks must form symbiotic relations with their physical environment. In these relations, natural processes (such as wind, solar energy, bird migration, and everyday human activity) can be taken advantage of to help various network functions. In turn, network output should lead to the optimization of environmental processes. The resulting interactions can produce new cyber-physical phenomena that should be more efficient than their natural (purely physical) counterparts. Early deployment might occur in application areas where significant human modification of the environment is already the norm. One example is agriculture. Cyber-physical environments might lead to a better food production process that is both economically viable and environmentally friendly in the sense of not disturbing natural cycles and diversity currently affected by present agricultural practices. The challenge of planetary-scale symbiotic cyber-physical sensor and actuator networks gives rise to several directions of multidisciplinary research that span hardware design, distributed operating systems, (biological, ecological and computing) system modeling, distributed control, and programming interfaces. The convergence of these problems poses a CPS grand research challenge.

2.2. Disaster Response: Large-Scale Emergency Evacuation

Consider how a large-scale evacuation due to weather might be managed. When hurricane Katrina hit the US Gulf Coast, tens of thousands of people were unable to leave for several days, and those that did leave were sent to a random destination, despite having friends or family able to house them elsewhere. Highways were closed due to congestion, and air travel came to a standstill. Although the incurred damage was not comparable, the evacuation of Houston due to hurricane Rita also demonstrated the potential for unmanaged transportation chaos.

In a managed transportation system, individual cars can travel together in fleets, with shorter following distances. Vehicles are staged and routed via main arteries as well as surface streets to match outbound flows to road capacities and fully utilize the road infrastructure. Bus, air, and rail transportation are coordinated, and evacuees are assigned to coordinated routes to most efficiently transport people where they want to go. Total evacuation would be cut substantially, and evacuees would have been reunited with friends and family, reducing the mass confusion and concern over the whereabouts of loved-ones. This urban evacuation scenario illustrates how a single event can render a normally orderly transportation network inoperable, providing a "grand challenge" problem for smart transportation. Critical CPS issues include how to ensure the seamless and symbiotic interactions of multiple, heterogeneous systems especially under stress conditions.

2.3. Assistive Devices

As the percentage of people over 65 in the population of the United States and elsewhere continues to increase, tele-services and assistive devices will play an ever-increasing role in providing home, assisted living and hospital services, prevention of falls, injury mitigation, and a host of other services. In this regard, tele-presence through multiple entities such as tele-immersive displays, tele-operated, and haptic devices can be beneficial. Consider a tele-physical home helper that would assist the elderly in cleaning up the home, preparing food, administering medicine and other tasks. Such a helper would be semi-autonomous, carrying out many operations in a fully autonomous mode, such as navigating through the home, scrubbing and vacuuming, recognizing voice commands and gestures from the patient (or client), maintaining the inventory of food and medicine, and ordering supplies over the Internet, while also accepting direct commands remotely, say, from a physician or family member. Achieving this vision requires, in part, trust of personal devices as well as trust in transmitted information. This means that one needs multiple dimensions of trust such as (i) the safety of using the devices in tele-presence spaces (e.g., safety of blood-pressure devices attached to a user or safety of a sensory instrument such as a haptic device attached to a user), (ii) reliable and timely information delivery, (iii) stability of the overall system, (iv) low risk in receiving wrong information, and (v) privacy guarantees. Current systems still do not have this level of sophistication, and an appropriate trust configuration remains a challenge. Other challenges in formal methods and certification techniques must also be met to provide this trust. Note that the verification and validation of cyber physical system is not a one-time event. Instead, it should be a life-cycle process that produces an explicit body of evidence for the certification of safety critical services.

2.4. Summary

In summary, a scientific and engineering CPS discipline should advance the conceptualization and realization of future societal-scale systems characterized by: (a) deep integration and pervasiveness of real-time processing, sensing, and actuation across logical and physical heterogeneous domains; and (b) systematic analysis of the interactions between engineering structures, information processing, humans and the physical world.

3. Scientific Foundations and Challenges

A new theory that explicitly addresses the interaction between the physical and cyber subsystems is necessary. This scientific foundation must provide the basis for overall understanding of the design, development, certification, and evolution of cyber physical systems. It must integrate the theories of computing and communication systems, sensing and control of physical systems, and the interaction between humans and CPS.

