# Cyber Physical Systems

## 1 Definition

Cyber Physical Systems (CPS) are smart networked systems with embedded sensors, processors and actuators that are designed to sense and interact with the physical world (including the human users), and support real-time, guaranteed performance in safety-critical applications where the proverbial "blue screen of death" can have catastrophic consequences. In CPS systems, the joint behavior of the "cyber" and "physical" elements of the system is critical - computing, control, sensing and networking are deeply integrated into every component, and the actions of components and systems must be carefully orchestrated. This "convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet" has also been called the Industrial Internet [1].

## 2 Drivers

Transportation: CPS technologies can eliminate 93% of the 6M automotive crashes each year caused by human error, and the cost of highway congestion (currently over $80B/year) can be greatly reduced. The FAA has been mandated by Congress to integrate UAVs into "manned" airspace by 2015. Congestion in our most crowded airports has resulted in an increase in the rate of runway incursions (over 1000 in 2011). There is an urgent need to improve efficiency and safety in our transportation network [2].

Manufacturing: The complexity of what we are able to design and build, and what society (and military) wants is constantly increasing (complexity measured by source lines of code and number of parts has grown several orders of magnitude over the last decade), while the time scale for products and the lead time are decreasing, even as product variety is increasing. CPS technologies are vital to preserving our national competitiveness in manufacturing and for national security [3,4].

Healthcare: The healthcare challenges arising from our aging population (the ratio of retirees to workers in the US is expected to reach 40% by 2020) combined with the opportunities provided by inexpensive sensing, ubiquitous communication and computation and the demand for 24/7 care will lead to an explosion of cyber-physical medical products. CPS correct-by-construction design methodologies are needed to design cost-effective, easy-to-certify, and safe products [5,6].

Energy: Renewable electric energy resources such as solar and wind and clean products such as (plug-in) electric vehicles are expected to grow significantly, especially as prices come down. The integration of intermittent and uncertain wind and solar sources and plug-in devices necessitates not only new sensors, switches and meters, but also a smart infrastructure for realizing an adaptive, resilient, efficient and cost-effective electricity distribution system. CPS technologies are essential for the creation of this infrastructure, enabling the optimization and management of resources and facilities and allowing consumers to control and manage their energy consumption [6,7].

Agriculture: With a projected global population surpassing 9 billion people by 2050, an uncertain and changing climate future, and up to 50% of food lost between production and consumption, our agricultural systems that generate food, fiber, feed, and biofuels need to be smarter and more efficient. Producing the needed agricultural products for future generations will require practices, processes, systems that are sustainable (economically, environmentally, and socially). CPS technologies are key to increasing efficiency (less waste) throughout the value chain, improving our environmental footprint, and creating opportunities for a high-skill, middle-class workforce.

Defense: Complex, networked systems are increasingly critical for meeting military and national defense needs. The Department of Defense has identified 7 critical cross-cutting S&T emphasis areas. CPS science and technology are fundamental to at least 3 of these 7 areas: Engineering Resilient Systems (expediting design and delivery of trustworthy, adaptable and affordable defense systems), Cyber (DOD operations in cyberspace), and Autonomy (autonomous systems to augment military operations).

Emergency Response: Approximately 700 disasters occur each year with annual worldwide impact of over $100B/year [8]. CPS technologies including next generation public safety communications, sensor networks, and response robotics can dramatically increase the situational awareness of emergency responders and enable optimized response through all phases of disaster events such as earthquakes, hurricanes, tsunamis, tornadoes, fires, and bombing attacks.

Cyber Security: Attacks such as those on the financial system, intelligence data bases and e-commerce sites can be easily replicated to networked, cyber-physical systems with grave consequences for our safety and wellbeing in addition to being a threat to our economy. It is critical that CPS systems be resilient to cyber-attacks [6].

Economics: The cost of software in CPS systems is becoming an increasingly larger fraction of the cost of the product (currently 25% in airplanes and expected to rise to 50% in the next generation of airplanes). Open reference architectures and standards, model-based engineering methodologies, and powerful simulation, verification and validation tools, are essential for reducing the cost for developing CPS systems [7].

Society: “Apps” that seamlessly network with the physical world are gradually becoming part of our lives. Consumers increasingly want special purpose software for automating tasks and expect interoperability across different hardware devices. It is timely to invest in CPS technologies since commercial applications will more than pay for the investments in basic research.

The potential macro-economic benefit of the development and deployment of CPS systems in the coming decades is enormous, and one analysis [1] suggests it could be comparable to the economic productivity gain attributable to the Internet revolution of the late 20$^{th}$ century—providing a needed and significant new growth engine for the US economy.

