Strategic Vision and Business Drivers for 21st Century Cyber-Physical Systems

Strengthening opportunities for U.S. leadership and competitiveness

January 2013

Report from the Executive Roundtable on Cyber-physical Systems

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EXECUTIVE ROUNDTABLE HIGHLIGHTS

January 2013

National Institute of Standards and Technology ● U.S. Department of Commerce

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Government and Academia

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- Pradeep Khosla, Dean of Engineering, Carnegie Mellon University (CMU), incoming Chancellor of the University of California San Diego (UCSD)
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Executive Summary

The National Institute of Standards and Technology (NIST) sponsored the Executive Roundtable on Cyber-physical Systems (CPS) in June 2012 as the third in a series of events to explore challenges that must be addressed to meet the fast-paced need for advances in CPS. Earlier events included a roundtable held in February 2012 with federal agencies who are or will be CPS stakeholders, from research and/or user perspectives. A major workshop on research and development (R&D) needs for CPS was held in March 2012 and brought together scientists and engineers from industry, academia, and government.

The Executive Roundtable on CPS was organized around panel discussions by industry, technology and service providers, and academic and government leaders in CPS. Each panel discussed their view of CPS in the future and compelling drivers for their involvement in moving the technology forward. Panel viewpoints are summarized in Table E.1.

Table E.1. Summary of Vision and Compelling Drivers

	INDUSTRY USERS	TECHNOLOGY/SERVICE PROVIDERS	GOVERNMENT/ ACADEMIA
VISION	• Increasing cyber threats are changing our view of security. • The U.S. must think globally to realize the potential of CPS. • Great strides are needed in multi-disciplinary system-level thinking. • Human factors must be effectively addressed. • Systems must be adaptable to changing environments and events.	• Large data sets will require new levels of controls for privacy and security. • Multi-disciplinary approaches will shape future CPS. • New liability issues will arise and need to be addressed. • Global, standardized data will be available for expert systems to extract. • Advanced testing and modeling will lower the life cycle costs – operations and maintenance as design – and improve efficiency. • IT, networking, manufacturing, and automation will converge.	• Breakthroughs, synergies, and new frontiers will epitomize future CPS. • A common science for CPS will be established. • Availability, security, and safety of systems will be assured by integrated, multi-disciplinary scientific approaches. • Risk assessment and management metrics will link technical and business issues. • A skilled CPS workforce will remain a high priority.
BUSINESS DRIVERS	• Attacks and intrusions on networks will grow, making protection of data harder and more expensive. • Societal needs for CPS will increase consumer demand for functionality and reliability. • U.S. leadership in CPS could open strategic markets in vital industries and grow domestic jobs.	• Solving hard problems in security will continue to drive CPS design and use (both safe and secure). • Payback will drive the implementation and expansion of CPS and infrastructures. • Industry requirements will shape future CPS: advanced human-in-the-loop systems; accident-free actions; and monitoring and control integrated with data.	• Sectors and agencies will demand a secure CPS infrastructure and technology. • Collaboration on CPS will be strongly driven by resource constraints. • The ease and cost of systems integration and validation is a key driver for implementation. • National priorities for defense, homeland security, energy, and public health and safety are major drivers for CPS.

COMMON BUSINESS DRIVERS

Cyber-security is a top driver for CPS across all public and private sectors. The number of attacks and intrusions on networks has grown exponentially and the vulnerability threat is expected to grow as systems become larger and more complex. The cost of cyber-security and staff is now a significant portion of operating costs for many organizations – and potentially on a par with purchases of hardware and software. A dilemma is to create systems that safe as well as usable – not systems that have so many layers of security they are difficult to use. Cyber-security must also be balanced with the ability to meet societal and market needs and be competitive in global markets. Entirely new levels and types of security will be needed to meet a wide range of domain-specific requirements.

Growing consumer and user demands, regardless of where they originate (ordinary citizens, industrial users, or mission-driven agencies) will shape the characteristics of future systems. As the advantages of CPS become more apparent and they penetrate wider markets, consumers will demand more functionality, reliability, and safety. Decisions will be increasingly removed from humans and become the purview of the computational core. This will require an even greater need to design systems that you can trust your life with.

