Cyber-Physical Systems - New Challenges for Science and Technology

A CPS (Cyber Physical System) is a system in which computing, communication and physical processes are so strongly connected that it is not possible to identify whether behavioural attributes are the results of computing, communication, control, physical laws or all of them working together. In these types of systems, the functionality and salient characteristics are emerging through the interaction of physical and computational objects. Therefore, computers, networks, devices and their environments in which they are embedded, have interacting physical properties, consume resources and contribute to the overall system behaviour. Quality of Control (QoC) and Quality of Services (QoS) are designed as integrated systems with defined behavioural attributes.

Cyber Physical Systems – smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components, sensing and changing the state of the real world – represent a real challenge and opportunity for the innovation economy in the 21st century.

These types of systems include Smart Transportation, Smart Medical Devices and Technologies, Smart Buildings, Next Generation Air Transportation and Smart Grid, Smart Manufacturing, a.s.o. Such systems are difficult and costly to design, build, test and maintain, involve the intricate integration of large networked software and hardware components and multiple subsystems.

The design of CPS is much more than a union of designing both computational and controlled physical systems.

Cyber Physical Systems are becoming ubiquitous, pervading every sector of the critical infrastructure and every aspect of an individual's daily life, including medical care and health, energy, transportation and mobility, manufacturing, materials and other sectors. CPS are "systems-of-systems" whose interactions are exponentially complex and we need a new vision about systems science.

A new science of CPS design will allow us to create new machines with complex dynamics and high reliability, to be able to apply the principles of CPS to new industries and applications in a reliable and economically efficient way. We must reintegrate the physical and information's sciences; we must construct a new science and technology foundation for CPS, that is simultaneously physical and computational.

We have to consider all agents of processing and transmission of information and knowledge into large and very complex hardware and software architectures.

We have reached the limits of our knowledge of how to combine computers and physical systems. The transition from C2 paradigm (computer for control of physical systems) to C4 paradigm (computer, communication, cognition for control of physical systems) is a natural way to create open generation of CPS. Considering the technical limitations of separate design of information processing and physical systems, we must understand and define the foundations of CPS and develop methods and tools to integrate the design of computers, communications, control and physical systems (IDCCCPS).

Cyber-physical systems are inherently heterogeneous in terms of their components and in terms of essential design requirements. From the functional properties, CPS are subject to a wide range of physical requirements, such as dynamics, power, physical size and to system-level requirements, such as safety, security and fault tolerance. The compositional frameworks design has successful application to homogenous systems. CPS products are heterogeneous systems comprising multiple types of physical systems and multiple models of computation and communication, and that makes design flows increasingly product specific with severe impact for design automation.

To develop a CPS, three distinct areas of expertise are needed: Physical systems engineering, Computer systems engineering, Embedded systems engineering.

The current technology cannot provide predictability for partially compositional properties, and it is not possible to integrate complex components into complex systems in a reliable way. We must consider the science of systems integration as a part of any basic engineering curricula.

Another very important aspect of the new generation of CPS is connected with the security and privacy which must be considered from both economical and security point of views, as well as from the quality of life one. Physical systems can be attached through cyberspace and cyberspace can be attached through physical devices into a CPS.

To model the interactions between the cyber and the physical worlds, we have to introduce two directed connector types, P2C Connector (physical to cyber) and C2P connector (cyber to physical). The sensor and actuators can be modelled as connectors into a large integrated CPS architecture, considering large networks of sensors and actuators.

In this framework of severe limitations of the current methods and tools for design and analysis of complex heterogeneous systems, we must create a new scientific and technological understanding of the interactions of information processing, networking and physical processes. The new science of CPS will allow designing complex systems more economically, by sharing both abstract knowledge and concrete tools.

The challenges of CPS design as heterogeneous complex systems need to create a new systems science foundation and new technology infrastructure based on the fundamental concepts from computer science, communication, control and physical systems into an integrated way.

To create this new science and technology of CPS we have to consider some very important requirements as:

- **to realign abstraction layers in design flows.** Computational abstraction must include physical concepts, such as time and energy. The physical representation must be include dynamics and some uncertainties included by network delays, finite world length. These abstractions layers will allow the synthesis of computations with physical properties and physical system dynamics that are robust against implementation uncertainties considering all aspects of information processing.

- **to develop semantic foundations for composing heterogeneous models and modelling languages** to describe different physics and logics, to develop mathematical frameworks that make semantics explicit, understandable and practical for developers.

- **to develop new understanding of compositionality** in heterogeneous systems taking into account the physical and computational properties, to create large, networked systems with required functionality and high reliability into a real disturbed environment.

- **to transform system integration** from a high risk engineering practice into a science-based engineering discipline as a integrative vision.

- **to create new theories and methods for computational certification of CPS**. We must be able to compose CPS components into a large CPS in a way that allows us to reuse the certification of the components as proper evidence in certifying the global complex systems.

- **to develop new open architectures for CPS** that allow to build global-scale capabilities with adaptive facilities to different operational conditions and high capacity to dynamic reconfigurations.

Networked ICT-Systems (e-Networks) have pervaded in all traditional infrastructures, rendering them more intelligent but also more vulnerable at the same time. Increasing the complexity of critical infrastructures, which supports the orderly functioning of the society and economy, imposes a new vision on designing the control systems with the integration of computers and communications.

Networking (wired or wireless) introduces new vulnerabilities that are not well understood and the verification of a high integrity system or component, takes more effort and time that its initial development.

CPS in general are built on upon wireless sensors and actuator networks (WSANs), through the networks within a real-world CPS could potentially be much more complex and heterogeneous. The use of WSAN distinguishes CPS from traditional embedded systems and wireless sensor networks. From this point of view, some widely recognized characteristics of CPS could be identified as: Network Complexity, Resource Constraints, Hybrid Traffic and Massive Data, Uncertainty.

Ubiquitous applications and services that could significantly improve the quality of our daily lives will be enabling by

CPS, which will make applications more effective and more efficiently, based on QoS provided by the employed networks.

Main challenges of this century as global warming, reducing natural resources, ageing population, climate changes and the competition in a multipolar world need to accelerate the transition to a smarter and greener economy based on knowledge in action; and CPS could be a solution.

By deeply embedding computational intelligence, communication, control and new mechanisms for sensing and actuation, CPS transform our world with systems that respond more quickly, are more precise, work in dangerous or inaccessible environments, provide large-scale distributed coordination, are highly efficient, augment human capabilities etc.

CPS represent the new technological revolution, they are more than Networking and Information Technology. We identify the Information and Knowledge in action integrated on physical systems. They are complex at multiple temporal and spatial scales, are dynamically reorganizing and reconfiguring.

The development of CPS will require computer scientists and network professionals to collaborate with experts in control engineering, signal processing and biology. The education system and research programs must be reconsidered to give answers to CPS challenges and the multidisciplinary could be a real challenge.

It seems at this moment that CPS will make a real difference in engineering education and practice – and this is the reason for our Journal has dedicated an issue to this topic, which deserves a real attention from the automation and control engineering community. We will try to stimulate the best people in control computer and communication to rethink new generation of complex systems.

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