## 3 Technologies

Despite the fact that the drivers for CPS come from different sectors, the technology gaps in the different sectors stem from the same set of fundamental challenges. The key cross-cutting platform technologies needed to overcome these challenges and accelerate the development of CPS applications in *all* sectors are:

*Abstractions, modularity and composability*– to enable CPS system elements to be combined and reused while retaining safety, security, and reliability

*Systems-engineering based architectures and standards*– to enable efficient design and development of reliability systems while ensuring interoperability and integration with legacy systems

*Adaptive and predictive hierarchical hybrid control* – to achieve tightly-coordinated and synchronized actions and interactions in systems that are intrinsically synchronous, distributed and noisy

*Integration of multi-physics models and models of software* – to enable co-design of physical engineered and computational elements with predictable system behaviors

*Distributed sensing, communication*s and perception– to enable flexible, reliable, and high performance distributed networks of CPS that provide an accurate and reliable model of the world

*Diagnostics and prognostics* – to identify, predict, and prevent or recover from faults in complex systems
*Cyber-security*– to guarantee safety by guarding against malicious attacks on CPS systems
*Validation, verification, and certification* – to speed up the design cycle for bringing innovations to market while ensuring high confidence in system safety and functionality
*Autonomy and human interaction* – to develop models of autonomous CPS systems and humans interacting with them to facilitate model-based design of reactive systems that are used by humans

**4 Multiagency Plans for CPS**

A synergistic approach to CPS: While a number of federal agencies have begun independent research efforts to address CPS science and engineering challenges, many gaps remain in the federal R&D portfolio. Technical barriers to rapid, predictable development and deployment of CPS arise throughout the stages of technology development, from basic science through applied R&D, demonstration, manufacturing, and deployment. Trying to address the gaps agency by agency, sector by sector, or company by company will result in inefficiencies and insufficient progress to meet system development timetables and objectives. Instead we advocate a multi-agency, multi-sector comprehensive focus on the difficult cross-cutting R&D challenges in CPS. There are many benefits and synergies in this approach. For example, attempts to establish extensible architectures for unmanned aerial vehicles or self-driving cars in the transportation sector will directly benefit the designers of networked industrial control systems in manufacturing. Similarly there is a natural synergy between designing secure but easy-to-monitor and reprogrammable networked medical devices and developing services for the smart grid that ensure uncompromised safety while allowing operators to adapt to changing conditions.

Partnership for Innovation: Addressing the R&D gaps will require close collaborations between industry, university, and government contributors. Private-public partnerships are expected to play a central role in bringing these stakeholders together.[1] Such partnerships should be designed to optimize the movement of people across sectors and intellectual capital flow across organizational boundaries, and be structured to ensure that IP concerns do not impede progress, while promoting industrial competitiveness. Models for strategic management of intellectual property rights will need to be developed by each agency consistent with their mission authorities. We should incorporate mechanisms to reinvigorate our workforce by including education and training in the mix of engineering and computer science skills that are critical to CPS.

Mechanisms for Implementation
We expect that the diverse capabilities and communities represented by the different agencies could support a spectrum of mechanisms that could be considered. Desired features of this cooperation include: (a) participating funding agencies are represented in a Senior Steering Group (SSG); (b) reporting requirements include, for example, participation by funded projects in a common PI meeting, dissemination through the CPS Virtual Organization, and participation in workshops as deemed necessary by the SSG; (c) In the various models, an agency funding a project could grant access to proposals to allow for supplementary funding by another agency; and (d) either joint or coordinated solicitations may include a mix of intramural and extramural funding.

By way of illustration, we outline below three possible funding mechanisms, starting from a tightly coupled mechanism (joint solicitation) to a loosely coupled mechanism (independent solicitations with collaborative research):

[1] Industry drivers for CPS are firms which build, deploy, and/or operate cyber-physical systems across multiple business sectors (e.g., GE, United Technologies, Rockwell Automation, Honeywell, IBM, Lockheed Martin, and Cisco Systems) or across multiple production and product platforms within a single business sector (e.g., Boeing, GM, Ford, and Medtronic Systems).

1. Joint Solicitations: Applications are made to joint solicitations that advertise the topics of interest to the multiple funding agencies. The agencies would work out appropriate mechanisms for joint review and shared investment. (Peer review would be desirable for at least some of the investment.) Panelists might include agency/sector specific reviewers as necessary.
2. Coordinated Solicitations: All solicitations will be coordinated to ensure there are no R&D technology gaps. All funding opportunities will be advertised though the VO via a common portal but each agency will be responsible for accepting, reviewing and funding proposals. Agencies will coordinate during the review process to the extent possible by inviting members from other agencies to serve on their review panels.
3. Independent Solicitations with Collaborative Research: All solicitations will be independent but program managers will identify synergistic research projects allowing PIs funded by one agency to collaborate with PIs from another funding agency. (Say, one agency funds extra-mural research and sees value in having its PIs engage with another agency's intramural research, or with industrial participants supported by another agency.)

In Joint or Coordinated Solicitations, it is probably desirable to require grantees to attend a common PI meeting and disseminate their research results through the VO. Further, funding agencies could have access to proposals to allow for supplementary funding by one agency for projects selected by another agency. All three models can include mix of intramural and extramural funding. Agencies are invited to suggest other models that would make sense for desired forms of cooperation and co-funding.