Multi-disciplinary system-level thinking must be employed to shape future CPS. The availability, security, and safety of systems will be assured by the application of integrated, multi-disciplinary scientific approaches to design and implementation. A culture shift in this direction will be facilitated by multidisciplinary education and training to build a 21st century CPS workforce.

COMMON TECHNICAL DRIVERS

Interoperability and communication protocols are required for highly connected and networked components to work together effectively as a total system and will drive future development. These include, for example, universal definitions for ultra-large heterogeneous systems; protocols to bridge digital and physical system components; and natural, more seamless human-CPS interactions.

Common reference architectures are needed for a range of CPS that enable model-based systems integration by combining cyber and engineered physical elements, adaptive and predictive systems with distributed control, wired and wireless systems, semi-autonomous and autonomous systems, and emerging and legacy systems. Current architectures have limited vocabulary to adequately represent physical elements and their interactions, and to enable structural consistency within these heterogeneous systems.

Standards-based platforms will help to assure performance and quality – both essential for spurring future investment, acceptance, and use of innovative systems. Standardized platforms will provide consistent requirements for security, safety, resilience, and reliability of systems, as well as a foundation for verification and validation of CPS in both design and practice.

CROSS-SECTOR COLLABORATION

There was strong consensus that achieving the potential of CPS will require an expeditious and concerted approach. While the advantageous applications have been identified, a 20-year timeline for research outcomes may be too long and too late to realize the opportunities. Collaboration will be needed to create the critical mass needed to move technology forward, at least in some areas. New mechanisms will be needed for cross-sector collaboration; existing models of collaboration may not be adequate to meet future needs for CPS. Important factors for successful collaboration in CPS R&D include communicating the importance of CPS, setting priorities, focusing on high-impact subjects, and developing collaborative relationships that take into account wide-ranging, diverse perspectives and interests.

1 Introduction

1.1 The Importance of Cyber-Physical Systems

Systems that integrate the cyber world with the physical world are often referred to as cyber-physical systems (CPS). The computational and physical components of such systems are tightly interconnected and coordinated to work effectively together, sometimes with humans in the loop (see Figure 1.1). The convergence of cyber and physical systems can yield many advantages. For example, in some cases a computational core can detect and respond faster than a human, be more precise than a human, never get tired, or can go into zones that are dangerous to humans.

Figure 1.1. Characteristics of Cyber-Physical Systems

Cyber physical systems are hybrid networked cyber and engineered physical elements co-designed to create adaptive and predictive systems for enhanced performance.

Essential CPS characteristics:

- Cyber, engineered, and human elements as treated as integral components of a total system to create synergy and enable desired, emergent properties
- Integration of deep physics-based and digital world models provides learning and predictive capabilities for decision support (e.g., diagnostics, prognostics) and autonomous function
- Systems engineering-based open architectures and standards provide for modularity and composability for customization, systems of products, and complex or dynamic applications
- Reciprocal feedback loops between computational and distributed sensing/actuation and monitoring/control elements enables adaptive multi-objective performance
- Networked cyber components provide a basis for scalability, complexity management, and resilience

CPS are enabling a new generation of 'smart systems' – and the economic impacts could be enormous. The disruptive technologies emerging from combining the cyber and physical worlds could provide an innovation engine for a broad range of U.S. industries, creating entirely new markets and platforms for growth. New products and services will bring the creation and retention of U.S. jobs. The nation will also benefit through greater energy and national security, enhanced U.S. competitiveness, and improved quality of life for citizens.

A number of reports have focused on the importance of CPS and the need to pursue R&D that will establish U.S. leadership in the field and enhance competitiveness in global markets (PCAST 2012, PCAST 2011; PCAST 2010, NITRD 2009). Improving public health and safety is also a national priority where CPS can have a significant impact. The European Union is already investing $343 million per year for 10 years to pursue "world leadership" through advanced strategic research and technology development related to CPS (include $199 million per year in public funds and $144 million year in private funds) (EU 2012).

