
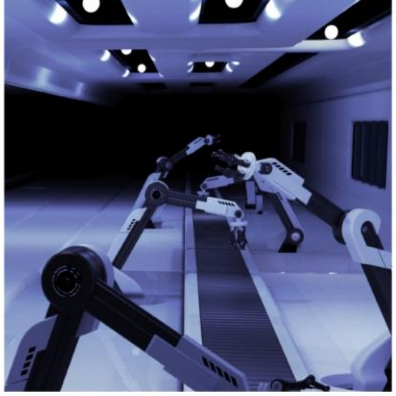

Foundations for Innovation in Cyber-Physical Systems

WORKSHOP REPORT

January 2013

Prepared by
ENERGETICS INCORPORATED
Columbia, Maryland 21046

For the
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

NIST
National Institute of
Standards and Technology

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Acknowledgments

Many thanks to all those who participated in the workshop *Foundations for Innovation in Cyber-Physical Systems* held March 13-14, 2012 in Rosemont, Illinois. The presentations and discussions that took place at the workshop provided the foundation for this report. A complete list of attendees is provided in Appendix A. Special thanks are extended to the members of the workshop steering committee and plenary speakers, listed below.

Steering Committee

Susan Ying, Boeing
Janos Sztipanovits, Vanderbilt University
David Corman, Boeing
Venkatesh Prasad, Ford
Isaac Cohen Director, United Technologies Research Center
Pieter Mosterman, MathWorks
Lonny Stormo, Medtronic, Inc.
Jim Davis, UCLA and Smart Manufacturing Leadership Coalition
Himanshu Khurana, Honeywell Automation and Control Solutions

Plenary Speakers

David Vasko, Rockwell Automation
Joseph D'Ambrosio, General Motors
Brent Brunell, General Electric
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Special thanks are due to the Energetics Incorporated team who provided support for workshop planning, facilitation, and preparation of the workshop summary report.

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1.0 Introduction

1.1 Cyber-Physical Systems

Cyber-physical systems (CPS) can be described as smart systems that encompass computational (i.e., hardware and software) and physical components, seamlessly integrated and closely interacting to sense the changing state of the real world. These systems involve a high degree of complexity at numerous spatial and temporal scales and highly networked communications integrating computational and physical components.

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 (see Figure 1-1). 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.

Figure 1-1. 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

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.

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, reliable, safe, and secure.

1.2 Workshop and Report Overview

In view of recent reports and the potential opportunities for economic growth and competitiveness, the National Institute of Standards and Technology (NIST) sponsored a workshop *Foundations for Innovation in Cyber-Physical Systems* on March 13-14, 2012 in Chicago, Illinois to identify crosscutting technical barriers and knowledge gaps limiting innovation and U.S. competitiveness in CPS. Particular attention was given to current and future technology and measurement capabilities that can fill in these knowledge gaps.

Five technical topics were considered during the workshop:

- Reliable, Safe, and Secure Systems You Can Trust Your Life With
- Networked, Cooperating, Human-Interactive Systems
- Engineering Across the Digital-Physical Divide
- Architecture and Platforms for Cyber-Physical Systems
- Education, Workforce Training, and Technology Transition

The ideas generated during the workshop are summarized in this report and organized around the breakout topics shown above. For each topic area, discussions are summarized for the future envisioned for CPS systems and technologies, transformative ideas, and the priority challenges that need to be addressed. In addition, some of the unique sector-specific challenges are described.

It should be noted that the results presented in this report reflect the opinions and ideas of the workshop participants, not necessarily the entire CPS community. However, a significant effort was made to ensure that participants represented all segments of the stakeholders involved with the development and use of CPS community.

The workshop results will be used to inform strategic planning efforts at NIST and provide planning information to other government agencies, customers, and stakeholders with a vital interest in the future of CPS technologies. As a follow-on to this workshop summary report, a high-level perspective will be published outlining some of the high priority recommendations for future research and development.

2.0 Reliable, Safe, and Secure Systems You Can Trust Your Life With

Issues of reliability, safety, and security play a large role in the acceptance and use of the cyber-physical systems of today and the future. Some of the key challenges to be considered include what is needed to cost effectively and rapidly build in and assure safety, dependability, security, and performance of next-generation cyber-physical systems; how to ensure these systems become fault tolerant and adaptive; and developing the mechanisms and methods for efficiently upgrading and recertifying systems.

2.1 Vision

For CPS to be reliable, safe, and secure, systems must be able to adapt to the physical environment and withstand both cyber and physical attacks while maintaining data integrity and robustness. Visionary characteristics range from improved management of system development and lifecycle to cost-effective verification and validation of CPS. The vision for the reliability, safety, and security of CPS are summarized in Table 2-1.

Table 2-1. Vision for Reliability, Safety, and Security in CPS
• Future **CPS characteristics** will be bio-inspired, self-healing, adaptive, and resilient to attacks. CPS safety and security will be designed using a compositional approach. Total system development and lifecycle management will be completed with an understanding of the tradeoffs concerning the economics of reliability and safety. • **Metrics** for reliability, safety, and security will be both quantifiable and comparable among systems. The regulatory environment will achieve a balance of regulation framework and incentives to promote CPS development. A design methodology will be developed that can define prescribed levels of reliability, safety, and security. • **The cost of verification** will decrease ten-fold for the same level of safety and reliability. Verification will take advantage of logic that integrates continuous, discrete, and stochastic system and engineering compositionality. • **CPS applications** will span a broad segment of industry and academia, with notable advances. For example, future CPS in intelligent traffic control systems will be adaptive and responsive, capable of optimizing performance criteria, such as fuel consumption or idling time. Low-cost medical technologies will be able to use off-the-shelf devices to capture medical conditions of patients and transmit data reliably and securely to doctors.

2.2 TRANSFORMATIVE IDEAS

A number of transformative ideas that could improve or revolutionize the reliability, safety, and security of CPS were identified (see Table 2-2).

Table 2-2. Transformative Ideas for Achieving Reliability, Safety, and Security in Future CPS

Science and Engineering Foundations
• Incorporate knowledge integration from multiple sources (physics-based model, data, and expert knowledge) to understand fault-error-symptom characteristics • Devise monitoring mechanisms to accurately detect incipient faults and perform system recovery from adverse conditions • Use tools that can model, synthesize, and analyze high-dimensional probabilistic systems, which balance performance, fidelity, and scalability • Enhance high-level programming languages, verified runtime, and virtualization • Achieve safety through prediction and adaption by automatic understanding of societal environment and human interactions, enabled by the ability to read human brains • Design future artifacts to be highly actuated and instrumented, with resilience enabled by massive redundancy Develop swarm intelligence to build systems that adapt given a set of optimization criteria
Modeling and Computation
• Operate systems based on models of all connected entities adapting their behavior as connected entities change • Apply a compositional, model-based (formal) approach to system development, enabling low-cost creation of assurance cases (safety, security) • Use quantum computing to explore large state spaces for validation • Apply knowledge and experience from digital circuit design to model synthesis and CPS implementation, so that CPS can be constructed directly from a model • Use goal-based programming as opposed to programming for specifications • Build optimization into infrastructure of CPS using ensemble optimization and loading • Improve correct-ability to keep pace with market-sourced verification which relies on extremely fast feedback cycles
Systems Integration
• Build a property gateway that ensures safety, reliability, and security of interacting subsystems • Focus on systems architecture to yield outcomes (concept of operations focus) underlying modularity and independence to enable economical systems • Develop systems that manage themselves toward graceful and non-disruptive failure and build on platform of system-wide built-in self-test
Metrics
• Develop systems that continuously re-construct themselves (virtually and physically), with the system life defined by the trajectory in an expanding design space with a sequence of instantiations as needed • Include metadata in representational state transfer-like interfaces to support resilience • Synthesize code and proofs from high-level specifications • Use embedded privacy systems agents to ensure systems do not compromise data privacy concerns

Table 2-2. Transformative Ideas for Achieving Reliability, Safety, and Security in Future CPS

Technology Applications
Biology and Medicine
• Use antibodies and lymphatic systems as a model in system design and cyber-physical agents
• Develop CPS with biological traits that can evolve/reproduce, lower energy use, and incorporate chemistry
• Develop non-invasive systems to record a person's daily work patterns that can be used by doctors to predict his/her future health condition
Infrastructure
• Develop warning system for buildings and bridges so that active dampers can be automatically tuned to specific earthquake characteristics
Transportation
• Implement vehicle-to-vehicle and vehicle-to-controller communications, which provide safety metrics (e.g., safety distance) for the vehicles and controller to avoid collisions
• Develop future vehicles that can communicate seamlessly with environment, including infrastructure (e.g., traffic control), drivers (e.g., sensing fatigue), other cars, and buildings
• Receive upcoming traffic information from the sensors and model it to determine the optimal traffic signal timings instead of using fixed traffic signal timings

2.3 Challenges

A number of challenges were identified that impede the development of reliable, safe, and secure CPS (see Table 2-3). From these, a set of high priority challenges were selected for more in-depth discussion. These are described below and in detail in Figures 2-1 to 2-4.

Structural Frameworks for High Fidelity Models: Formal, precise models at the appropriate level of abstraction are lacking for CPS design. These models must include precise specification of properties relevant to the purpose of the model. Development of these models could reduce project duration and costs while improving design quality, performance, resilience, and dependability. Aerospace, defense, transportation and other industries could use these models for safety-relevant and high-reliability systems. Figure 2-1 provides additional details about this challenge.

Universal Definitions for Large Heterogeneous Systems: Developing a method to align CPS is complicated by the lack of a common definition and language for large heterogeneous systems. An improved, consistent set of definitions would lower integration and development costs, and clarify top-to-bottom system behavior. Figure 2-2 provides additional details about this challenge.

Cost-effective Verification and Validation of Complex CPS: Verification and validation (V&V) of complex CPS is challenged by V&V of the whole system, extreme cost pressures, and incorporating multiple time scales. Cost effective methods of verifying and validating CPS are needed to increase reliability, reduce recalls, and decrease system verification cost. Figure 2-3 provides additional details about this challenge.