Coordinated Investment: The table in the next section lists current federal agency CPS R&D activities, gaps in the federal CPS R&D portfolio, and recommended agencies to lead the coordinated R&D effort for each gap area. Although sector-specific and cross-cutting R&D are shown separately in the following table, the research would be carried out as joint efforts that span CPS agencies, industry, and academia.

## 5 Projected CPS Needs and Investments

The following table lists federal agency CPS R&D activities, gaps in the federal CPS R&D portfolio, and agencies that are most qualified to lead the coordinated R&D effort for each gap area.

| **R&D Gaps** | **Agencies** |
|---|---|
| **Mission R&D: Crosscutting Research and Development** | |
| Core CPS Science and Technology – control, real-time computing, communication concepts, modeling, hardware and software platforms. Advanced engineered systems: manufacturing, energy, medical devices, transportation. | NSF |
| Science of Security for CPS | NSA, DHS, DOE, NSF |
| CPS Virtual Organization | NSF, others |
| Complex systems, cascading failure, engineered resilient systems, fault identification, diagnosis and recovery | OASD (R&E) |
| **Mission R&D: Sector-Specific Challenges** | |

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|---|---|
| Aviation safety, certification, enabling bold, visionary aviation systems and technology for a safe, efficient Next Generation airspace. | NASA |
| Intelligent transportation infrastructure systems, enabling technology for high confidence next-generation transportation (NextGen, automotive autonomy, intelligent vehicles). | NASA/ NextGen JPDO, DOT[2], NSF |
| New control architectures/algorithms and power electronics for distributed generation, storage, and managed consumption | DOE/ARPA-E |
| Smart food systems that support safety, logistic efficiencies, cold-chain integrity, and traceability | NIFA |
| Time-critical systems, mixed criticality architectures, verification, aviation autonomy | DOD/Services |
| Rapid design and manufacturing of advanced CPS technologies. Rapid verification and real-time health monitoring and reconfiguration/re-verification. Application to autonomous systems. | DARPA |
| Real-time physiological sensing, modeling, control, and feedback; advanced medical devices and system interoperability, integration, and certification | HHS (NIH[3], FDA) |
| **Mission R&D: Crosscutting Standards-Based Platform Technologies** | |
| Cyber-Physical Systems Engineering Testbed | NIST |
| Measurement Science and Standards for Model-Based Diagnostics & Prognostics, Time Synchronization, Industrial Cybersecurity | NIST |
| Measurement Science and Standards for Quality Measurement Systems for CPS, Wireless Networking for CPS, Advanced Battery Technology for CPS, Multi-Physics Modeling and Optimization, Adaptive and Predictive Control in CPS | NIST |
| Standards-Based Integrated Architectures and Prototype Platform for CPS | NIST |
| **Education and Crosscutting Research Centers** | |
| Future of skills development and instructor resources for CPS including online CPS training and educational infrastructure resources (e.g., CPS virtual laboratory) | NSF |
| Center of Excellence in CPS Measurement Science and Engineering | NIST |
| Research and Infrastructure for innovation in Medical CPS Pilot | NIH, NSF, FDA, NIST |
| CPS Outreach Centers (CPS Government, Industry, Academia cooperative research model) | Multi-agency with NSF lead |
| Industrial Internet Consortium | NIST |
| Transportation CPS Pilot (ERC model) | Multi-agency with NSF/DOT co-lead |

[2] DOT program managers have expressed interest; to date DOT has not designated a representative to the SSG.
[3] NIH program managers have expressed interest; to date NIH has not designated a representative to the SSG.

**References**


[1] *Industrial Internet: Pushing the Boundaries of Minds and Machines*, November 2012.

[2] *Strategic Vision and Business Drivers for 21st Century Cyber-Physical Systems,* draft report from the Executive Roundtable on Cyber-Physical Systems, June 18, 2012.

[3] *Strategic Opportunities for 21st Century Cyber-Physical Systems*, Foundations for Innovation in Cyber-Physical Systems workshop, Chicago, IL, March 13-14, 2012.

[4] *CRICIS: Critical Real-Time Computing and Information Systems*, A Report from a Community Workshop, April, 2012.

[5] *Winning the Future with Science and Technology for 21st Century Smart Systems*, NITRD white paper, March 2011.

[6] *Ensuring American Leadership in Manufacturing*, PCAST report, June 2011.

[7] *Designing a Digital Future*: Federally Funded Research and Development in Networking and Information Technology, PCAST report, December 2010.

[8] *High Confidence Energy Cyber-Physical Systems,* workshop report (draft), Baltimore, MD, June 2009.

[9] *High Confidence Transportation Cyber-Physical Systems*, community workshop report, April 2009.

[10] *High Confidence Medical Devices: Cyber-Physical Systems for 21st Century Health Care*, 2009.