Cyber-physical systems are rapidly becoming critical to the business success of many companies and the mission success of many government agencies. In transportation, manufacturing, telecommunications, consumer electronics, and health and medical equipment, and intelligent buildings the value share of electronics, computing, communications, sensing, and actuation is expected to exceed 50% of the cost by the end of the decade. CPS technologies, in the form of advanced robotics, computer-controlled processes, and real-time integrated systems, are critical for improving U.S. manufacturing competitiveness.

With their unique functionalities, cyber-physical systems have the potential to change every aspect of life (see Figure 1.2). Concepts such as connected vehicle and highway systems, robotic surgery, intelligent buildings, smart electricity grid, and embedded medical devices are just some of the real-world examples that have already emerged.

As systems continue to evolve they will rely less on human decision-making and more on computational intelligence. As we become more dependent on CPS, the challenge is to design systems that are dependable and reliable – systems we can trust our lives with.

There is an opportunity for the United States is to gain competitive leadership through the ability to develop new cyber-physical systems with built-in assurance of their critical properties, including safety and security, and correct, timely performance of their intended functions. While progress is being made every day, advancements to cyber-physical systems continue to be challenged by a variety of technical (i.e., scientific and engineering), institutional, and societal issues. These range from technical system-level issues such as interoperability, infrastructure, and reliability, to institutional challenges such as building a 21st century CPS workforce and better business models and value propositions for next generation systems. A critical mass of research and development (R&D) will be required to overcome some of these challenges.

Figure 1.2. Applications of CPS

Manufacturing: smart production equipment, processes, automation, control, and networks; new product design

Transportation: intelligent vehicles and traffic control, intelligent structures and pavements

Infrastructure: smart utility grids and smart buildings/ structures

Health Care: body area networks and assistive systems

Emergency Response: detection and surveillance systems, communication networks, and emergency response equipment

Defense: soldier equipment systems, weapons systems and systems of systems, logistics

GM Volt automated, robotic powertrain assembly. Photo: General Motors Image Gallery

1.2 Strategic Opportunities for CPS R&D

In March 2012 the National Institute of Standards and Technology (NIST) sponsored the ***Foundations for Innovation in Cyber-Physical Systems Workshop*** to discuss the most important barriers and knowledge gaps affecting innovation and U.S. competitiveness in CPS. From that event emerged a set of strategic R&D opportunities for overcoming the critical barriers to CPS. Realizing these opportunities will ensure that the United States is a technology leader in the field of CPS and facilitate the development of reliable, safe, and secure systems. The strategic R&D opportunities identified include:

- **Robust, effective design and construction of systems and infrastructure—**key to designing reliable systems from the ground up and reducing cost and time to market. The focus is on science and engineering foundations for cost-effective and secure system design, analysis, and construction; and managing the role of time and synchronization in architecture design.

- **Improved performance and quality assurance—**essential for spurring future investment, acceptance, and use of innovative systems that could provide revolutionary improvements to conventional practice. System performance, quality, and acceptance would be improved through system-level evaluation, verification, and validation of cyber-physical systems; science-based metrics for security, privacy, safety, resilience, and reliability; and uncertainty characterization and quantification.

- **Effective, reliable system integration and interoperability—**required for highly connected and networked components to work together effectively as a total system. Applied development and deployment efforts would focus on universal definitions for representing ultra-large heterogeneous systems; inter-connected and interoperable shared development infrastructure; an abstraction infrastructure to bridge digital and physical system components; natural, more seamless human-CPS interactions; and systematic inter-process and interpersonal communication for sensors and actuators.

- **Dynamic, multi-disciplinary education and training—**will make possible sustained growth and innovation as well as the next generation of cyber-physical systems with a focus on workforce development for continuing innovation through multi-department CPS degrees and resources; and dynamic training and certification in CPS.

The above strategic R&D opportunities are recurring themes that appear in multiple technology areas and consequently could have far-reaching impacts if addressed.

1.3 Executive Roundtable Objectives and Approach

The U.S. is well positioned to exploit the benefits of cyber-physical systems and has made significant strides in cutting-edge technology development and deployment. However, concerted efforts to conduct R&D as well as a global understanding of the business issues could be needed to remove barriers and find solutions to the challenges ahead.