Objective, Measurable, and Comparable Design Metrics for Reliability and Safety: Design metrics need to be developed to be objective, measureable, and comparable over time. One major challenge is developing design metrics with sufficient flexibility to be applicable to a wide variety of situations. While difficult to develop, the design metrics are required in all phases of CPS technology including design, testing, deployment, and ongoing operation. Figure 2-4 provides additional details about this challenge.

Table 2-3. Barriers and Challenges for CPS Reliability, Safety, and Security

(● = one vote)

Metrics and Tools for CPS Verification, and Validation	
High Priority	• Limited metrics for reliability and regulating a certain minimum level of reliability ●●●●●●●●●●●●●●●●●●●●●●● • Increasing coverage of verification and validation while reducing costs ●●●●●●●●●●●●●●● • Coping with complexity and scale of systems when performing verification and validation ●●●●●●●
Medium Priority	• Lack of parametric and non-parametric performance models ●● • Lack of models for verification research and associated component model libraries for compose-able and verifiable CPS ●●
Lower Priority	• Limited prediction capability in coupled systems (i.e., degradation of one system affects another) and metrics for estimating system-level reliability ● – Existing algorithms are component-centric – Translation of component or subsystem reliability to system-level reliability • Lack of methods for measuring level of security ● • No agreement on framework or standards for quantitative, acceptable safety or reliability, including assurance cases and arguments (rather than check lists) • Lack of methods to perform trusted security evaluation of software
Modeling Fidelity	
High Priority	• Inability to apply formal methods at appropriate abstraction levels, especially for a typical engineer (e.g., Z is a “write only” language) and lack of formality in modeling (unified modeling language and systems modeling) ●●●●●●●●
Lower Priority	• Unknown levels of model fidelity needed to simulate CPS systems ● • Unreliable testing-based methods for complex systems with software; formal methods are not integrated effectively with commercial tools
Systems Integration and Compositionality	
High Priority	• Interoperating various modules and unifying standards from different domains and sectors ●●●●●
Medium Priority	• Lack of clear ownership of performance interfaces (e.g., between code, hardware, multiple vendor interfaces) ●●● • Difficulty developing self-diagnosis output that is understandable by humans ●●● • Lack of good systems engineering and architecture practices to fully enable CPS ●● • Formalizing and modularizing specifications for large systems where possible ●●
Lower Priority	• Lack of infrastructure to link CPS systems to each other, other infrastructure, and integrated

Table 2-3. Barriers and Challenges for CPS Reliability, Safety, and Security (● = one vote)	
	control mechanisms • Limited ability to engineer ultra large systems of deeply heterogeneous systems technologies ● • Deficient methods for handling emergent behaviors in integrated systems
Compositionality	
High Priority	• Achieving compositionality of heterogeneous systems for safety, security, and reliability: ●●●●● – Precise property taxonomies – Metrics that can be formalized – Standard, virtual test benches for evaluating metrics – Mathematical models for design spaces

Figure 2-1. Structural Frameworks for High Fidelity Models

There is a lack of formal, precise models at the right level of abstraction for the design of cyber physical systems. These models must include precise specification of properties relevant to the purpose of the model.

Measurement Challenges

- Including all the right properties
- Using the right level of precision for properties
- Specifying the right scope, pre-conditions, and assumptions
- Verifying the model
- Determining how to show consistency between models

Performance Targets

- Measured acceptance of the approach in CPS community
- Reduction in maintenance costs and complexity unit
- Reusability of design assets (models)
- Reduction in design and verification cost per complexity unit

Potential Applications

- Aerospace and defense
- Energy (smart grid)
- Medical
- Automotive and other transportation
- Other safety-relevant and high-reliability systems

Benefits/Impacts

- Code synthesis
- Test synthesis
- Automated test execution
- Reduction in project time/cost
- Reduction in delivered defect rate
- Improvement in design quality and performance
- Improved reuse of models
- Potential for improved resilience and dependability of systems

Major Tasks

- Construct an ontology of model types
- Conduct education, mentoring, and training on high-fidelity modeling
- Create process assets (e.g., tasks, guidance, checklists, examples, templates, tools)
- Create tooling to automate some parts of modeling (construction, mining, translation, checking, verification)
- Explore consensus on a CPS model paradigm
- Construct industry-specific and problem domain-specific CPS reference models

Key Milestones

- CPS modeling ontologies
- Standard set of modeling practices
- Adaptation of process assets to industry- and problem-specific standards
- Wide-spread adoption of rigorous modeling tools
- Release of model-designed CPS systems

Stakeholders and Roles

Industry: System software, test (hire engineers, grad students); build systems, manage, use approaches and tools

Academia: Educate workforce (in modeling), research on approaches and tools and theory of CPS

Government: Create standards, regulate, commission systems

Industry Tool Vendors: Build tools, codify practices

Consumers: Buy products and provide feedback to industry

Figure 2-2. Universal Definitions for Large Heterogeneous Systems

A standard method is needed for aligning a large, heterogeneous group of systems technologies, including technology, specific applications, human elements, and time and space. Aligning these groups would help to collectively accomplish key outcomes using an effective, non-iterative approach. In addition to the lack of a common definition or description for such systems, a common language is also lacking (e.g., German, English, Mandarin, etc.).

Measurement Challenges

- Inability to measure how well system is integrated and/or performs
- Inabilty to meaure the correctness of requirements
- Inability to measure how "good" the solution is within the context of the entire system

Performance Targets

- Key CPS industries compliance to standard definitions by 2017
- Key suppliers (sub-systems) compliance to standard definitions (or standard interface) by 2019

Potential Applications

- All ultra-large cyber-physical systems incorporating multiple technologies and heterogenous groups

Benefits/Impacts

- Lower cost of integration
- Less expensive and lengthy development
- More clarity on top-to-bottom system behavior

Major Tasks

- Develop a way to universally (and visually) represent heterogeneous system behavior
- Develop a way to provide real-time feedback on impact of local decisions up to systems scale to satellite decision bodies
- Complete virtual systems integration early during subsystem development

Key Milestones

- Meeting of cross organizational and disciplinary teams on the topic of standardizing system modeling techniques and definition
- Agreement on parameters that should be standardized

Stakeholders and Roles

Industry/Subsystem Developers: accountable for aligning around concept description and strategy for articulating system definitions; test and use approaches

Standards Organizations: Support standard development

Figure 2-3. Cost-effective Verification and Validation of Complex CPS

The current challenges of verification and validation (V&V) of complex CPS include whole system V&V, the extreme cost pressures of conducting V&V, and incorporating multiple time scales, as well as discrete, continuous, and stochastic elements.

Measurement Challenges

- Fidelity and coverage of V&V models
- Percentage of systems covered by testing and V&V
- Determining what percentage of thread model is covered by V&V and testing
- Degree to which system can detect and respond to unknowns

Performance Targets

- 10-fold cost reduction in V&V of complex CPS

Potential Applications

- Broad range of industries,from energy to medical to buildings to transportation

Benefits/Impacts

- Increased reliability
- Greater value, including more features, higher-performing systems, lower cost
- Greater certainty in system performance
- Higher quality and fewer recalls

Major Tasks

- Establish precise abstraction relationship between models included in V&V
- Explore pathways to compositionality
- Develop abilities for quantitative verification
- Establish the safety and security envelope
- Develop advanced computational methods (e.g., quantum simulation, satisfiability (SAT) solving)
- Integratie simulation with V&V, integrating specific logics and tools

Key Milestones

- Creation of benchmark problems and comparison of various approaches
- Complete V&V of a know application, e.g., single-engine small amphibious vehicles with autonomous mission controller (10,000 lines of code in embedded code)

Stakeholders and Roles

Universities and Research Labs: Conduct research

Government: Support studies, apply approaches and techniques

Industry: Apply approaches and techniques

Figure 2-4. Objective, Measurable, and Comparable Design Metrics for Reliability and Safety

There is a need for the development of metrics for reliability and safety in a wide variety of CPS. These metrics will support more than system reliability; they can also be used to formulate regulations for a minimum level of reliability.

Measurement Challenges

- Difficulty creating consistent or common metrics for application -and situation-specific conditions for safety, resilience, and reliability
- Large and diverse number of systems that require effective metrics for reliability and safety

Performance Targets

- Design phase: metrics/measurements used to build in the desired safety, resilience, and reliability or SRR (much of this already exists – load, jitter, delay, etc.)
- Test phase: metrics/measurements used to test desiresd characteristics/built-in SRR but limited in testing (scale, severe conditions, malicious/stupid behavior)
- Deployment: metrics/measurements of system behavior that relate to SSR
- Ongoing operations: predictive/steady state/emergent property metrics or measurements that give indication of emerging issues

Potential Applications

- Cyber-security of infrastructure (defense, energy, buildings, roads, bridges)
- Broad range of CPS across multiple industrial sectors
- Health care and financial systems

Benefits/Impacts

- Increased reliability and safety of critical systems
- Greater certainty in system performance

Major Tasks

- Develop risk framework for coming up with acceptable levels of SRR
- Develop metrics/ measurements at the meta level for each situation
- Create metrics/measurements to underly the meta level metrics (strength of materials, load, etc.)
- Develop solid cyber metrics/measurements (strength of code, security, etc.)

Key Milestones

- Complete design phase , incorporating risk frameworks
- Complete test phase using meta and sub-metrics
- Refine metrics and measurements based on test results
- Deploy metrics in a variety of systems and continue to test/refine

Stakeholders and Roles

Industry: Participate in metrics development and test

Research Labs: Develop and test metrics

Academia: Conduct supporting research and development

3.0 Networked, Cooperating, Human-Interactive Systems

Cyber-physical systems can be highly connected and integrated in multiple ways, even across business operations and domain boundaries. Achieving effectively networked, cooperating, and human-interactive systems will be an integral factor in the adoption of such systems in the future. Some of the key questions to be considered include what is needed to enable streamlined and predictable development, deployment, and evolution of networked and integrated cyber-physical systems, particularly as systems become interconnected with legacy systems and across industry boundaries; how to effectively achieve compositionality within heterogeneous, dissimilar but connected systems; and how to model and integrate the role of humans in systems with variable levels of autonomy.

