Prolog to the Section on Cyber–Physical Systems

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Today, societies across the globe, and the planet itself, are faced with several challenges in many domains such as water, energy, environment, transportation, and health-care. Overcoming these challenges requires another step forward in the technological revolution involving the conjoint deployment of advanced computation, communication, and control.

Cars along highways will need to be networked with each other and the infrastructure for greater safety and reduced delays. Renewable but unreliable energy from wind and solar will need to be integrated into the power grid, homes which have traditionally been the only consumers of energy can occasionally become producers, and batteries of hybrid cars can be used as reservoirs of energy to store energy and smooth fluctuations. Telesurgery can make surgery more reliable by reducing tremor while also enhancing access for patients. Large networks of sensors can monitor the environment and reveal important information about ecological and environmental processes.

All these are next-generation engineered systems in which computing, communications, and control technologies are tightly integrated to achieve high level performance, reliability, flexibility, robustness, and efficiency in dealing with physical systems in many application domains. Dubbed cyber–physical systems (CPSs), they involve the interaction of computers, networks, sensors, and actuators, and are attracting much attention from academia, industry, and governments.

One of the biggest challenges to the implementation of cyber technology systems is their complexity which makes it more difficult to design and develop software systems.

These developments constitute an acceleration of a trend that has been happening over the past few decades. Looking back at the history of the technological evolution, one sees that there has been synergetic interaction among computing, communication, and control technologies that has accelerated further advancements in each area. As an example, computers were originally developed and used for calculations. However, when they started to be used in control loops, the necessity to deal with timing constraints of physical systems stimulated the development of real-time computing technology. Indeed this is a good example of what is meant by a CPS, though this name is a recent invention. Conversely, the evolution of computing technology has played a significant role in the development of control theory. When the platform began shifting from analog computers to digital computers, attention started shifting from the development of frequency-domain theory to state–space theory.

There are several research challenges to the deployment of next-generation CPSs. Their dynamics are quite challenging to deal with since there is a tight interaction between the typically continuous dynamics of physical systems and the discrete dynamics of computing systems. Moreover, there is an interposed communication network mediating interactions, which can cause delays or packet losses between the computing and physical systems. One important focus within CPSs is networked control systems, where it is critically important to address the stability and performance of the control loop, focusing on the interaction between the physical system and the controllers over a communication network. Another important focus is the study of the dynamics of hybrid systems which involve both continuous and discrete dynamics, since it is valuable to provide formal verification of properties such as safety. Yet another focus is on real-time computing and networking, where it is important to deal with the timing constraints of physical systems and ensure temporal correctness of the interactions with both computing systems and the communication network.

Wireless sensor networks are an important class of CPSs that can consist of a large number of computing nodes equipped with wireless communication and sensing capabilities. Some of the important issues are ensuring extremely energy-efficient networking, synchronization of their clocks, and performing in-network computation to extract relevant information from large-scale sensor data.

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With the increasing usage of cyber technologies and networks, CPSs are becoming more vulnerable to cyber attacks. Furthermore, with their increased deployment in safety-critical systems, the consequences of such attacks can be more physically harmful.

One of the biggest challenges to implementation of CPSs is their complexity, which makes it much more difficult to design and develop software systems.

The 21st century could well be the century of large-scale system building. Not only must we act with much greater awareness of fundamental ecological limitations, but also we must cater to the demands of large sections of the globe for advanced transportation systems, energy systems, water systems, and the healthcare system. Next-generation CPSs will play a critical role in meeting these twin challenges. ■

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Dr. Kumar is a member of the National Academy of Engineering of the USA, as well as the Academy of Sciences of the Developing World. He was awarded an honorary doctorate by the Swiss Federal Institute of Technology (Eidgenossische Technische Hochschule), Zurich, Switzerland. He received the IEEE Field Award for Control Systems, the Donald P. Eckman Award of the American Automatic Control Council, and the Fred W. Ellersick Prize of the IEEE Communications Society. He is a Guest Chair Professor and Leader of the Guest Chair Professor Group on Wireless Communication and Networking at Tsinghua University, Beijing, China. He is also an Honorary Professor at IIT Hyderabad. He was awarded the Daniel C. Drucker Eminent Faculty Award from the College of Engineering at the University of Illinois, the Alumni Achievement Award from Washington University in St. Louis, and the Distinguished Alumni Award from IIT Madras.