On June 18, 2012, NIST convened a roundtable of senior executives from industry, government, and academia to explore the compelling business and mission drivers for CPS and to further articulate the strategic vision for research and development (R&D). The event built upon two prior events held to explore challenges that must be addressed to meet the fast-paced need for advances in CPS. These included a roundtable held in February 2012 with federal agencies and the March 2012 workshop discussed above.

The Roundtable was assembled to provide an opportunity for sharing of crosscutting interests and ideas among the many stakeholder groups. Stage-setting remarks and presentations provided context; a roster of speakers is shown in the roundtable agenda, provided as Appendix A of this report.

The Roundtable was structured around moderated panels focused on (1) industrial users of CPS, (2) technology and service providers, and (3) academic and government perspectives. Each panel was charged with addressing:

- **Strategic vision:** In 10-20 years, what do you see as the future role of cyber-physical systems in your products, processes, and organizational or business models?
- **Compelling business drivers:** What are the compelling business drivers for these changes? What changes in market demand do you foresee as drivers for CPS in your industry?
- **Collaboration opportunities:** What collaborative opportunities exist to accelerate the pace of progress and adoption of CPS? What could potentially be gained through collaboration?

The highlights of Roundtable discussions are presented in this report and organized around the respective panels. They provide a cross-sector perspective on what the future holds as well as the key business drivers for moving technology forward. It is anticipated that this report will help guide high-level and strategic decision-makers as they plan research and development efforts to advance CPS and related platform technologies.

2 Industry Perspectives

The Roundtable's industry panel included executives from companies for which CPS is a key factor to future success and an integral part of operations or products (see Figure 2.1). Panelists ranged from small companies in emerging CPS markets to larger, global companies that have been involved with CPS for many years and are increasingly challenged by the rapid pace of advances in the field.

With business interests ranging from healthcare to defense, panelists had a wide range of comments on CPS's role in their future endeavors. Several key themes emerged from this panel session.

Figure 2.1. CPS Roundtable Industry Panel

- ***Isaac Cohen***, *Director Systems Department, United Technologies Corporation*
- ***Brent Brunell***, *Technology Leader for Controls, Electronics & Signal Processing, General Electric*
- ***Mark Rice***, *President, Maritime Physics Corporation*
- ***Lonny Stormo***, *Vice President of Pre-market Quality and Reliability, Medtronic, Inc.*
- ***Don Winter***, *Vice President, Engineering & Information Technology, Boeing Phantom Works*

2.1 Strategic Vision

The industry panel reinforced the view that the future business opportunities made possible by advances in CPS are enormous. CPS will enable companies and industries to be at the forefront of technological advances in many critical industries. The strategic vision for the future encompasses a number of tenets for achieving the promise of CPS.

The future potential for CPS is enormous, but we must think globally for U.S. industry to realize the opportunities.

- The market and product opportunities for CPS span all sectors of the economy – and there are significant markets outside the U.S.
- To be a leader in CPS, companies need to think globally. Systems must work in all countries – so standards and interfaces must be compatible around the world. Other countries are working on global compatibility – the U.S. must also if we want to be global leaders in CPS.

Great strides must be made in multidisciplinary system-level thinking.

- Multidisciplinary approaches at the system-level (and at large scales) will need to be employed to advance CPS.

Human factors must be effectively addressed from a variety of perspectives.

- CPS must allow for integration of humans with varying degrees of training into operational loops.
- Systems must be able to account for unpredictable human interventions and work seamlessly with humans when needed.

- Practitioners of the physical domains should be able to design CPS without becoming software engineers.

Increasing cyber-threats and attacks are changing the way we view security.

- Future systems that are highly integrated within companies and across supply chain boundaries will require entirely new kinds of security systems to deal with multiple wireless and other networking technologies.
- Systems will not be isolated but instead more closely connected; this could require a united approach to cyber-security and resilience to attack.

Systems must be adaptable to the changing environment.

- Ability to adapt and change with environmental conditions, including unforeseen events, is an essential capability for some CPS.
- Increasing complexity and heterogeneity of systems will increase challenges of engineering for flexibility.

Flexible collaboration is essential to industrial CPS R&D.