3.1 Vision

The ongoing implementation of an increasing number of CPS requires developers to consider how new, highly networked systems will interconnect with legacy systems, across industry boundaries, and with humans. New systems will have characteristics that enable compositionality within dissimilar but connected systems, while also considering the integration of humans into systems with variable levels of autonomy. The vision for the future of networked, cooperating, human-interactive systems addresses these issues and is outlined in Table 3-1 below.

Table 3-1. Vision for Networked, Cooperating, Human-Interactive Systems
Overarching Vision
In the future, networked, cooperating, human-interactive systems will optimize the power of human operations through high levels of situation awareness and adaptability. These dynamic and predictive systems will learn as they operate to maximize performance and resiliency, creating safe, secure, and reliable systems that can function as autonomously as desired by human systems designers. A level of certification will also be incorporated into these systems to enhance inter-system connectivity. While humans will interact more seamlessly with the CPS of the future, the ethical issues surrounding the human-machine interaction will be resolved prior to determining whether the human role will be as the operators of the machines (“human-in-the-loop”) or as the partners of the machines (“human-in-the-mesh”). As emergent system behavior begins to occur, humans will monitor and determine both its positive and negative effects on overall system operation.

3.2 TRANSFORMATIVE IDEAS

As stated in the vision, networked, cooperating, human-interactive systems will play an integral role in optimizing human operations in the future. With the potential for humans and machines to operate more seamlessly and systems to interconnect better than ever before, the possible advances that these new systems can enable are practically limitless. Radical possibilities include everything from enabling machines and humans to act more like one another, to improving data collection for better productivity, to taking better care of human health and welfare. For example, CPS could be used to enable humans to achieve complex tasks with minimum specialized education and skills, making the systems themselves more efficient and productive while opening up employment opportunities to more people. A set of radical ideas for the next generation of networked, cooperating, human-interactive systems is outlined in Table 3-2 below.

Table 3-2. Transformative Ideas for the Future State of Networked, Cooperating, Human-Interactive Systems

Human-Machine Interaction
• Use CPS to improve understanding of human knowledge and behavior so that machines know how and why humans make certain decisions • Develop machines with a transparent understanding of human intent and desire • Create a collective consciousness shared by machines and humans • Integrate CPS to the point where people behave more like machines and machines behave more like humans • Develop robots that are fully capable of interpreting human brain signals and controlling humans • Develop self-learning and autonomous robots, such as robots that can learn to smell
Information/Knowledge Collection
• Create CPS that can effectively collect, organize, and present data and use it to offer assumption-based options and consequences • Develop a game-ified world in which systems interact to maximize what humans are capable of at both a local and global level • Build machines that can learn and adapt to a human's personal communication style and interests and provide relevant and overlooked data to him/her as needed • Develop perfectly efficient systems • Create an "internet of things" that collect and organize information all over a person's daily life • Cultivate a searchable, indexed world that would prevent humans from losing things • Use CPS to explore space and find new planets
Workforce
• Enable humans to achieve complex tasks with minimum specialized education and skills • Use CPS to ensure that everyone who desires a meaningful job has a meaningful job • Use CPS to reduce and/or eliminate accidental, industrial-related injuries and deaths
Transport and Civil Infrastructure
• Create and implement smart utilities that integrate electricity, water, and gas • Develop CPS that optimizes multi-modal travel

Table 3-2. Transformative Ideas for the Future State of Networked, Cooperating, Human-Interactive Systems
• Use CPS to reduce and/or eliminate transportation-related injuries and deaths • Develop secure and reliable wireless technology • Use CPS to minimize and/or eliminate the impact of deviant human behavior • Create an “Iron Man” that integrates transportation, communication, and defense knowledge with degrees of power and responsibility
Human Welfare
• Create smart, sustainable agriculture with CPS that can improve productivity to feed the world and prevent starvation • Design CPS that can rebuild the world after natural disaster • Develop systems that can provide caregivers with the real-time status of children • Create smart homes that can take care of humans and themselves • Develop robots that can serve as geriatric caregivers • Use CPS to empower all people with physical, mental, and/or cognitive disabilities so that they can operate in a world that is not designed for them • Apply swarm technology for pest control applications
Medical Devices and Healthcare
• Enable non-stop ambulatory personal health monitoring with CPS that can diagnose problems in real time • Develop health systems that not only treat humans when there are problems but also keep humans healthy throughout their lives • Develop autonomous robots that can perform brain surgery or emergency room duties • Create hospitals where work is divided seamlessly between man and machine

3.3 CHALLENGES

Systems must overcome a number of barriers and challenges to attain higher networking and connectivity and to address issues regarding the human-machine interface, as identified in Table 3-3. A set of high priority challenges were selected for more in-depth discussion. These are described below and in detail in Figures 3-1 to 3-3.

Natural, Seamless Interaction Between Humans and CPS: There is a need to better model human strengths and weaknesses and corresponding machine strengths and weaknesses. Such models will enable a more natural, seamless interaction between humans and CPS and will help to manage risks and safety as systems move toward mixed-initiative modes of operation. Specific applications for these models include human-machine cooperative manufacturing, vehicles and transportation systems, warfighting, smart buildings, health care, and home care assistance. Figure 3-1 provides additional details on this challenge.

Uncertainty Characterization and Quantification: System uncertainty must be characterized and quantified in order to understand the implications of the inputs and their variability on system operation. Characterization and quantification of uncertainty will improve understanding of the potential risks to system operation, enable design feedback and facilitate graceful system degradation. The result will be robust and resilient systems that can maintain the same quality and level of service even under duress. The characterization and quantification of uncertainty would be particularly beneficial in the automotive, health care, manufacturing, and renewable energy industries. Figure 3-2 provides additional details on this challenge.

Interconnected and Interoperable Shared Development Infrastructure: The current market does not have governance or business models in place to motivate the development of networked, cooperating, human-interactive systems. Developers must assume the risk of sharing proprietary information with competitors and the liability of integrating their systems with external systems to ensure high levels of performance and functionality. Building an infrastructure foundation that is interoperable, contains open source and proprietary information in balance, and operates under the same standards will provide a protected starting point from which interoperable issues are minimized and system development could be profitable. For example, automatic car producers will have to work with each other and with traffic regulating infrastructure to develop functional products. Building from a standard foundation will save time and cost by sharing critical information and will avoid the liability of a solely proprietary product. Figure 3-3 provides additional details on this challenge.

Table 3-3. Barriers and Challenges for Networked, Cooperating, Human-Interactive Systems

(● = one vote)

Modeling, Simulation, and Verification	
High Priority	• Lack of a human model, complete with cognition, learning, and adaptation, that can be integrated into systems analysis and synthesis and inform design ●●●●●●●●●●●
Medium Priority	• Time consuming and expensive verification and validation as compared to development ●●●●● • Incomplete and improperly captured system specifications ●●● • Lack of integrated models with common semantic domains ●●●
Lower Priority	• Lack of multiscale and multiphysics modeling and simulation ●● • Developing a CPS "theory of everything" that networks every person and physical thing into one massive, intelligent system ●● • Difficult maintenance of heterogeneous generation gap due to systems integration evolution ● • Uncertainty about the ability to model CPS mesh capability, casting doubt on the facility of the creation of predictable systems • Difficulty in combining and/or integrating differing time- and event-based system representations • Lack of probabilistic certification standards • Lack of model integration across domains and industries • Variable interaction of different system models(e.g., integrating models of people and machines could produce different results than models of combined networks of people and machines)
Communication Systems	
Medium Priority	• Integration of wireless technology (e.g., 3G, 4G, NFC, Wifi, ZigBee, RFID) to meet the mobility needs of CPS ●●●

Table 3-3. Barriers and Challenges for Networked, Cooperating, Human-Interactive Systems (● = one vote)	
Lower Priority	• Decreased wireless capability from lost bandwidth packets • Lack of communication protocols for hybrid networks regarding data and controls
Human-Machine Interface	
Lower Priority	• Lack of a well-defined benchmark problem that can help balance resources for performance and robustness and break down resources into a well-defined structure between humans and automation ●● • Material limitations of current sensor and actuator technologies ● • Inability of current sensors of CPS applications to efficiently integrate a human-in-the-loop • Increasing need for human-machine interfaces for CPS beyond the iPad • Inability of machines to understand, rather than just sense, human intent • Lack of automation to address scale and complexity increases and determination of whether to do so top down or bottom up • Difficulty preventing undesirable emergent behaviors
Data to Knowledge	
Medium Priority	• Lack of methods for data processing (data to knowledge) ●●●●
Lower Priority	• Limited data processing technologies (e.g., data center, data mining, cloud computing)complicates obtaining knowledge from a large amount of data • Gaps in ability for processing sensory data into actionable information in real time • Poor analytics (e.g., machine learning, adaptable systems, awareness)
Design	
Medium Priority	• Lack of a unified, multidisciplinary design framework and standard software and hardware ●●●●●
Lower Priority	• Difficulty in determining and maintaining balance between open standards and proprietary standards ●● • Establishing correct interface rules and formalisms for design of sub modules through system integration • Practice of incremental design limits the potential of CPS • Limited new high-level programming paradigms that are platform-specific (i.e., multicore GPU) • Lack of research in interactive artificial intelligence
Metrics for Performance and Uncertainty	
High Priority	• Unsatisfactory uncertainty characterization and quantification ●●●●●●●●●● • Lack of publicly available data sets and test beds to conduct sufficient testing and data collection for benchmarking purposes ●●●●●●●●●● • Insufficient metrics, or feedback loops, for highly networked CPS ●●●●●●●●● • Convincing developers, regulators, users, and other CPS stakeholders to relinquish the idea of systems being 100% certifiable, except in extreme cases ●●●●●●●●●

Table 3-3. Barriers and Challenges for Networked, Cooperating, Human-Interactive Systems (● = one vote)	
Security and Privacy	
High Priority	• Limited system security against attacks ●●●●●●● • Maintaining privacy, including information security, information integrity, and intent management ●●●●●●
Medium Priority	• Limitations of measuring the quality of security ●●●●● • Instilling trust in data collection, what the CPS is allowed to do, and whether or not the CPS will respond to human users properly ●●●●
Low Priority	• Maintaining privacy even after a breach ●

Figure 3-1. Natural, Seamless Interaction Between Humans and CPS

A better model of human strengths and weaknesses and corresponding machine strengths and weaknesses is needed to create a more natural, seamless interaction between humans and CPS. Models that are adaptive, implementable at varying degrees of sophistication, and compelling to humans will help manage risks and safety as systems move toward mixed-initiative modes of operation and will make humans more comfortable with and accepting of interactions with machines.

