ASME Journal of Computing and Information Science in Engineering (JCISE)
Guest Editorial by Vijay Srinivasan[1]
Title: Why should we care about Cyber-Physical Systems?

For over a decade this journal has supported and advanced the research and applications at the intersection of information science and mechanical engineering. In that process it has established itself as a premier outlet for cutting edge research in the field of engineering information systems, covering such areas as computer-aided design and manufacturing. The intersection of information science and mechanical engineering has just grown bigger thanks to the emergence of Cyber-Physical Systems (CPS). It is already attracting national and international attention because of the recognition that CPS products and services will continue to account for an increasingly large fraction of a country's gross domestic product. It has not escaped this journal's attention either – it created an associate editorship for CPS in 2013.

To understand the emerging importance of CPS we only need to look around us. Physical products that have long been primarily designed and manufactured by mechanical engineers are now tightly integrated with – and enhanced beyond recognition by – cyber elements such as embedded computing, wireless communication, and digital controls. From smart phones to cars to drones, it is nearly impossible to come across any new product that does not qualify as a member of CPS. These products also present new opportunities for research and development to the audience of this journal.

What are the strategic research and development opportunities for 21st century cyber-physical systems? The National Institute of Standards and Technology (NIST) recently released a report[2], developed with input from nearly 80 experts from industry, academia, and government, to answer this exact question. The report is a call to action. It has an inviting subtitle 'Connecting computer and information systems with the physical world' that unwittingly places it at the sweet spot of this journal's scope. So it is quite apropos to examine a few highlights from that report in the following sections.

Scientific Foundations

To start with, CPS are fiendishly complex. Engineering such complex systems in the absence of sound scientific foundations adds significantly to the complexity. It starts with the modeling of CPS.

Engineers who have built and used mathematical models of physical systems have had the advantage of several centuries of scientific advances in fields such as classical, solid, and fluid mechanics. If the models don't capture reality, they then go back to refine their models to account for what nature has in store, and humbly accept the fact they can only approximate reality – however closely – by mathematical models. A curious inversion is witnessed in

[1] Fellow ASME, National Institute of Standards and Technology, Gaithersburg, MD 20899, U.S.A.
[2] Strategic R&D Opportunities for 21st Century Cyber-Physical Systems: Connecting computer and information systems with the physical world, January 2013.
http://www.nist.gov/el/upload/12-Cyber-Physical-Systems020113_final.pdf

modeling some of the cyber systems. Here an abstract model is posited first, and then computational elements are manipulated to strictly adhere to the abstraction. Success in such an approach, albeit limited to some logical tasks, in the computational domain over the past few decades has given a false sense of expectation that it can be extended to the whole space of CPS. Current challenges in modeling CPS stem in large measure from these radically different philosophical approaches to modeling.

As complex systems are composed (or assembled, as we say in physical systems) from subsystems and components, two major questions arise. The first is whether an individual subsystem or component is fit for such a composition; in the CPS parlance it is called composability. The second is whether the behavior of the whole system can be inferred from the behaviors of its subsystems and components; it is called compositionality. While engineers who deal with the physical domain have addressed the same two questions for over a century and have come up with an impressive set of tools and methodologies – which are increasingly based on solid scientific foundations – these questions have vexed the practitioners in the cyber domain, and are seeping into CPS.

Management of time and synchronization is another critical issue for CPS. Zero (computational) execution time and zero communication time are no longer acceptable assumptions, just as zero geometric variability is not an acceptable assumption in manufacturing physical products. To illustrate this point, observe that it is only now control systems engineers and embedded software developers are attempting to come up with a standardized means of communicating through a ‘contract’ the allowable tolerance in the computational execution time. Scientific and technical developments in managing tolerances in the spatial domain have a long and successful history in the physical world. Similar advances are needed in the time domain.

Systems Engineering and Integration

Systems engineering and systems integration have been practiced and codified, to varying degrees of success, in industry and academia for over 50 years. They continue to be hot topics, and have become even hotter in CPS.

System engineers are supposed to start from higher level requirements for a system, and break them down to requirements for subsystems all the way to components. In that process they also define the structure and behavior of the subsystems, and recur all the way to the components. They engage in various validation and verification exercises – in the form of modeling, simulating, and testing – to ensure that they have captured correct requirements at every stage and created subsystems that correctly satisfy the specified requirements. Such validation and verification are challenging tasks even when undertaken for physical and cyber domains separately. They become Herculean tasks for large CPS; in fact, our ability to design, build, and field large CPS in the future is limited by how well we can simplify and carry out these tasks.

Every engineered system will fail, sooner or later, and CPS are no exception. The engineer’s creed has always been to learn from failures, either during in-house testing or in the field, and to take corrective actions to mitigate such failures. Failure modes and effects analysis

(FMEA) and root cause analysis (RCA) are but two of the most commonly used tools for this purpose in industry. CPS test the limits of such tools, leading to well-publicized exasperations in large CPS projects. An increasingly alarming trend is the frequent exhibition of emergent behaviors by complex CPS. By definition such behaviors are not accounted for and we don't know how to anticipate them. They can be detrimental to safety and security, causing us to launch heroic engineering efforts to salvage the system and the reputation of the firm.

Workforce Development

To prepare our workforce to deal with CPS, we need to attack the problem along two fronts. The first is the education and training of new students in colleges and universities; the second is the continuing education of engineers in industry.

A college curriculum that is already straining under an overload of required and elective courses seems to leave very little room for new courses dealing with CPS, especially at the undergraduate level. But there are some bright spots that give us cause for optimism. Some leading universities are already introducing mandatory systems engineering courses and are using capstone projects to enforce systems learning. Even more encouraging is the fact that the incoming student population is well versed in the use of CPS in their daily lives; they are itching and demanding to learn more about these new technologies.

Continuing education of engineers in industry in CPS poses a different set of challenges. But here again necessity could prove to be the mother of invention. CPS courses that are targeted to specific needs of a particular industry can be developed and delivered using the very technologies and media made possible by CPS.

You can read more about these opportunities in the aforementioned NIST report. I will conclude this column with a few remarks about the current state of mechanical engineering in industry. It is a well-acknowledged fact that senior mechanical engineers in several industrial sectors, such as automotive and aerospace, have long seen their role morph into that of a systems integrator. Their basic training in geometry, materials, mechanics, and energy has given them mastery over the physical domain. Now they are called upon to extend their skills to a tightly integrated space of cyber and physical domains. They are well positioned to lead industry in CPS integration as well, but only if they broaden their skills set. This journal could play a vital role to enable that exciting transition.
