

Cyber-Physical Systems: Past, Present, and Future

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ACS 560
December 2, 2011

Coined in 2006 by Helen Gill (National Science Foundation), the term “cyber-physical systems” (CPS) refers to the “integration of computation with physical processes”[1]. CPS can be further described as “any physical or engineered system whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.” Many scientists and engineers agree that “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”[2]. Cyber-physical systems have emerged from the simple embedded systems of the past, are becoming increasingly entwined in present day infrastructure and promise to play a vital role in future engineered systems.

The majority of microprocessors in use today are actually in embedded devices, defined as a microprocessor-based system which controls a function or range of functions. Not intended to be programmed by the end user, these devices are typically stand alone devices whose software is not exposed to the outside world. Originally, the software in the



Figure 1: Embedded systems control many of the common devices in use today.

device was intended to enhance the inherent functionality of the product or offer a finer level of control thus improving performance. Over time, the software has evolved to include code that is absolutely necessary for the functionality of the system, known as “firmware”, which is involved with lower level operations and higher level software which can be replaced without changing the hardware. Embedded systems are attractive because upgrades to the system functionality can be realized by swapping the software instead of changing the hardware improving cost effectiveness. Also, software upgrades can often be achieved remotely improving safety and ease of maintenance. Embedded systems typically contain several basic components—processor, memory, peripherals, software and algorithms [3]. The ubiquity of such systems is demonstrated in home appliances, games and toys, and automotive electronics, which all contain embedded devices.

Until fairly recently, the fields of computer science and systems control engineering have progressed as separate disciplines, both technically and culturally, [4] but as relatively simple or single-device embedded systems have gradually developed into more

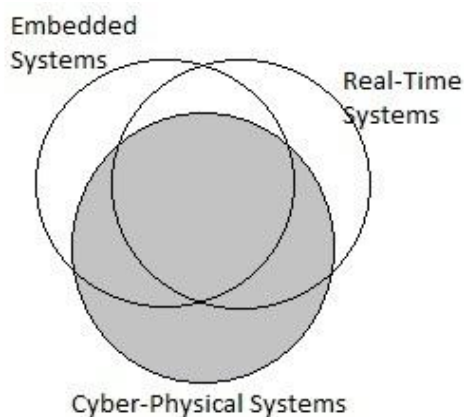


Figure 2: Cyber-physical systems are more than simply embedded systems

complex systems of systems, communication and interoperability between the physical and computational units have become essential design issues [5]. The confluence of embedded systems, real-time systems, distributed sensor systems, and controls in conjunction with the

availability of increasingly low-cost, small-size, low-power and high-capability sensors and

computing devices has pushed the development of CPS systems into a variety of domains

[2]. CPS systems are unique in that components can be distributed both spatially and temporally and involve complicated networks for feedback control and real-time communication. Additionally, the synergism between the cyber and physical systems can be at the nano-scale level or at the large-scale wide area “system of systems” level [2].

CPS systems can provide several advantages, including quick response times, increased levels of precision, improved efficiency and resource utilization, the ability to work in dangerous or previously inaccessible environments, large-scale, coordinated distributed systems, and augmentation of human capabilities [4]. Classic examples of cyber-physical systems in use or development today include high confidence medical devices, distributed robotics for “telemedicine”, traffic control systems to improve safety