Measurement Challenges

- How to measure situation awareness and interaction of the system with/by humans and of the human with/by the system
- How to measure the engagement of humans with the system
- Developing an approach to modeling human behavior that includes a general cognitive model that is substantiated and adapted through interaction

Performance Targets

- Robot assistant that interacts as a person would (at a test-type scale)
- Robot assistant that is effective in aiding people with different levels of abilities
- Decreased number of car crashes due to more human-like machines

Potential Applications

- Manufacturing fabrication and assembly, maintenance, and other functions
- Automotive and other transportation 'smart' systems
- Smart buildings and civil infrastructure
- Surgical and other robotic-assisted medical procedures
- Search and rescue
- Energy exploration and production (mines, oil platforms)

Benefits/Impacts

- Natural, seamless human interactions with CPS
- Manage risks and safety as systems move toward mixed-initiative modes of operation
- Accelerate and ease the adoption of systems that provide performance benefits
- Human acceptance of, comfort with, and confidence in interacting with machines and systems
- Increased career longevity, quality of life, and independence for humans

Major Tasks

- Develop a state-of-art survey and taxonomy of human behavior
- Architect a container for physical and cognitive models of human with respect to machine
- Develop proper abstractions and structures for model, including representations
- Create a pilot or challenge to develop and validate models and components, along the lines of the DARPA grand challenge

Key Milestones

- Year 1: Establish an ongoing effort to conduct periodic assessments of progress, such as challenges of increasing level of difficulty with periodic reductions in constraints; a robot assistant could be a possible challenge target (will continue past 1 year).

Stakeholders and Roles

Industry: Provide industrial engineers and device developers and manufacturers

Academia: Provide expertise on human behavior

Government: Provide expertise on human behavior (e.g., National Science Foundation human/social behavior)

Marketers, cognitive psychologists: Provide insight into human/social behavior

Figure 3-2. Uncertainty Characterization and Quantification

System uncertainty must be characterized and quantified to understand the implications of the inputs and their variability on system operation. Characterization and quantification of uncertainty will ensure that systems are robust and resilient, enabling them to maintain the same quality and level of service even under duress. It is also a key enabler for modeling and capturing the human element, and leads to a greater understanding of the boundaries for stability.

Measurement Challenges

- Determining level of service
- Determining productivity enhancement (i.e., do cyber-physical systems improve or degrade task completion)
- Conducting marginal risk assessment
- Uncertainties of experimental design (e.g., Bayesian Theory, correct test beds)
- Quantifying the "brittleness" of the system (i.e., gain margin)

Performance Targets

- An evolutionary system that can adapt to changing naturalistic inputs
- A tool to compose disparate systems with quantified uncertainty
- Reproducible results (e.g., tool should eat its own garbage)
- Use uncertainty characterization and quantification to identify potential risks in a mixed-mode system and provide feedback to design

Potential Applications

- All systems where the highest level of certainty is critical (medical, national security and defense, energy infrastructure, food safety, etc.) and/or where systems are likely to be exposed to duress or impactors on stability and reliability

Benefits/Impacts

- Better understanding of the potential risks to system operation
- Feedback to design
- Enable graceful degradation
- Create safe, robust systems
- Reduce the risk of catastrophic error
- Have the ability to estimate risk
- Enable complex systems to evolve

Major Tasks

- Develop a modular, composable approach to uncertainty quantification
- Conduct a baseline study to understand performance and range of inputs

Key Milestones

- Year 1: Complete an evaluation of a mixed-mode system (could take 1 to 3 years).
- Year 2-3: Baseline a system in development or in place.
- Year 4+: Have the ability to model composable systems.

Stakeholders and Roles

Academia: Develop uncertainty characterization and quantification modeling

Industry: Develop test bed, data sets, and scenarios

Academic Public-Private Partnerships: Establish a framework for public-private partnerships, including a funding arrangement, and help establish a test bed

Figure 3-3. Interconnected and Interoperable Shared Development Infrastructure

The current market does not have governance or business models in place to motivate the development of networked, cooperating, human-interactive systems. Developers must assume the risk of sharing proprietary information with competitors and the liability of integrating their systems with external systems to ensure high levels of performance and functionality. Building an infrastructure foundation that is interoperable, contains open source and proprietary information in balance, and operates under the same standards will provide a protected starting point from which interoperable issues are minimized and system development could be profitable.

Measurement Challenges

- Defining minimum standards of performance and enforcing compliance with standard infrastructure
- Gauging stakeholder buy-in

Performance Targets

- Commercial success for stakeholders
- Stakeholder acceptance of the standards and infrastructure (e.g., 5 states are running it)
- A solid product that meets the minimum standard (as simple as possible)

Potential Applications

- None identified

Benefits/Impacts

- Smoother, faster roll-out of quality technology
- Drives down costs for manufacturers and consumers
- Improves economic competitiveness and creates jobs
- Faster and more efficient development processes are better for the environment

Major Tasks

- Conduct a gap analysis to determine what is missing, who the stakeholders are, and where the opportunities are
- Create basic infrastructure and make it affordable for people to use
- Compartmentalize different CPS systems for different industries and build separate standard foundations for them

Key Milestones

- Year 1: Conduct gap analysis to determine the “state of practice,” identifying issues, opportunities, and stakeholders, both domestically and internationally.
  - Year 2-3: Implement a test pilot project to develop a standard system in one industry to create industry buy-in; encourage government to participate as investor and legislator to test the development of a public-private partnership.
  - Use pilot project as proof-of-concept for a draft of standard design guidelines and an infrastructure model.
  - Develop a roadmap to drive the test pilot project and development of the draft guidelines and infrastructure model.
- Year 4: Continue revising standard design guidelines and infrastructure model, and use as the basis for other industries to develop tailored versions.

Stakeholders and Roles

Industry: Agree to implement test pilot project and buy into idea

Trade Groups: Assist development of standards and provide a collaborative environment for industries

Standards Developers: Work with industry and trade groups directly and use pilot test project as a guide

Government: Support for programs, regulation and legislation during pilot project

4.0 Engineering across the Digital-Physical Divide

Successfully integrating cyber and physical system components will require an understanding of the multi-scale, multi-physics models and abstractions that will be needed to enable co-design of software, communications, and interacting physical subsystems. Other questions to be considered include how to enable consideration of a wide range of design trade-offs across digital and physical systems; and the engineering foundations and tools needed to support CPS throughout the entire system lifecycle.

4.1 Vision

CPS have hardware, software, and communications systems that are deeply embedded in and interacting with physical components and the physical environment. While these aspects of CPS do work together today, significant development efforts are required to realize the next generation of secure, synchronized, and seamless CPS. Table 4-1 summarizes the future engineering vision for CPS and provides other concepts that should be taken into consideration as the future of CPS is strategically considered.

Table 4-1. Vision for Engineering Across the Digital-Physical Divide
Overarching Vision
By 2020, the CPS community will develop multi-scale, multi-physics models and abstractions that create engineering foundations and tools for future CPS that 1) can dramatically reduce risk in design and operations; 2) allow for scalable and composable co-design; 3) have systematic methods for integration; 4) are secure systems; and 5) have predictive, diagnostic, corrective, and adaptive characteristics.
Visionary Concepts for Engineering Across the Digital-Physical Divide
• Hierarchical co-design • Costs that are scalable (and predictable) • Secure interoperability • Seamlessly move between levels of abstraction technology • Integration as a first principle of design and development • Universal languages • Standards for processes, equipment, and evaluation of performance • Tools for verifiable software at scale • Risk is quantified (at all design stages), articulated to non-experts, and standardized

4.2 Transformative Ideas

Identifying a transformative idea set for CPS could be the impetus to help drive the development of the hardware, software, and communications systems necessary for robust digital-physical systems. One simple but far-reaching idea is the establishment of the 'science of CPS,' thereby creating a systematic basis of knowledge covering the general scientific principles behind CPS. A comprehensive review of CPS basics and expounding the fundamentals will establish a critical foundation on which all future CPS systems could be reliably and methodically built. Table 4-2 provides examples of other radical ideas, functionalities, and applications that could be realized with next-generation CPS.

Table 4-2. Transformative Ideas for Engineering Across the Digital-Physical Divide

Design and Development

- Create capability for automated design refinements
- Develop assisted design with tools to co-emulate components in system and provide on-demand knowledge
- Create general design software that would enhance transparency from smallest component to largest
- Develop collaboration and co-design tool with domain translator
- Establish hierarchical co-design
- Mitigate risks through redundancy; create diffuse and ubiquitous risk; recognize greater cyber-security risk as opposed to physical security risk
- Enable open source for all CPS software
- Establish marginally (not over) engineered systems; minimize system complexity
- Allow vendors to differentiate their business within an expansive standards ecosystem

Usability and Function

- Improve automated modeling
- Create interactive feedback systems
  - Individual and global community linked
  - Self-diagnosing
  - Self-alerting/repairing/adaptable, configurable self-healing
  - Adaptive, self-monitoring systems with single integrated monitor (redundant, reliable)
- Create learning databases
- Build an advanced problem visualization tool
- Individualize physical analysis and coaching
- Functionality to automatically synthesize analog from digital

Applications

- Advance autonomous passenger (civilian) aircraft
- Develop citizen power generation control
- Expand demand response in the power industry with CPS
- Create a CPSNET that sends energy like the internet sends information
- Crowd source (virtual) utility companies

Table 4-2. Transformative Ideas for Engineering Across the Digital-Physical Divide

- Link human brain directly to CPS for computing power
- Harness high computing systems for modeling and simulation
- Incorporate quantum computing-massively parallel processing
- Upgrade to very high bandwidth communications to allow computing in Cloud environments

4.3 CHALLENGES

While CPS has become part of contemporary applications from healthcare to the power grid, major improvements in functionality and the ability to navigate complex situations will require significant advances and developments in CPS technology. A number of challenges and barriers exist before these next-generation capabilities can be realized. The major challenges identified are outlined in Table 4-3. From these, a set of priority challenges was selected; these are summarized below and in more detail in Figures 4-1 to 4-3.