- Some companies want to collaborate pre-competitively, while some will want to collaborate on technology areas outside of their usual realm (e.g., technology companies are not necessarily software companies). Flexibility will be essential.

2.2 Compelling Drivers

The industry panel referenced a number of business drivers impacting the development and use of CPS. Several that were underscored are noted below.

- **SECURITY:** The number of attacks and intrusions on networks has skyrocketed. Vulnerability at the interfaces is especially great. In 10-20 years, it is anticipated that the access and vulnerability threat will continue to grow. While IT costs were historically incurred primarily for purchasing hardware, computer security staff is now a significant portion of operational costs. The day-to-day business of protecting data is getting much harder and more expensive.

- **SOCIETAL NEEDS:** CPS are increasingly fulfilling important societal needs and improving quality of life. For example, CPS could enable healthcare providers to manage chronic disease within the individual body. As society becomes more dependent on CPS, they will demand greater functionality and reliability – all with an affordable cost.

- **COMPETITIVENESS:** By leading advances in CPS, the United States has the opportunity to capture strategic markets in healthcare, manufacturing, transportation, and other vital industries. This could improve our competition position in world markets, while accelerating domestic jobs creation along with new export and product markets.

3 Technology and Service Provider Perspectives

The technology and service provider panel was comprised of technology executives from companies with a wide range of interests, including those involved with Internet and network technologies, modeling and design tools, software, manufacturing automation, energy controls, and cyber-security (see Figure 3.1). All have a common interest – playing an integral role in the development of technologies and services that will drive future CPS.

Figure 3.1. CPS Roundtable Technology & Service Provider Panel

- ***Vinton Cerf****, Vice President and Chief Internet Evangelist, Google*
- ***Sujeet Chand****, Sr. Vice President, Advanced Technology, and CTO, Rockwell Automation*
- ***Himanshu Khurana****, Senior Technical Manager, Honeywell*
- ***Sky Matthews****, CTO, IBM Rational Complex and Embedded Systems*
- ***Pieter J. Mosterman****, Senior Research Scientist, MathWorks*

3.1 Strategic Vision

A recurring theme for technology and service providers was the need for CPS to be robust, safe, secure, and trustworthy—with safety and security for both physical- and cyber-systems together forming an overarching need for CPS. The future for CPS was envisioned in terms of characteristics of success, with an emphasis on the following.

A multi-disciplinary approach will be employed in developing future CPS solutions.

- Cultural and organizational challenges will be overcome; a convergence of application lifecycle, product lifecycle (hardware and software), and technical disciplines will be achieved.
- Physics and physical sciences will be integrated with computer science and mathematics to aid in understanding the overall system.

Privacy and security issues will be addressed as advances are made in CPS.

- Large amounts of data integrated with CPS will increase privacy issues considerably.
- Authentication and access control, authorization, and duration will be effectively addressed (ephemeral access/authority, e.g., access to medical records).
- Controls developed in the past were designed to operate in a very trusted environment; a new level of security will be needed.

New liability issues will arise and require clarity.

- Designing software that is safe to use is paramount; regimes will be defined to clarify when and how and under what conditions parties are liable.

An agreed-upon set of global data will be established.

- A set of global data with agreed-upon structure and format will be accessible to expert systems to extract knowledge and support decisions.
- Standards will be established to enable data to link with different kinds of models and life cycle artifacts.

Advanced test and modeling capability will facilitate and lower cost of system design.

- Testing is more than 50% of the cost to deploy engineered systems. In future this cost will be reduced, making systems integration faster, cheaper, and more efficient.
- More personalization of products and services, from search results to vehicles is being demanded. As a result, CPS will need to handle self-organizing systems and emergent behaviors.
- Model-based design is a key competitive differentiator and will be used across the design process, including co-design and integrating design.

CPS will take into account the practical environment of various industry sectors, such as manufacturing.

- CPS must integrate with legacy systems having billions of dollars of installed capacity, including dozens of different networks, multi-member products, and systems that are at least 20-25 years old.
- CPS must be usable by the humans involved.

Technologies supporting CPS will continue to evolve.

- CPS will mature over the next decade, and we will see a convergence between IT and networking, and manufacturing and automation. The Ethernet will be the common network used in manufacturing, rather than those used today.

