Goals and Challenges in Cyber-Physical Systems Research Editorial of the Editor in Chief

THE present issue is a Special Issue dedicated to Cyber-Physical Systems (CPS) research and I would like to thank the Authors, the Reviewers and the Guest Editors, especially Professor Karl Henrik Johansson, for making such a Special Issue possible.

Being able to design and deploy large, resilient and secure networks of CPS is absolutely necessary to sustain the growth in several important technological areas from transportation, to energy, to manufacturing, to health care. This is a view which I believe is shared by many researchers.

In this short article some background on CPS is presented. The present editorial should be considered together with the Guest Editorial of the Special Issue on Control of CPS that follows.

The sources of the background materials below come primarily from government and specialists' reports, from funding agencies' descriptions of research initiatives and also from my personal experiences, from my research on CPS. I have used various versions of these materials on many occasions at technical meeting presentations and talks at universities for several years. Please note that the selections and descriptions of materials certainly reflect, to some extent, my personal views and preferences of topics in CPS research.

A Brief Introduction to CPS

As computing and communication devices become ever-smaller and ever-cheaper, they are ubiquitously embedded in objects and structures that interact directly with the physical environment and extend human capabilities. Multiple sensing and actuation units that gather, process, exchange and use information as a team are the next generation of engineered systems. Such collection of units that bridge the cyber-world of computing and communications with the physical and biological worlds are called Cyber-Physical Systems. CPS span engineered, physical and biological systems and create new applications with enormous societal impact and economic benefit.

Cyber-Physical Systems are characterized by large numbers of tightly integrated heterogeneous components in a network, which may expand and contract dynamically. Cyber-Physical Systems are common and are becoming ubiquitous.

CPS already exist, at some level, in medical devices (pacemakers, insulin pumps), in critical infrastructure (supervision and direct control of power plants, oil and gas distribution networks, refineries), in chemical process industries, manufacturing, transportation (airplanes and air-traffic control, rail), in consumer products (camcorders, cameras, mobile phones), and automobiles (anti-lock braking system (ABS), electronic stability control, fuel injection, emission control). For example, in an ABS, the embedded computer senses road conditions and applies pumping action to the brakes when the driver pushes the brake pedal; in addition, the ABS may also interact directly or indirectly with other systems such as adaptive-cruise control and lane keeping control. In a camera, the CPS senses light conditions and adjusts the settings directly or just informs the photographer—human in the loop. All these applications mark the beginning of an upcoming revolution where the cyber and physical worlds are so integrated that it is not clear whether the functional properties are due to cyber or physical components, or both. Advances in CPS will make it possible to build systems that will far exceed the capabilities of the simple embedded systems of today.

CPS will transform the way we interact with the physical world just like the Internet transformed how we interact with one another, with perhaps unintended implications on privacy, individual freedom and ethics. As a NSF director put it, "you should care about CPS because your life depends on them."

According to NSF, research advances in cyber-physical systems promise to transform our world with systems that respond more quickly (e.g., autonomous collision avoidance), are more precise (e.g., robotic surgery and nano-tolerance manufacturing), work in dangerous or inaccessible environments (e.g., autonomous systems for search and rescue, firefighting, and exploration), provide large-scale, distributed coordination (e.g., automated traffic control), are highly efficient (e.g., zero-net energy buildings), augment human capabilities, and enhance societal well-being (e.g., assistive technologies and ubiquitous healthcare monitoring and delivery).

In the future, examples of CPS will be found in smart transportation systems, smart medical devices, smart buildings, smart energy systems, the smart grid. In more detail, it is envisioned that in the future, in ***Medical Care and Health***, there will be life-supporting micro-devices embedded in the human body; body area wireless sensor nets; mass customization of heterogeneous, configurable personalized medical devices; natural wearable sensors (clothing, jewelry) and benignly implantable devices. In ***Energy***, there will be systems for more efficient, effective, safe and secure generation, transmission, and distribution of electric power, integrated through the smart grid; there will be smart ("net-zero energy") buildings for

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energy savings and systems to keep nuclear reactors safe. In ***Transportation and Mobility***, there will be vehicle-to-vehicle communications for enhanced safety and convenience ("zero fatality" highways), drive-by-wire, autonomous vehicles; there will be the next generation air transportation system (NextGen) together with autonomous vehicles for off-road and military mobility applications. In ***Manufacturing***, there will be smarter, more connected processes for agile and efficient production; manufacturing robotics that work safely with people in shared spaces; computer-guided printing or casting of composites; design for manufacturability and programmable foundries. In ***Materials and other sectors***, there will be sustainable mass production of "smart" fabrics and other "wearables" with applications in many areas; actively controlled buildings and structures to improve safety by avoiding or mitigating accidents; emerging materials such as carbon fiber and polymers offer the potential to combine electrical and optical functionality with important physical properties (strength, durability, disposability).