Abstraction Infrastructure to Bridge Digital and Physical System Components: For the last several years, computers and networks have pushed ahead into monitoring and controlling a variety of physical processes, typically using feedback loops. Issues arise from the safety and reliability requirements of the physical components which are qualitatively different from those of the computing components. Because physical components are qualitatively different from object-oriented software components, standard abstractions based on method calls and threads fail when used in CPS.[1] Figure 4-1 provides additional details on this challenge.

Testing and Certification of Compositional Systems: The desire for autonomously operating systems requires dependable and certified CPS systems. The challenge is to create compositional certification, which consists of certification of components (physical and cyber) separately without re-certifying them after the system is integrated.[2] Currently, system architecture, design, integration, and design space exploration are only robust enough to allow for building systems first, then testing them and finally certifying them (see Figure 4-2). Certification of complex systems is extremely difficult and hard to bind in the preliminary design phase.

Cost-effective, Secure System Design, Analysis and Construction: Lengthy design to product cycle and numerous iterations and interactions result in long and costly system development. Major issues are conflicting requirements and methods causing unintended consequences, the need to co-design tools and framework, lack of scaling ability, and lack of design standards for interoperability. New simulation tools are needed to fully model CPS systems as they collect, analyze, process, and react to the many types of sensing, communications, and other data types that will be captured during service operations. The

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[1] http://chess.eecs.berkeley.edu/pubs/427/Lee_CyberPhysical_ISORC.pdf
[2] http://precise.seas.upenn.edu/events/iccps11/_doc/CPS-Executive-Summary.pdf
[2] http://precise.seas.upenn.edu/events/iccps11/_doc/CPS-Executive-Summary.pdf

challenge is to create robust, relevant real-world simulations that accurately re-create scenarios that CPS systems will experience before they placed in service.

Table 4-3. Barriers and Challenges for Engineering Across the Digital-Physical Divide

(● = one vote)

Design, Development, and Construction	
High Priority	• Lack of simulation tools ●●●●●● • "Unknown unknowns" or ability to map out variables comprehensively ●●●●● • Poor CPS operation or failure with conventional abstractions ●●●●● • Inability to design, analyze, build CPS cost effectively ●●●●
Medium Priority	• Ineffective operation outside the design-space (e.g., robust and reliable) ●●● • Reconciling design paradigms or multi-paradigm modeling ●
Lower Priority	• Inability to scale methodology ● • Inability to quantify states of the cyber system • Instability of systems under cyber variations • Unpredictable interferences in para-functional properties, which are further complicated in CPS • Lack of filtering of poor data using adaptive filtering
Interoperability and System Integration	
High Priority	• Insufficient ability to enable all devices to communicate in a universal language ●●●●
Medium Priority	• Limited integrated infrastructure ● • Limited measures of system security ●
Standardization, Certification, and Verification	
High Priority	• Lack of methods for certifying heterogeneous systems ●●●●●●●●● • Insufficient testing and validation capabilities ●●●● • Lack of standards development ●●●
Lower Priority	• Gaps in data coordination

Figure 4-1. Abstraction Infrastructure to Bridge Digital and Physical System Components

There is a need to develop the correct abstractions for CPS design, simulation, control, build, maintenance, etc., that span the digital and physical divide. An approach is to design corresponding syntax and semantics that are executable and enable a framework to span various domains (physics, analog, digital, information, communication, computation, controls, etc.) and related abstractions and refinements.

Measurement Challenges

- Lack of metrics on the abstractions and necessary metrics to guide the choice of abstraction
- Making useful properties available
- Limited metrics on execution, bit-error rates (BER), mode switching
- Limited mode-dependent metrics (execution mode) – metrics determined by the mode of analysis

Performance Targets

- Abstraction framework and infrastructure to span a multitude of domains

Potential Applications

- Wide variety of CPS across multiple domains

Benefits/Impacts

- More effective design space exploration
- Enabling of compositionality – even across nonfunctional space
- Reuse of information within various abstractions
- Reconciliation of different design paradigms
- More confidence in integration (given framework)
  - Greater openness of systems
  - Ability for system evaluation

Major Tasks

- Conduct inventory study across existing systems; understand bottlenecks; conduct iterations and transpose abstractions to different domains (fundamentals, commonalities, etc.)
- Develop highly configured abstractions, transformations between abstractions (with little loss of information), preserving semantics
- Implement flexible framework – (collaborative) open; highly evolvable (technologies and methodologies)

Key Milestones

- Year 1: Complete inventories of existing abstractions
- Year 2: Development of abstraction framework
- Year 3: Test and adopt framework and infrastructure in practical system development

Stakeholders and Roles

Academia: Develop abstractions

Research Labs: Develop abstractions, test

Industry: Test/implement frameworks

Figure 4-2. Testing and Certification of Compositional Systems

There is a need for autonomously operating systems to be dependable and certified. In the context of CPS, system level testing, validation and certification is a significant challenge. Compositional certification (i.e., certification of physical and cyber components) is challenging, especially after integration. Today systems are built first, then tested and certified.

Measurement Challenges

- Lack of methods for certification compositional systems
- Difficulty of certifying complex systems with multiple cyber and physical components working together
- Limits of existing design paradigms (systems must be built individually

Performance Targets

- Methods for testing and certification of cyber and physical components working together in heterogeneous systems
- Design systems to incorporate compositionality and facilitate later certification and test processes

Potential Applications

- Large, heterogeneous, integrated CPS in a variety of domains and applications (e.g., smart grid, FAA NextGen system)

Benefits/Impacts

- Improves customer confidence in the system and encourages market adoption
- Early adoption of testing reduces overall development and deployment cycle time
- Mitigates need to re-certify components after system is integrated

Major Tasks

- Develop preliminary methods for compositional certification, that is performance-based as opposed to early process-based
- Develop and incorporate models and simulation into certification and test methods
- Establish a voluntary certification organization for CPS

Key Milestones

- Year 2-3: Implementation of LCA in new construction; achieve provable, correct model testing tools within next two years
  - Year 4: Updated metrics adopted by ANSI
  - Year 5 and beyond: Affordable testbeds (cost reduced by some order in the next five years)

Stakeholders and Roles

Industry: Industry

Academia: Academic and industrial researchers for provably correct model development

Government: Support research/test beds

Figure 4-3. Cost Effective and Secure System Design, Analysis, and Construction

The lengthy design to product cycle and numerous iterations and interactions required result in long and costly system development. Development issues include conflicting requirements and methods causing unintended consequences, the need to co-design tools and framework, the lack of simulations and models for design, and the inability to scale designs and analysis. Integration of disparate designs also requires standards for interoperability. A major challenge is how to stand up a universal language that anticipates the requirements of designers.

Measurement Challenges

- Developing new abstraction layers, standards, and common languages for exchange and translation across domains
- Data representation changes cause data loss
- Representing the envelope and operation limits and environmental factors
- Lack of simulation tools and models for system design and analysis
- Lack of a universal language for interoperability at design stage

Performance Targets

- Reduce design, analyze, and build time or cost by a factor of 10
- Increase number of publications of CPS by a factor of 100
- Demonstrate a more efficient and lower cost systems (energy, transportation)

Potential Applications

- Aerospace, automotive, and other transportation systems
- Multiple domains in manufacturing and the energy sector
- Civil and buildings infrastructure
- Industries that benefit from co-design strategies

Benefits/Impacts

- Reduces time to market
- Increases safety and security
- Maximizes simplicity and manages complexity
- Reduces both development and recurring costs
- Reduce complexity in interfacing systems
- Increases competitiveness
- Facilitates thinking at the system level
- Enables co-design which is critical for CPS with extreme demands
  - Cost-weight, size, performance advances for CPS
  - Informs the standards and certification processes

Major Tasks

- Develop formalisms and abstractions of science for CPS
- Develop engineering methods and tools for co-design
- Stakeholder collaboration to develop consensus standards for interoperability,including defintionof metrics and how they should be measured
- Break down barriers across fields and domains
- Establish incentives for cross-disciplinary projects
- Develop simulation tools that capture knowledge
- Develop innovative concepts, e.g., knowledge wizard
- Develop scalable and adaptable tools for future CPS

Key Milestones

- Year 1
  - Formal metrics published
  - Demonstrate engineering co-design for CPS
  - Demonstrate tools and framework
  - Define metrics and needed standards to measure CPS performance, stability
  - Increase CPS communication, conferences, publication, and community
  - Define case studies for co-design of complex CPS

Stakeholders and Roles

Industry: Guide standards, develop tools, demonstrate and productize

Academia: Work on theories, simulations

Government: Enable/facilitate standards, support demonstrations at scales; support research programs; issue/update regulation based on new technology

5.0 Architecture and Platforms for Cyber-Physical Systems

Innovative architecture and platforms are needed to support highly complex and inter-connected cyber-physical systems. A key consideration is how to enable development and application of comprehensive architectural frameworks that include both the physical and cyber elements of CPS. Other issues to be considered include what new platforms will be needed to effectively extract actionable information from vast amounts of raw data; and how to provide a robust timing and systems framework to support the real-time control and synchronization requirements of complex, networked, engineered physical systems. Advances will also be needed in sensing, control, and wireless communications to enable optimized performance, diagnostics, and prognostics.

