Design Science for Cyberphysical Systems

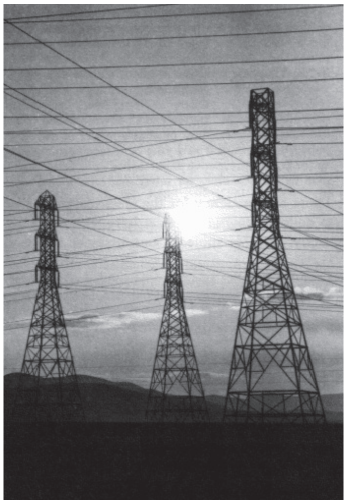
The integration of physical systems through computing and networking has become the most pervasive application of information technology, a trend now known as cyberphysical systems (CPSs). In many science and technology domains—transportation, healthcare, energy, and manufacturing automation—this intersection has yielded disruptive technologies, created new industries, and rearranged the status quo in entire economic sectors. The deep integration of computational, physical, and human aspects of engineered systems has spurred the development of cross-disciplinary approaches that are yielding new methods in science and engineering design. The tight integration of physical and information processes in CPSs necessitates the development of a new systems science, one that ensures efficiency, resiliency, robustness, safety, scalability, and security.

Why Is Systems and Control Relevant?

Control science and engineering have achieved remarkable success in the analysis and design of physical systems. New theories and tools are now needed to design networked heterogeneous systems, along with their automation and controls, that take into account interactions among the physical, communication, and computation systems.

CPSs represent an exciting opportunity for the controls community to extend its legacy of rigorous theoretical foundations and engineering methods and to thereby play a crucial role in ensuring the performance, reliability, safety, and feasibility of complex engineered systems.

Designing Complex CPSs



Among the hardest problems facing researchers and engineers are those associated with producing robust integrations of physical systems and computational processes for cyberphysical systems. Cyber components are steadily increasing and are essential for delivering advanced capabilities in airplanes, cars, spacecraft, power grids, medical devices, physical infrastructures, and other applications. CPSs are ubiquitous: well over 90% of all microprocessors are now used for cyberphysical systems—not in stand-alone computers or enterprise systems. But theoretical foundations and automated tools for designing tightly integrated computational and physical systems—encompassing modeling, control, verification, optimization, and the like—are lacking.

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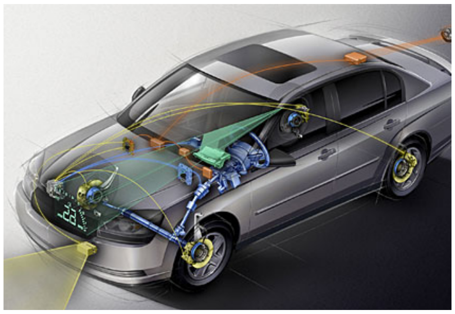

Automotive Systems

Cars and trucks are as much cyber as physical entities! A modern automobile can have more than 100 processors and more than 10 million lines of code. Multiple vehicle functions are under software control, such as engine, transmission, aftertreatment, suspension, and driver controls. Semiautonomous (and fully autonomous) cars are being developed and will pose further challenges for automation.

SCADA

Supervisory control and data acquisition (SCADA) systems perform vital functions in national critical infrastructures, such as electric power transmission and distribution, oil and gas pipelines, water and wastewater pipelines, and transportation systems. SCADA functions include monitoring and control of large-scale complex physical processes that may be distributed among multiple sites over long distances.

Biomedical Devices

Human lives are directly at stake in the operation of biomedical devices, especially implanted ones. Increasingly, such devices are incorporating embedded sensing, control, and actuation. Examples include insulin pumps, pacemakers, and implantable cardiac defibrillators.

CPS Design: Cross-Cutting Research Needs

Cyberphysicality spans the gamut of engineering domains. Although CPSs also pose application-specific requirements, control scientists and engineers can have an impact across industry and application sectors by addressing several broad research challenges:

- *Science of CPS integration.* CPS architectures need to bring together complex control algorithms, communication protocols, and computational platforms in integrated networked systems that provide real-time, high-confidence assurance of performance and robustness.
- *Dynamic configuration and scalability.* In many applications, CPSs will have plug-and-play components, including physical and cyber elements. CPS control must function seamlessly under reconfiguration and as the systems scale.
- *Co-design of system/platform/control.* Historical practices of developing the physical system, then the information technology platform, and then the control approach and algorithm are no longer tenable—an integrated, synthetic design paradigm is needed.
- *Human-automation interaction.* Human operators and users are an inherent part of many CPSs and are an additional source of complexity in control system design. In several respects, semiautonomous systems are harder to design than fully autonomous ones!
- *Verification and validation.* Most CPSs operate in safety- or mission-critical environments; costs of failures are typically intolerable. Automation and control design processes must provide assurance of safe, reliable operation under normal and abnormal conditions.
- *Cybersecurity.* From medical devices to the power grid, CPSs are cyber-connected systems. Security against and resilience under cyber attacks are an increasingly critical need.