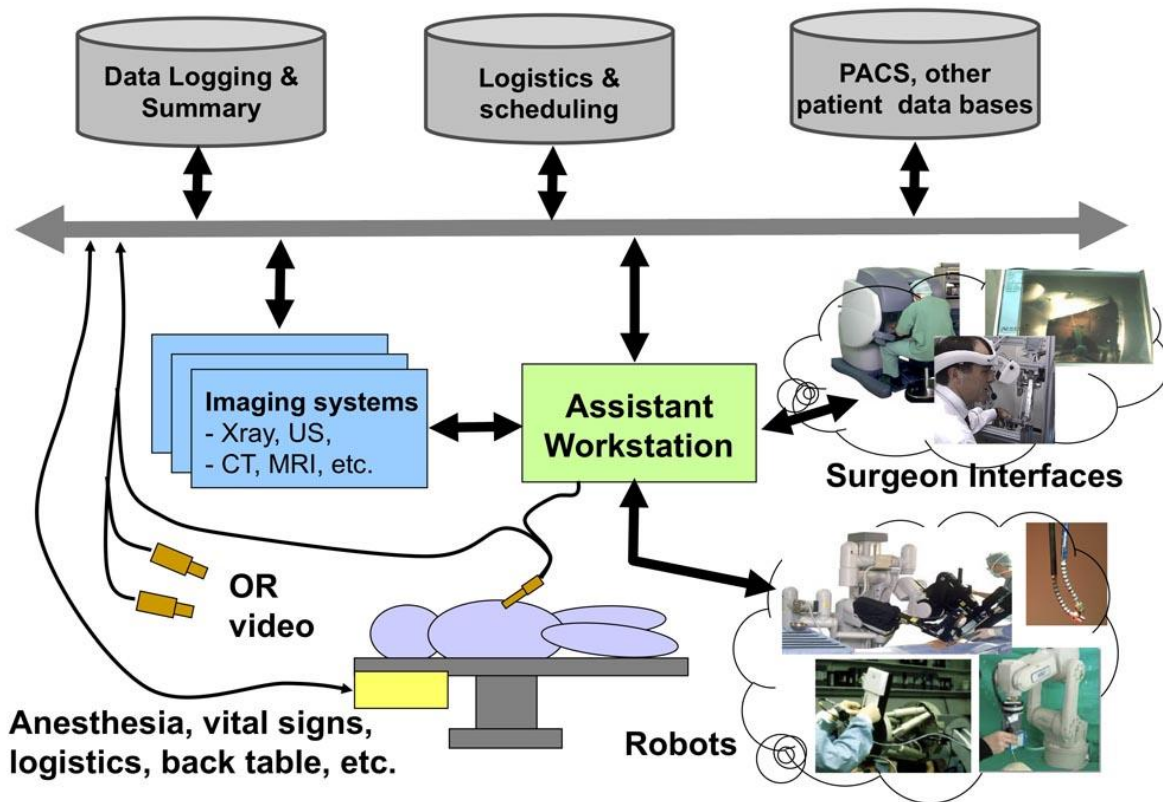


Figure 3: Medical cyber-physical system

and efficiency, energy and environmental control through smoothing variability in demand, avionics instrumentation, and defense systems [5].

CPS systems offer many advantages that can be utilized to improve quality of life; however, the real-time, distributed nature of these systems also creates technical, security and philosophical issues which also must be considered. Cyber physical systems will be expected to operate in environments that are loosely controlled and often unpredictable. The systems must be designed to be robust, adaptable to environmental variability and capable of recovering from unexpected failures. Timing assurances may be part of a CPS system and must be guaranteed for nondeterministic program execution. “Best effort” networking may simply be inadequate to deliver predictable and real-time performance necessary for reliable, time-critical cyber physical systems, so new or redesigned communication infrastructure will be required [5]. As it may be virtually impossible to test a system under all possible conditions, appropriate modeling tools will need to be acquired