The science of CPS composition must comprise of new architecture patterns, hierarchical system composition from components and subsystems, theories of QoS (Quality of Service), protocol composition, and new modeling languages and tools to specify, analyze, synthesize and simulate different compositions. The envisioned scientific and engineering foundation will enable us to (a) Utilize new and effective programming abstractions and hardware functions, (b) Capture the constraints imposed by physics, chemistry and material that interact with the constraints from the cyber systems such as complexity, robustness, safety and security, (c) Iteratively develop both system structure models with system behavior models, and to map behaviors onto structures and vice versa, (d) Perform quantitative trade-off analyses to take into account the available technologies and constraints from cyber components, physical components, and human operators, and (e) Ensure CPS safety, robustness, stability, and security against realistic models of environment uncertainties, operator mistakes, imperfections in physical and/or cyber components, and security attacks.

We now describe several research challenges for CPS.

CPS Composition: The "science" of composition is one of the grand themes driving many research questions in networking and distributed systems.

Robustness, Safety, and Security of CPS: Uncertainty in the environment, security attacks, and errors in physical devices make ensuring overall system robustness, security, and safety a critical challenge. Security solutions can exploit the physical nature of CPS by leveraging location-based, time-based and tag-based mechanisms.

Control and Hybrid Systems: A new calculus must merge time-based systems with event-based systems for feedback control. This calculus must apply to hierarchies involving asynchronous dynamics at different time scales (from months to microseconds) and geographic scope (from on-chip to planetary scale).

Computational Abstractions: Physical properties such as the laws of physics and chemistry, safety, real-time and power constraints, resources, robustness, and security characteristics should be captured in a composable manner by programming abstractions.

Architecture: CPS architectures must be consistent at a meta-level and capture a variety of physical information. New network protocols must be designed for large-scale CPS. An innovative paradigm can be built around the notion of being "globally virtual, locally physical".

Real-Time Embedded Systems Abstractions: Bandwidth allocation protocols, new queuing strategies, and new routing schemes (including resource virtualization) can reduce and accommodate network delays. Networks must provide for real-time resource allocation, data aggregation, global snapshots, in-network decision making, and the ability to provide QoS. Faults must be handled. Scalability is essential. New distributed real-time computing and real-time group communication methods are needed.

Sensor and Mobile Networks: The need for increased system autonomy in practice requires self-organizing (and re-organizing) mobile and ad hoc CPS networks. Knowledge creation from the vast amount of raw data being collected will be essential.

Model-based Development of CPS: Models are used today to generate and test software implementations of control logic. Abstractions that cover the entire CPS design space must be developed, modified and integrated. Communications, computing and physical dynamics must be abstracted and modeled at different levels of scale, locality, and time granularity.

Verification, Validation, and Certification of CPS: The gap between formal methods and testing needs to be bridged. Compositional verification and testing methods that explore the heterogeneous nature of CPS models are essential. V&V must also be incorporated into certification regimes.

Education and Training: Scientists and engineers who are properly trained in the fundamentals of computation, control, networking, and software engineering are critically needed. CPS basics need to be added to the *lingua franca* of all technical graduates. Creative trade-offs between depth and breadth may need to be adopted.

4. Social Impact and Infrastructure

Investments in CPS hold great promise for national competitiveness in the global economy. It will lead to not only a renaissance in traditional industry sectors, but also to the creation of new industries. In particular, as discussed in previous sections, CPS advances will have a profound societal impact on many areas from blackout-free electricity generation and distribution to self-correcting cyber physical systems for "one-off" applications. This section discusses the impact of CPS on two of the greatest challenges of our time: (a) global warming coupled with energy shortage; and (b) the rapid aging of the population and related healthcare demands.