The control of such systems presents enormous challenges and requires approaches drawn from Systems and Control, such as those in traditional control, hybrid control systems, discrete event systems, networked control, and also approaches drawn from Computer Science, such as abstraction and verification, Networks, and many other areas depending on the applications of interest. The large scale and heterogeneity of components in CPS introduce grand research challenges. Robustness, resilience, reliability, safety and security issues for changing and reconfiguring dynamical systems must be addressed and these are novel research areas of great importance. The integration of different technologies and scientific domains presents new and challenging fundamental problems underlying the theoretical foundations for this class of systems.

From a Controls perspective, hybrid dynamical systems appear to be at the core of CPS. General methods involving energy like methods such as passivity and dissipativity that can be used to significant benefit in designing CPS by integrating components, model-predictive control that has been successful in controlling complex processes, game theoretic and many other approaches have been used. Feedback mechanisms are pervasive as they appear at all levels of interaction. Feedback of course is present independently of the models used as feedback transcends models!

Human in the Loop: Although the emphasis in CPS terminology has been on cyber and physical systems it is important to note that substantial real progress in applications could be made if humans were included in the loop. It appears that only in this way one can talk meaningfully about highly autonomous systems for the near future. It is envisioned that in such cyber-human-physical systems there will be a close synergy with the human operator. The varying degrees of authority assigned will be determined by abilities, specifications and demands.

What are the CPS research drivers? They include the decreasing cost of computation, networking, and sensing. Note that a variety of social and economic forces will require more efficient use of national infrastructures; also, environmental pressures will mandate the rapid introduction of technologies to improve energy efficiency and reduce pollution. The need to make more efficient use of health care systems, ranging from facilities to medical data and information is an important research driver. Networking and Information Technology (NIT) have been increasingly used as universal system integrators in human-scale and societal-scale systems; functionality and salient system characteristics emerge through the interaction of networked physical and computational objects; engineered products, as they evolve, turn into networked interacting systems of physical and computational processes, and into CPS.

What CPS have as defining characteristics? They include cyber capability (i.e. networking and computational capability) in every physical component; they are networked at multiple and extreme scales; they are complex at multiple temporal and spatial scales; they are dynamically reorganizing and reconfiguring; control loops are closed at each spatial and temporal scale, and maybe there is a human in the loop; operation needs to be dependable and in certain cases certifiable as well; computation/information processing and physical processes are so tightly integrated that it is not possible to identify whether behavioral attributes are the result of computations (computer programs), physical laws, or both working together.

It should be emphasized that a system should be considered to be a CPS only when there is tight interaction between the physical and cyber parts necessary to achieve the systems stated goals; such tight interaction for example may necessitate cross layer design, and specifications on timing issues. The implication here is that not every system controlled by a digital controller is a CPS; it may or may not be depending on the specifications and the design approach taken.

There is a set of pervasive underlying problems for CPS not solved by current technologies. They include: How to build predictable real time, networked CPS at all scales; how to build and manage high-confidence, secure, dynamically-configured systems; how to organize and assure interoperability; how to avoid cascading failures; how to formulate an evidential basis for trusted systems that leads to simpler certification procedures.

CPS Design Considerations. Assuming exact knowledge of the components and their interconnections may not be reasonable. Dynamic changes should be expected, especially when the whole life cycle of the system is considered. The physical part may cause the CPS to change; links may disappear, modules may stop operating. Security, safety, verification of properties need to be reevaluated regularly, because of the expected changes in CPS and these are very challenging problems.

In closing, the design of CPS represents a very challenging research area, but the payoffs are also great. The articles in the present Special Issue define important problems and offer innovative solutions towards the goal of having systematic methods for analysis and design of large CPS.

For Further Reading

There has been a series of significant research initiatives and activities in CPS over the past decade, including several federally funded workshops. Information may be found at the CPS Virtual Organization website (http://cps-vo.org/).

It should be noted that the importance of CPS was clearly recognized in the 2007 report of the USA President's Council of Advisors on Science and Technology (PCAST) "*Leadership*

Under Challenge: Information Technology R&D in a Competitive World", PCAST report, 2007 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-07-nitrd-review.pdf). The report ranked research in CPS as number one funding priority and it did pave the way for significant research funding.

The importance of CPS was reaffirmed in the 2010 PCAST report "*Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*", PCAST Report, December 2010 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf) and in subsequent reports. See for example the 2013 PCAST report "*Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology*", PCAST Report, January 2013 (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd2013.pdf).

See also "Winning the Future with Science and Technology for 21st Century Smart Systems" by the Office of Science and Technology Policy-White House (OSTP) found at http://cps-vo.org/node/6110.

Additional information may also be found in the Impact of Control Technology report; see http://ieeecss.org/general/impact-control-technology at the website of the IEEE Control Systems Society.

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