3.2 Compelling Drivers

The technology and service provide panel emphasized drivers related to economic payback, security, and industry needs.

- **PAYBACK:** Companies that have invested billions in building IT infrastructures are now looking for payback. They have put enormous effort into redoing and connecting their systems, but challenges continue to emerge as technology rapidly advances.

- **SECURITY:** Solving hard problems in security will continue to be a driver for CPS. For example, manufacturing is designed for safety, but security is critical. Access to machines is needed to make real-time changes in the plant, but this can create a security challenge. One extreme is to provide no access; another extreme is virtual private network (VPN) tunnels—this may not be feasible when some plants have thousands of VPN tunnels into their operations.

- **Industry Needs:** A range of industry requirements will drive future CPS. For example, in a smart electricity grid, the goal is a manageable, usable system supported by advanced analytics that provide highly effective timing and synchronization of power sources. While these are domain-specific, general requirement include:
    - Monitoring and control systems integrated with an information layer;
    - Accident-free actions managed by rule-based frameworks, from both regulatory compliance and enterprise rule perspectives; and
    - Advanced human-in-the-loop systems for higher productivity—CPS must support user needs through access and decision-making.

4 Academic and Government Perspectives

The academic and government panelists included program leaders from the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and the Air Force Research Laboratory (AFRL), as well as leading researchers from top universities (see Figure 4.1). NASA and AFRL both emphasized the need for mission-relevant advances in CPS. NSF noted that CPS is woven into a number of its programs and is a key focus area. In the universities, CPS is pursued from a multidisciplinary, systems viewpoint applicable to a wide variety of industry sectors.

Figure 4.1. CPS Roundtable Government and Academia Panel

- ***Tom Irvine***, *Deputy Associate Administrator, Aeronautics Research Mission Directorate, National Aeronautics and Space Administration*
- ***Pradeep Khosla***, *Dean of Engineering, Carnegie Mellon University (CMU), incoming Chancellor of the University of California San Diego (UCSD)*
- ***Keith Marzullo***, *Division Director, CISE Computer and Network Systems, NSF*
- ***Jennifer Ricklin***, *Chief Technologist, Air Force Research Laboratory*
- ***Bill Sanders***, *Donald Biggar Willet Professor of Engineering, University of Illinois*

4.1 Strategic Vision

This panel underscored the need for those seeking to advance CPS R&D to communicate to decision-makers simply and effectively what the outcomes and benefits are. The need for system-level thinking and program design by funding agencies was also emphasized; the capability to conduct research on large systems will be necessary to foster advances in CPS. Motivating students and the workforce to gain skills in CPS was identified as a high priority. Research and development 'grand' challenges focused on visionary ideas in CPS could be one way to excite students and build the next generation workforce. Engaging people at all levels to support and embrace new technology is a key objective.

Visionary themes discussed emphasize revolutionary technologies and outcomes from successful development of CPS.

Breakthroughs, synergies, and new frontiers will epitomize future CPS.

- Citizen-sensing could emerge, such as phones that correlate vibrations to predict earthquakes;
- Affordable smart homes will enable elderly and disabled people to live independently;
- Assistive medical technology will use sensors to activate paralyzed muscles; and
- A smart grid could guarantee no blackouts.

A common unified system of science for CPS will be established.

- Approaches will make use of sound mathematical techniques with proven quality.
- Multi-disciplinary approaches will be incorporated.
- A common roadmap will help to guide R&D across domains in critical cross-cutting fields (e.g., like the semiconductor industry).

Availability, security, and safety of systems are assured by integrated approaches based on sound science and engineering.

- A science of cyber-physical resilience will emerge; physical as well as cyber-infrastructure will be engineered for resiliency.
- Systems respond to and manage cyber and physical events in a holistic manner including sensors, actuators, response algorithms and engines, etc.;
- Systems will be engineered via multi-disciplinary, system-level thinking and integration strategies;
- Both physical and cyber infrastructures are engineered for resiliency; and
- Systems operating in possibly hostile environments perform as expected; control is provided at multiple levels, so systems are trustworthy, including both physical and cyber components and their interaction; when intrusions do succeed, systems detect and respond.