5.1 Vision

Architecture and platforms are key components of CPS. The key properties envisioned for architecture and platforms in the years beyond 2020 include plug and play capability, self-healing, interoperability, and adaptability (i.e., an architecture that can adapt in response to changing and often unpredictable situations). In addition, it is expected that future CPS architecture and platforms are robust, verifiable and secure, as well as cost-effective. Table 5-1 provides more detail on the future vision for CPS architecture and platforms.

Table 5-1. Vision for Architecture and Platforms for CPS

Overarching Vision
A system that integrates Information Technology (IT) and Operational Technology (OT) at multiple abstraction levels to exhibit self-healing, adaptability, and learning, while still being applicable across multiple domains. This system is expected to be secure, scalable, reliable, flexible, meaningful, and interactive; with open interfaces for interconnection, while still allowing proprietary components to be utilized. Systematic heterogeneity will be achieved via a notion of abstract semantics (as opposed to a grand unifying modeling language). Essential components will include multi-form and multi-resolution models of time, discrete and continuous dynamics, multi-modeling (functionality vs. architecture), composability and decomposition, and parameterization (i.e., reusability).

5.2 Transformative Ideas

A number of transformative ideas will be needed to achieve this vision of architecture and platforms for the year 2020 and beyond. Table 5-2 shows examples of radical ideas in the development of CPS architecture and platforms. As shown in the table below, a number of ideas address a rethinking of the fundamental architecture design, for example, potentially informed by biological system design in the future. Other ideas focus on system interaction with the external world (i.e., input-output), in terms of communications, as well as self-adaption to external stimuli.

Table 5-2. Transformative Ideas for Architecture and Platforms for CPS
Architecture and Platforms
• Create an application-specific open-source platform that the CPS community can collaboratively populate and strengthen • Utilize a platform for interoperability, allowing for automatic negotiation of function and capabilities • Develop a layered architecture that is not subverted by issues of time, (e.g., a three layered architecture encompassing communications, utility, and value added) • Apply understanding of biological or social systems to promote radical CPS architecture and platforms design • Utilize abstractions that encapsulate multiple aspects (e.g., functional, behavioral, timing, quality of service, quality of control) and multiple layers (e.g., application, network, and physical layers) • Utilize plug and play components that produce predictable results, even for unanticipated interactions • Employ automatic adapting and reconfiguring architecture in response to failed/aging/drifting components • Deploy architecture containing multi-level “safety nets” and security defenses • Develop architectures that treat every component, product, and person as an active “node” on a network, for consumers and producers of information
Intelligence and Cognition
• Incorporate understanding of human intent into input (in real-time) • Develop components with extreme intelligence, allowing components to act as individuals in a human organizations (e.g., reporting status or skills to a component “manager”) • Utilize natural language to serve as the medium connecting heterogeneous data, linking perception and cognition (knowledge) to action • Employ intelligent system designs that are able to decide in real-time when to violate certain constraints in order to protect other constraints • Utilize distributed, swarm intelligence to achieve large-scale distributed complex models that combine physical and machine learning models
Unique Functionalities and Applications
• Enable multi-dimensional applications to comprehensively interact with our four dimensional world, unleashing dramatic innovation • Share middleware across CPS domains • Develop systems where communications bandwidth and processing power are not limiting factors for the vast majority of applications • Deploy embedded technologies that can evolve with integration

Table 5-2. Transformative Ideas for Architecture and Platforms for CPS
• Provide the capability for automatic, synergistic systems integration with measureable security
Sensing and Data Collection
• Deploy systems that make sense of data, with the ability to process large amounts of data to make intelligent run-time decisions, optimizing control and performance • Utilize self-powered, multi-level sensing devices • Incorporate 99.999+% wireless penetration in networked CPS

5.3 CHALLENGES

A number of barriers and challenges currently impede progress in the development of CPS architecture and platforms, and are summarized in Table 5-3. From these, a set of priority challenges were selected; these are briefly described below and detailed in Figures 5-1 to 5-5.

Scientific-based Metrics for Security, Privacy, Safety, Resilience: It is technically challenging to identify scientifically-based definitions of measurement for the broad concepts of security, privacy, safety, and resilience. And if such definitions are identified, how will they be utilized and reasoned with? For example, if the idea of privacy is examined, under what conditions or system attributes is privacy considered violated? These properties could be represented by a variety of models or combinations of models, which can be chosen based on their compositionality and ability to describe the constellation of attributes that are being certified (see Figure 5-1). Specific applications include medical device systems (professional, in the loop), smart buildings and vehicles, democratized power (i.e., allowing users to set and follow policy), and manufacturing or consumption networks (e.g., food).

Systematic Structured Design and Process Integration: CPS need a structured design method that systematically relates signals and symbols, both for inter-process and interpersonal communications across domains. Potential application areas include smart manufacturing, cross-domain applications (e.g., modular, fielded robotics), shared infrastructure data across industries, and the development of a reliable electric grid increasingly dependent on renewable energy. Figure 5-2 provides additional information details about this challenge.

Correctness of CPS in the Presence of Environmental Uncertainty: Ensuring the correctness of CPS systems in an ever-complex, uncertain environment is an increasingly challenging problem. Environmental uncertainty factors include potential adversaries and unanticipated human interactions. CPS would not only need to be able to respond to these environmental factors, but systems would also need to exhibit a degree of reconfigurability and adaptability in order to independently redefine correctness as conditions change. Specific applications that would benefit the most from addressing this challenge include autonomous vehicles, aircraft, control systems, the smart grid, and other complex CPS. Figure 5-3 provides additional details about this challenge.

Trustworthy, Holistic Infrastructure for the Evaluation of CPS: Currently, there is a lack of infrastructure for use in the evaluation of traditionally closed systems (see Figure 5-4). This type of evaluation infrastructure can be developed by leveraging the strength of individual evaluation methods and tools already in use in other systems into an integrated approach, enabling a deeper understanding of the behavior of both the individual components and the larger systems. For example, measurement data can be integrated to drive modeling processes, which in turn can drive simulations and other forms of analysis. The results of simulations and other forms of analysis can then be used to drive optimized measurement processes. Specific applications could include CPS components and systems in medicine, the smart grid, smart manufacturing, and transportation. Overcoming this barrier would also enable the compositionality of different evaluation methods.

Managing the Role of Time in Architecture Design: Managing, in a characterized way, issues related to time in architecture is a complex yet critical issue for real-time CPS systems. The issues include time synchronization, developing a unified, common view of our sense of time, time measurement, unifying the time-scale, defining a reference time, and how to communicate these time characteristics to application and/or sensors. These issues could be addressed through the development of a multi-layered architecture, consisting of at least three layers: a communication layer, utility layer, and function/application layer. The communication layer would address all aspects of time management and time synchronization. The utility layer unifies the time scale and time scheduling across all the layers. And the application layer facilitates for applications how to define, manage and coordinate their timing requirements, definitions, acceptance and services. Overcoming these challenges will have a great impact on any data-driven, real-time applications and modeling/simulation functions and responses. Figure 5-5 provides additional details about this challenge.

Table 5-3. Barriers and Challenges for Architecture and Platforms for CPS

(● = one vote)

Infrastructure for Design, Test, and Validation	
High Priority	• Lack of scientific-based metrics for security, privacy, safety, resilience ●●●●●●●●●●●●●●● • Lack of a trustworthy, holistic infrastructure for the evaluation of CPS ●●●●●●●●●●●●● • Inability to ensure the correctness of CPS in the presence of uncertainty in the environment ●●●●●●●●●●●●● – Accommodating nondeterministic behavior of humans in human-in-the-loop control systems – Developing automatic generation of interface rules for use in distributed systems • Managing the role of time in architecture design (i.e., lack of models that make semantic distinctions between discrete events and continuous processes) ●●●●●●●●●● • Lack of systematic structured design and process integration for CPS (i.e., determining a method to systematically relate signals to symbols) ●●●●●●●●● • Inability to continuously measure and ensure CPS only provides desired functionality ●●●●●●●
Medium Priority	• Lack of a secure and trust-worthy virtual infrastructure for remote testing, evaluation, and development of systems including medical devices and automotive ●●●●● • Inability to determine the optimal trade-off between assessment metrics (e.g., safety, security, cost) ●●●●

Table 5-3. Barriers and Challenges for Architecture and Platforms for CPS (● = one vote)	
	– Lack of support tools to understand the consequences of behavior, engineering requirements, and other impacts on performance and cost • Inability to develop predictive models for CPS architecture behavior ●●●
Lower Priority	• Systems lack automatic correctness and/or behavior bounding ● • Lack of distributed learning algorithms ● • Difficulty achieving global optimality using game theory rather than rules ● • Inability to scale architecture for safety and security and still mass-marketing low-cost consumer products and components ● • Lack of robust description and languages for applications and value-added services ● • Lack of a common architecture and metrics and definitions for architecture • Lack of standards maturation to support end-to-end integration
Data Collection and Use	
Medium Priority	• Lack of self-powering or extremely low-power wireless sensors to enable functionality for the duration of the sensor lifetime ●●●●● • Lack of low-power sensors that are easily calibrated and stay calibrated long-term ●●●●
Lower Priority	• Inability of the user or the CPS to measure learning and improvements resulting from CPS adaptability ● • Inadequate sensing and monitoring in extreme (harsh) conditions

Figure 5-1. Scientific-Based Metrics for Security, Privacy, Safety, and Resilience

Different properties are measured over distinct, but not necessarily disjoint features of each system: Can common representations that acknowledge such nuance be found? How can complexity be evaluated based on them? For a property, what defines the violation of that property? What conditions or system attributes are implicit in the violation of this property? Potential applications include medical device systems (professional, in the loop), smart buildings and vehicles, democratized power (where users both set and follow policy), and manufacturing/consumption networks (i.e., global hunger issues).