"More than 90 percent of the energy coming out of the ground is wasted and does not end as useful. This is the measure of what's in front of us and why we should be excited." [6]. Buildings and transportations are the major energy users. Green buildings hold great promise [7]. Energy used in lighting and cooling buildings is estimated at 3.3 trillion KWhr. Technologically, it is possible to reach the state of "Net Zero Energy" Buildings, where 60-70% efficiency gains reduce demand and the balance is supplied by renewable sources. However, to reach the goal of Net Zero Energy Buildings, the cyber and the physical worlds must be tightly integrated. The science of computation has systematically abstracted away the physical world and vice versa. It is time to construct a "Hybrid Systems Science" that is simultaneously computational and physical, yielding a unified framework that captures a robust design flow with multi-scale dynamics with integrated networking for the flows of mass, energy and information.

The transportation share of U.S. energy use reached 28.4% in 2006 which is the highest share recorded since 1970 [8]. U.S. passenger and cargo airline operations alone required 19.6 billion gallons of jet fuel in 2006. Furthermore, 88% of all trips in the U.S. are by car [9]. Hence, daily commuting and business travel represent a significant fraction of the transportation cost. Tele-presence research seeks to make all interactions seem local rather than remote. It is one of the three grand challenges in multimedia research [14], to make interactions with remote people and environments nearly the same as interactions with local people and environments. Two problems are contained within this challenge-distributed collaboration and interactive, immersive three-dimensional environments. As tele-presence is integrated with tele-operation, work-related travel can be reduced.

Next, rapidly aging populations with age-related chronic diseases is another formidable societal challenge across the globe. It is alarming that the growth of per capital health cost has the shape of exponential curve as the population ages. Future CPS infrastructure can help foster advances in the understanding and cure of chronic diseases and also help the elderly to stay in the comfort of their homes for many more years.

More than 90 million Americans live with chronic illnesses [10]. Chronic diseases account for 70% of all US deaths. Medical care costs for chronic diseases account for 75% of the $1.4 trillion medical care costs in USA. Chronic diseases account for one-third of the years of potential life lost before age 65. Emerging stem-cell biotechnologies hold the promise to improve human health [11]. However, much of this potential is not tapped, largely due to the lack of sufficient knowledge of the complex and dynamic stem-cell micro-environment. To have a breakthrough, it is important to develop an automated approach using high-throughput microscopes and robotic equipment to conduct large numbers of biological experiments controlled by mathematical modeling and pattern analysis algorithms.

A closely related problem is providing elderly care at home without sending them to expensive nursing homes. In the United States alone, the number of people over age 65 is expected to hit 70 million by 2030, doubling from 35 million in 2000. Expenditures in the United States for health-care will grow to 15.9% of the GDP ($2.6 trillion) by 2010. A major cost is the loss of ability to remain in the home due to the need for greater supervision. One crucial factor is the need for assistance in physical mobility. Another is cognitive impairment that requires daily supervision of medication and health-condition monitoring. When CPS infrastructure supports tele-presence, persons with minor mobility impairments can regain their freedom of movement at home, since physiological parameters can be monitored remotely. When the elderly can live independently without loss of privacy, major financial savings in senior care will result.

5. Summary

Cyber-physical systems (CPS) will transform how humans interact with and control the physical world. Zero-energy buildings and cities, extreme-yield agriculture, near-zero automotive fatalities, perpetual life assistants, location-independent access to medical care, situation-aware physical critical infrastructure, blackout-free electricity, and safe evacuation from hazardous areas are but some of the many societal benefits that CPS will deliver. CPS must operate dependably, safely, securely, efficiently and in real-time. CPS represent a confluence of technologies in embedded systems, distributed systems, dependable systems, real-time systems with advances in energy-efficient networking, microcontrollers, sensors and actuators. Correct, affordable and flexible deployment of CPS can only be made possible by fundamental advances in science, engineering and education. CPS technologies must be scalable across time and space, and must deal with multiple time-scales, uncertainty, privacy concerns and security issues. A new CPS science will define new mathematical foundations with formalisms to specify, analyze, verify and validate systems that monitor and control physical objects and entities. New infrastructure will benefit different economic and industry sectors. Sophisticated design tools will capture both cyber abstractions and the dynamics of physical/engineered systems. CPS scientists and engineers must be educated and trained to have a common knowledge framework that bridges the discrete world of computing and communications with the continuous world of physics.

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