Metrics are developed for CPS risk assessment and management that link technical and business concerns.

- Metrics will enable comparison between alternatives and make a business case for design elements.
- Metrics for security are essential.

Growing the workforce in CPS remains a high priority.

- Multi-disciplinary educational programs will be needed to create a next generation workforce capable of designing, developing, and implementing CPS**.**

4.2 Compelling Drivers

Academic and government panelists emphasized that resources and security would be major drivers for R&D as well as deployment of CPS in future.

- **RESOURCES:** Academic and government panelists emphasized that collaboration on CPS is strongly driven by resource constraints. CPS R&D is underway in many programs, but with declining resources, critical mass is needed for federal programs and academic research to achieve the needed results.

- **SECURITY:** All sectors desire a secure CPS infrastructure and technology, and agency missions demand it. For example, in energy applications, trustworthy, algorithm-based, intrusion-tolerant CPS infrastructure and technologies are required for a wide variety of needs, such as wide area monitoring and control; and real time, secure, and convergent power grid networks.

- **SYSTEMS INTEGRATION:** The ease with which systems can be readily integrated will be a key driver for implementation of future CPS. System integration is a difficult and costly challenge and is tantamount to the elephant in the CPS china shop.

- **NATIONAL PRIORITIES:** National priorities for defense, homeland security, energy efficiency and diversity, and health and safety will continue to be major drivers for CPS. Affordable warfighting technologies for air and space, as well as a cyber-space fighting force, are heavily dependent on advances in CPS. Aerospace systems, information systems, materials and manufacturing, and munitions all incorporate CPS as integral components. Military bases across the country and around the world rely on private sector CPS.

5 Cross-sector Collaboration

The challenge of CPS cuts across industrial sectors and agency missions, and in some cases represents high-risk or complex R&D that exceeds the ability of individual organizations. The panels were asked to provide their perspectives on the opportunities and options for multiple sector collaboration to advance CPS.

There was strong consensus that achieving the potential of CPS will require an expeditious and concerted approach. The advantageous applications have already been identified – and a 20-year timeline for research outcomes may be too long and too late. Collaboration may be needed to create the critical mass needed to move technology forward, at least in some areas. New mechanisms will be needed for cross sector collaboration; existing models of collaboration will likely not be adequate to meet future needs for CPS. The most important factors for successful collaboration in CPS R&D discussed included communicating the importance of CPS, setting priorities, focusing on high-impact subjects first, and developing collaborative relationships using existing models that take into account wide-ranging and diverse perspectives and interests. These factors are further described below.

- **COMMUNICATION:** Communicating the importance and impact of CPS R&D is a collaborative priority. CPS is a complex subject, and effectively describing the benefits of R&D outcomes is essential to gaining buy-in from decision makers, researchers, and users. Engagement and commitment is needed to support collaborative CPS R&D, as well as policies and approaches that facilitate collaboration at all levels.

- **PRIORITY SETTING:** Priorities should be collaboratively set to create a focused plan for CPS R&D which covers a wide-open field of topics. Opportunities for collaboration within priorities can then be identified and nurtured. Stakeholders must accept that not all of the identified challenges need to be addressed to make progress. The CPS space is so large that efforts should be targeted to focus first on areas that constitute a resonant "call to action": those with the potential achieve the most rapid progress, maximize impacts, and engage as many stakeholders as possible. Early results are essential for the "call to action" research, whether precompetitive or applied. A two-pronged approach is possible—including (1) "call to action," short-term, high-priority research that can be implemented early on and (2) a more comprehensive "roadmap" based on cross-cutting opportunities, commonalities, and needs that can be implemented over the longer term. Such as approach might be the most effective for collaborative CPS R&D efforts. The semiconductor industry's approach was cited as an example collaboration model that might work for CPS.

- **COLLABORATOR PERSPECTIVES:** For collaborations to succeed, the diverse roles and interests of key government, industry, and academic participants must be understood, so the best options for collaborative models can be pursued. Considerations will include the constraints of declining R&D budgets, the need for some organizations to maintain a specific mission-centric focus, technical silos, disciplinary focus, and intellectual property or proprietary information concerns.

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