Measurement Challenges

- Labeling/differentiation of system states based on individual/combined properties (i.e., what are the classifiers/predicates?)
- Integrating diverse models into a combined reasoning/evaluation framework
- Understanding the complexity of multi-model checking, reachability, completeness, etc., and automating the process

Performance Targets

- Ability to evaluate physical, temporal, computational, etc. attributes of failures in a consistent and standardized manner
- Communicate those details and their implications effectively to each other, to decision makers and the larger populace
- Measurement and evaluation regimes can be applied to existing systems (possibly after change, or post hoc)
- Policy decisions (e.g., investment, design, use) can be scientifically evaluated based on measured properties (e.g., bridge usage, load policy, conformance to policy, monitoring)

Potential Applications

- Multiple and diverse CPS across domains and applications

Benefits/Impacts

- Greater reliability with fewer, lower-impact, less widespread consequences of failures
- More informed, effective and understandable policy and engineering decisions and outcomes (e.g., allowing medical practitioners to better explain decisions to patients)
- Monetary, intellectual, temporal, efficiency of systems and their productivity/lifecycles
- More fundamental basis for understanding and dealing with complexity

Major Tasks

- Mine existing engineering practice for examples of the property in question being violated and/or exhaustively verified or disproven
- Develop suitable models for expressing each property rigorously (rigorous, but comprehensible)
- Examine diverse combination of properties and evaluate which combinations of models remain suitable (can they interface well? e.g. time)
- Develop theories of compositional reasoning over suitable combinations of models
- Validate compositional reasoning over models by applying them to real (systems-of-) systems and evaluate system complexity and reasoning/model complexity. Models will be used to define what to measure in the system, compare measured values and their consequences to modeled behavioral expectations.

Key Milestones

- Year 1
  - Define what attributes of privacy, security, safety, and resilience are fundamental.
- Year 2-3
  - Extract attributes of real systems of non-trivial complexity and impact
  - Model & evaluate space of possible experiments and exercises to explore property evaluation capabilities (i.e., what can be used for engineering practice?)
- Year 4+
  - Conduct and evaluate experiments (long-running consortium based) in relevant domains (power, aviation, automotive).
  - Scientific review and refinement of approaches, methods, models, etc (ongoing agency level activity) for evaluating security, privacy, safety, and resilience

Stakeholders and Roles

Government Agencies (e.g., NIST, NSF, DOD): Anchor and organize the scientific review and refinement of models, methods, and approaches for evaluating privacy, security, safety, and resilience
Technical Organizations: Provide engineering and technical expertise
Research Organizations (including academia, industry, government): Provide engineering and technical expertise
Standards bodies and review boards: Developing appropriate standards
Public: Education and consent

Figure 5-2. Systematic Structured Design and Process Integration

CPS is in need of a structured design method that systematically relates signals and symbols, both for inter-process and interpersonal communications across domains. Potential application areas include smart manufacturing, cross-domain applications (e.g., modular, fielded robotics), shared infrastructure data across industries, and the development of a reliable electric grid increasingly dependent on renewable energy.

Measurement Challenges

- Difficulty measuring the behavior of a system that contains signal interpretation, planning and control components
- Integrating human component into the measurement
- Incorporating stochastic models in measurements of behavior.

Performance Targets

- Demonstrations of quick CPS implementation from generic plug-and-play components

Potential Applications

- Smart manufacturing, cross-domain applications such as fielded robotics

Benefits/Impacts

- Increases modularity
- Reduces costs of sensors and actuators
- Reduces development time and time-to-market
- Improves understanding of CPS complexity measurements

Major Tasks

- Define a universal description language for sensors and actuators that informa a system of their semantics
- Develop stochastic methods and tools for task decomposition that supports generic/modular system understanding
- Develop structural design for CPS (e.g. semiconductors)

Key Milestones

- Year 1-2
  - Principles for CPS structured design established (inspired by Dijkstra's structured programming).
- Year 3
  - Prototype tools for learning, creating, and understanding the structured CPS design is developed.
- Year 4+
  - Plug and play sensors are developed (Year 4)
  - Demonstrations of quick CPS implementation from generic plug and play components (sensors and actuators) (Year 5).

Stakeholders and Roles

Academic Researchers: develop design theory

Industry: test cases and data collection

Industry: develop novel sensors and actuators

Government: community building

Academic Institutions: develop a structured, universal CPS design

Figure 5-3. Correctness of CPS in the Presence of Environmental Uncertainty

Correctness of CPS systems must be ensured at all times, even in the presence of complexity, dynamic uncertainty in the environment, adversaries, or unanticipated human interactions.

Measurement Challenges

- How to define complete correctness
- How to characterize uncertainty

Performance Targets

- Increased uptime
- Design to correctness development time
- A known percentage of behavioral coverage (correctness)
- A known percentage of unknown coverage

Potential Applications

- Autonomous vehicles
- Aircraft
- Control systems
- Smart grid
- Other complex CPS

Benefits/Impacts

- Improves safety
- Increases robustness
- Reduces design time
- Reduces enhancement time
- Reduces cost

Major Tasks

- Define correctness as much as possible (i.e., formal description, simulations/models, testing)
- Develop robust run-time bounds checking (to detect when the system exceeds the original specifications of safe and secure operation)
- Develop adaptation/self-learning with incremental verification of changes through its lifetime.

Key Milestones

- Year 1
  - Development of a proof of concept in modeling/virtual world; encompassing correctness, bounds checking, and adaptation.
- Year 2-3
  - Pilot on a large-scale application.
- Year 4+
  - An architecture reference design and standard is developed.

Stakeholders and Roles

Industry (e.g., aircraft, automotive manufacturers): technology and application development

Academia: research collaboration

International Standards (e.g., IEEE, IEC): increased adoption

Government (e.g., DOE, DOD, DOT, NIST, DARPA): application development

Figure 5-4. Trustworthy, Holistic Infrastructure for CPS Evaluation

Currently, there is a lack of infrastructure for the evaluation of traditionally closed systems. This evaluation infrastructure can be developed by leveraging the strength of evaluation methods and tools used in other systems including the networking community or in vehicle systems. Overcoming this barrier would also enable the compositionality of different evaluation methods. Potential applications include CPS components and systems in medicine, the smart grid, smart manufacturing, and transportation.

Measurement Challenges

- Impact of domain – specific requirements on interface design
- Traditionally separated communities (e.g. dspace)
- How to ensure non-intransient evaluation given the safety-critical nature of many CPS systems

Performance Targets

- Demonstration of a generic CPS built using plug and play sensors and actuators

Potential Applications

- Aerospace and other transportation
- Medicine
- Smart grid
- Manufacturing

Benefits/Impacts

- Supports the lifecycle of CPS development
- Reduces development costs
- Supports open innovation

Major Tasks

- Integrate different evaluation methods (i.e. formal analysis and verification, simulation, and measurement);
- Develop an effective user interface for specific components (including behavior and fidelity, safety, and security properties), while also specifying context;
- Seamlessly integrate different tools that support compositionality and prediction.

Key Milestones

- Year 1-2
  - Integration of different evaluation methods.
- Year 3
  - Closed-loop integration of different methods for going from data to model to analysis and back to measurement and simulation.
- Year 4+
  - Compositionality of components within and across different methods
  - Support behavior prediction across different contexts

Stakeholders and Roles

Academic researchers: develop the evaluation infrastructure

Industry: resources, collaboration

Government: guidance, program support

Figure 5-5. Managing the Role of Time in Architecture Design

Facilitating time management (synchronization, scale, communication, scheduling) for distributed CPS applications (design, rapid prototyping, production) is an extremely challenging task. To address this challenge, a layered architecture based on functionality (communication layer, utility layer, and application layer) is to be designed, prototyped, and produced. This layered architecture will employ time management among/across all layers.

Measurement Challenges

- Maintaining a common sense of time
- Time and task synchronization and management
- Managing characterization of the sensors
- Accommodating the models and measuring the impact of environment

Performance Targets

- Check for architecture extendability
- Use of multiple types of test beds

Potential Applications

- Multiple systems and applications across domains where timing is a critical factor

Benefits/Impacts

- Ensures time correctness
- Makes it simpler for applications to run in a time-correct manner
- Increases application expanda-bility, lowers cost, and eases deployment (the result of the dissociation of time management activities and applications logic)

Major Tasks

- Define time characterizations for sensors and applications
- Develop a common language and protocol for specifying time requirements (i.e., real time, time constrained)

Key Milestones

- Year 1-2
  - Develop reference architecture.
- Year 3+
  - Develop common standards, languages and protocols for specifying time requirements (i.e., real time, time constrained).

Stakeholders and Roles

Industry: develop or provide the definition of problems, test cases, benchmarking

Government and Industry: develop reference architecture or reference framework and standards to develop standards, languages, and protocols

Academia: develop language, tools, protocols, algorithmic intellectual property to support other activities

6.0 Education, Workforce Training, and Technology Transition

Education and training provides a solid foundation for supporting continuing innovations and advanced in CPS. Key considerations include what will be needed to ensure that higher education provides a new generation of scientists and engineers qualified to develop, design, and implement an array of cyber-physical systems; and how to create a skilled workforce capable of operating and maintaining the highly complex CPS of the future. Once new CPS technology is developed, mechanisms must also be in place to help smooth the transition to suppliers and end-users.

6.1 Vision

An established field of study focused on CPS is not currently available in educational institutions. CPS encompasses a number of disciplines including computer science and various engineering specializations. A key visionary element of the future of education for CPS is the availability of recognized educational programs that offer the fundamentals of CPS though a multi-disciplinary curriculum. Similarly, future workforce training and technology transition of CPS require the availability of professional certification and other practice oriented programs. Table 6-1 summarizes the future vision for this area.

Table 6-1. Vision for Education, Workforce Training, and Technology Transition
Overarching Vision
A cross-disciplinary CPS curriculum is part of the university system to teach the foundations of CPS, is recognized as an undergraduate and post-graduate field of study, and offers opportunities for transition into the workplace.
Education
An academic CPS environment is available that is interdisciplinary and dynamic, provides laboratory experience, and covers human behavior as well as the business side of CPS.
Workforce Training and Technology Transition
Technology transfer takes place seamlessly, reliably, and painlessly. Potential opportunities include the availability of internships with industry, professional certifications, and other practice–oriented programs.