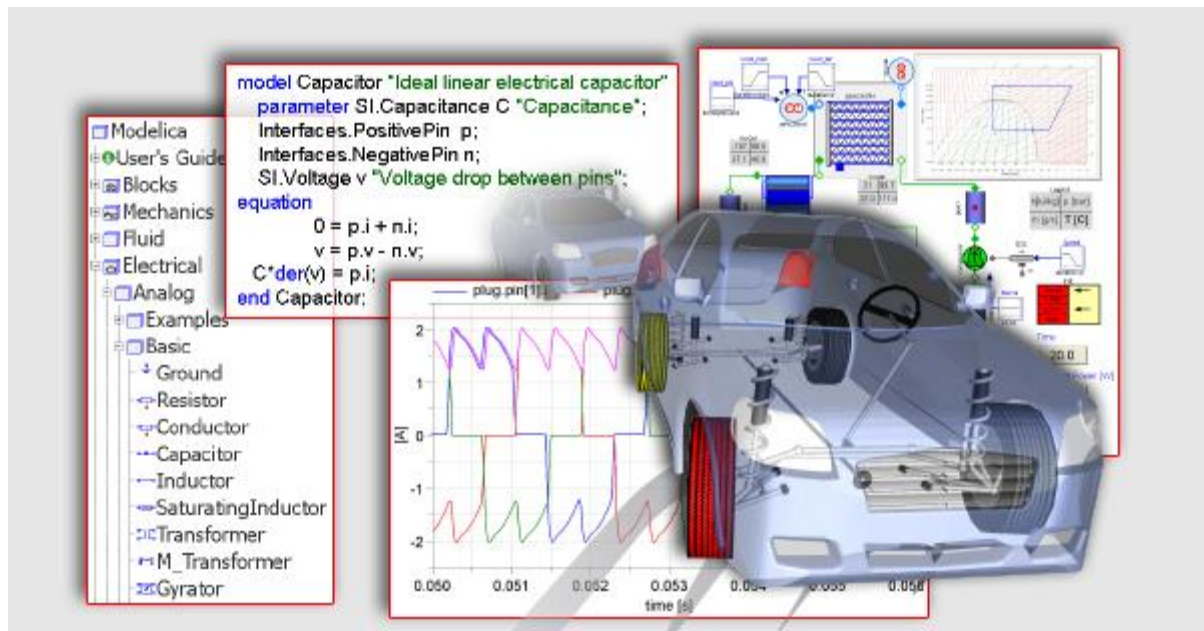


Figure 4: Modelica modeling tool

to “cover the entire cyber-physical system design space” [2]. Systems of systems may also give rise to emergent behaviors that further challenge designers’ ability to build large-scale predictive models [4]. Huge amounts of data will be created by CPS systems; moving this data from sensors to processors to actuators could result in quick depletion of energy reserves, so new types of energy storage devices will be required [5]. Time, identity, and location information are frequently available due to “physical layer fingerprints” associated with transceivers. Personal data and privacy must still be protected. Proprietary intellectual property issues will arise when systems utilize flexible connections [4]. New computational abstractions must be developed, new CPS-specific architectures designed. Finally, educational and training programs must be structured to incorporate the “fundamentals of computation, control, networking and software engineering” necessary to have a “common knowledge framework that bridges the discrete world of computing and communications with the continuous world of physics.”[2] In order to realize the full potential of cyber-physical systems, all of these challenges must be addressed.

Currently, the NFS is seeking research proposals that address challenges in three CPS “themes” [7]. *Foundations* research will “develop new scientific and engineering principles, algorithms, models, and theories for the analysis and design of cyber-physical systems.” *Research Methods and Tools* will “bridge the gaps between approaches to cyber and physical elements of systems through innovations such as novel support for multiple views, new programming languages and algorithms for reasoning about and formally verifying the properties of complex integrations of cyber and physical systems.” New software and hardware components will be designed for *Components, Run-Time Substrates, and Systems* infrastructure and platforms dealing with specific grand challenge applications

in sectors critical to national security and competitiveness. In the United States alone, funding for the first annual grant competition (2007) was set at approximately \$30 million; funding for future competitions is projected to be in the \$20 million - \$30 million range, dependent on the availability of funds [6, 7].

Cyber-physical systems are relevant to every individual. “These networked systems of embedded computers ... have the potential to change radically the way people interact with their environment by linking together a range of devices and sensors that will allow information to be collected, shared, and processed in unprecedented ways. ... The use of [these embedded computers] throughout society could well dwarf previous milestones in the information revolution.”[4] As a participant in an ever-changing, technology-dependent society, my world is and will continue to be impacted by CPS. I will likely use the medical devices, smart home technologies, and automated transportation devices that are in current development. As a student of computer science, my goals include developing my problem-solving skills, expanding my knowledge-base in computational analysis, and familiarizing myself with computational tools that I can ultimately apply to cross-curricular domains such as biology, mathematics and physics. CPS systems provide the type of interdisciplinary platform that I ultimately hope to be involved with. Because significant funding is funneled to CPS development both in the United States and abroad [8], an increase in the number of research and job opportunities in this area should continue—an important aspect to consider when training for future employment. “Cyber-physical systems are an emerging trend around the world because of fundamental technological and economic forces” [8]. Wherever my future takes me, I will need at least a minimal

understanding of the breadth of cyber-physical systems to be a globally competitive researcher and employee.

References

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[4] "Report: Cyber-Physical Systems Summit" summary report from the April 2008 CPS Summit in St. Louis, MO. Available: [http://varma.ece.cmu.edu/Summit/CPS Summit Report.pdf](http://varma.ece.cmu.edu/Summit/CPS_Summit_Report.pdf).

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<http://www.nsf.gov/pubs/2011/nsf11516/nsf11516.htm>

[8] Cyber-Physical Systems Executive Summary prepared by the CPS Steering Group, March 6, 2008. http://precise.seas.upenn.edu/events/iccps11/_doc/CPS-Executive-Summary.pdf

Figure 1: <http://www.alpha.co.jp/en/biz/devel/embedded.shtml>

Figure 2: <http://technorati.com/technology/it/article/cyber-physical-systems-the-new-wave/page-2/>

Figure 3: <http://robotics.case.edu/ICRA2010/MedicalCyberPhysicalSystems.html>

Figure 4: <http://www.qtronic.de/en/modelica.html>