6.2 TRANSFORMATIVE IDEAS

A number of transformative ideas that could improve or revolutionize CPS education and technology transition were identified. For example, CPS is a field that is continuously evolving both in terms of technology and information so it may be necessary to develop continuous education programs in addition to a structured degree. Table 6-2 summarizes the transformative ideas proposed for this area.

Table 6-2. Transformative Ideas for Future CPS Education, Workforce Training, and Technology Transition

Education and Workforce Training

- Create an industry-recognized certification for CPS professionals (degree-less education)
- Use elementary and secondary resource center programs for K-12 exposure of projects related to CPS
- Develop education programs that are continuous, not just four to six years
- Develop a virtual CPS computer world that allows for experiments, exercises, and games
- De-emphasize MBAs and reward Masters' programs in CPS
- Attract engineers at an early stage in their education and get them involved to instill a passion for life-long learning and commitment
- Improve community college policies and programs to help educate a CPS workforce
- Create a summer camp for CPS students with real-life games in real-life environments
- Develop a global standard for CPS education

Technology Transition

- Create an environment where individuals can develop collaborative "apps" for smart sectors, such as smart grid and smart buildings
- Have universities forgo all claims to intellectual property and, instead, offer new inventions as a social good

6.3 CHALLENGES

A number of challenges were identified that impede advancements in CPS education, workforce training, and technology transition (see Table 6-3). From these a set of priority challenges was selected for further discussion. These are described below and in more detail in Figures 6-1 to 6.3.

Multi-department CPS Degrees and Resources: There is a need for a CPS university program that integrates multiple disciplines (see Figure 6-1). Historically, university systems have been divided into traditional disciplines (computer science, electrical engineering, etc.). The challenge is to incorporate a multi-disciplinary CPS program within the existing university structure. The creation of a new prototype program would require participation from the National Academy of Engineering and the Accreditation Board for Engineering and Technology (ABET), as well as organization supporting research. The resulting program would provide a more formal teaching and training approach in CPS, and also reduce training cycles. Textbooks and courses (including virtual) are also needed to support new curricula as well as training.

Dynamic Training and Certification in CPS: CPS is a dynamic field that requires continuous education and retraining, and could be suited for certification and accreditation programs. A joint industrial and academic certification committee could produce a prototype test certification and accreditation for CPS training (see Figure 6-2). This initiative could result in the development of an educated workforce with fundamental backgrounds in CPS.

Value Proposition of CPS: CPS research is often described in terms that are too theoretical or include jargon that is not readily recognized. Simplified and enhanced descriptions of research goals, benefits, and risks are needed. These collaboration activities could facilitate quicker and less expensive industry adoption of research as well as improved understanding of the benefits and applications of CPS research. Figure 6-3 provides additional details about this challenge.

Table 6-3. Barriers and Challenges for Education, Workforce Training, and Technology Transition

(● = one vote)

Education	
High Priority	• Lack of a CPS degree that cuts across multiple disciplines, hindered by stove piped nature of university structure ●●●●●●●●●●●●●●●●●● – Need to define what aspects should be included in the CPS curriculum – Graduate programs may accommodate new, integrative courses more easily than undergraduate programs, which are saturated in terms of courses • Lack of mechanisms for continuous retraining, incentives, and funds to facilitate radical CPS innovations in universities, schools, industry, and government●●●●●● • Insufficient training of instructors and teachers ●●●●●
Medium Priority	• Need a reward/incentive structure that reinforces narrow disciplines● • Need to define the educational outcomes and objectives for a CPS-based curriculum● • Erroneous public perception of potentials and risks of inaction● • Deficient vested interests in the current educational approach/structure●
Lower Priority	• Inability of various groups in different domains (e.g., IEEE, ASME) to agree on standards • Lack of project-based activities that are sufficiently adequate in terms of reinforcing CPS • Obtaining the right mix of faculty and industry mentors from different backgrounds • False boundaries in cross-discipline skill sets from degree structures such as bachelors, masters, and post-doctorate degrees • Inability to handle shared or constrained resources (e.g., bandwidth, computer cycles, sensing, power, sampling) • Difficulty managing a myriad of sub-disciplines in which specializations and fellowships can be obtained

Table 6-3. Barriers and Challenges for Education, Workforce Training, and Technology Transition

(● = one vote)

Workforce Training	
Medium Priority	• Training future CPS engineers ●●●● • Need for rigorous tools that can effectively train workforce using a flexible delivery method while maintaining quality ●●● • Lack of funding and programs in community colleges to train students in CPS●●● • Lack of company incentives for certain amount of continuing education credits in CPS ●●
Lower Priority	• Continuing education certificates in CPS are lacking
Technology Transition	
High Priority	• Difficult to understand the substance of research, evidence for investment, target audience, and time to market, due to overly theoretical research descriptions ●●●●●●●●●●●●●●●●●●●● – Lack of model and simulation design, and cross-section design semantics between architects, automation engineers, and civil engineers. All parties should understand each other. • Lack of regulations focused on implementation versus probabilities of outcomes ●●●●●●●●● • Lack of governance or business models needed to motivate development, which creates liabilities ●●●●●●●●● • Incentivizing companies to make security of CPS a priority ●●●●●●●●●● • Lack of communications among CPS collaborators with different conceptual frameworks ●●●●●●● • Lack of proper incentives and funds to facilitate radical innovation at universities ●●●●
Medium Priority	• Resistance and fear of management, collaborators, and software vendors to changing a currently inadequate business model ●●●●● • Inability of business to accept risk of building/adopting CPS; conveying vision and impact of CPS value proposition ●●●● • Making CPS an open source to capture CPS technology, methods, and tools in shared modeling and simulation systems●● • Lack of open standards, which should be included in undergraduate training
Lower Priority	• Lack of a common definition of CPS ●● • Estimating the economical and societal costs and benefits ●● • Inability to put into effect a global architecture (e.g., and open-ended architecture guidelines) ● • Encouraging the public to understand risk (e.g., self-driving cars) ● • Legal and intellectual property implications of connecting into large non-isolated systems • Finding early adopters without incentives • Determining who is accountable when integrated human-machine systems cause harm • Elevated costs for technology transition • Limited number of people with skills to do validation and verification of CPS • Creating societal acceptance of the human-machine interface, ensuring that machine invasiveness is at a comfortable level for humans

Figure 6-1. Multi-Department CPS Degrees and Resources

Incorporating a cross-disciplinary CPS degree program into current university structure and administration is impeded by the historic separation of disciplines and departments. Evolving and revolutionary approaches will be needed to overcome this challenge. CPS is not a classic discipline, so few textbooks and curriculums exist to cover the topic, and incentives are low to develop these.

Challenges

- Establishing a designated degree, certificate, minor, cross-listed courses, and a full-fledged program
- Assessing the competence of students graduating from the program in CPS
- Assessing if course offerings satisfy CPS learning objectives and outcomes

Performance Targets

- National Academy of Engineering report in one year
- Adoption of CPS programs in 25% of U.S. colleges (top 200)
- First bachelor's degrees in CPS issued in 2017
- Preparing/adoption of textbooks (1-3 years)
- Number of CPS courses, virtual or regular

Potential Applications

- Mechanical Engineering: Next generation aerospace, transport
- Electrical and computer engineering: Smart grid
- Robotics: Autonomous vehicles
- Mechanical/chemical engineering: Automation
- Civil: Structural/ Smart buildings
- Biomedical: Medical networks

Benefits/Impacts

- Provides a more formal method/approach for teaching undergraduate students in CPS rather than the ad-hoc approach used now
- Saves five years of training in industry, after graduation
- Supports future workforce training for industry

Major Tasks

- Develop report (National Academy of Engineering/NAE)
- Obtain certification from the Accreditation Board for Engineering and Technology (ABET) for CPS-based curriculum/program
- Obtain buy-in at every level in the university (faculty, board of regents/trustees) and from local industry
- Establish faculty hiring incentives/opportunities in CPS programs
- Provide co-ops which will become an integral part of the CPS program
- Identify common backgrounds needs in math, science, etc.
- Develop textbooks
- Create CPS virtual training material
- Present the foundations of CPS through existing material – security for CPS, networking for CPS

Key Milestones

- 1 year: Creation of government-supported CPS educational centers with industry cooperation; public report by NAE that identify opportunities and needs for university ; virtual bridging courses
- 2 years: CPS-related textbooks
- 3 years: Prototype program in several select universities
- 5 years: Deployment of program across most universities
- Annual summer workshops tuned to education on CPS

Stakeholders and Roles

Government Agencies: provide motivation, support for education centers
Industry: partner in education and recruiting; identify CPS benchmarks; form alliances with educational initiatives
High-level University Administration: negotiate high-level politics in college, provide resource allocation
Universities: implement recruiting through hiring and outreach; incentivize CPS curriculum, interdepartmental programs
Students: customers, product of education system
Primary/secondary Education: provide exposure early on to facilitate success in higher education

Figure 6-2. Dynamic Training and Certification in CPS

CPS is a dynamic field (similar to the medical and other fields) with new methods, tools, techniques, and theories continuously emerging. It is also a concept that does not easily fit within traditional stovepipes but crosses multiple disciplines. Dynamic training programs are needed to provide the skilled workforce needed.

Challenges

- Creating a balance of training in sub-disciplines needed for a given CPS domain
- Lack of accreditation and/or CPS degrees
- Evolving advances across CPS fields requires retraining and keeping up with new technology
- Ability to measure the value of the CPS approach versus traditional solving of problems

Performance Targets

- Small start-up businesses addressing CPS training issues
- Students with CPS accreditations, degrees, or certificates,
- Requirements/specifications that rely on CPS capabilities

Potential Applications

- University degrees and education tracks
- Training in all CPS fields

Benefits/Impacts

- Educated workforce with fundamental background and CPS capabilities
- Ability of society to efficiently and safely implement their visions of complex systems

Major Tasks

- Support prototype test certification/accreditation programs between industry/academia for CPS training
- Create a municipal scale test site
- Robust internships supported through a national program in CPS

Key Milestones

- Certification committee with agencies to outline within two years , led by government agencies and universities)
- Build a business case for a municipal scale test site and advocate to investors – six months for business case, one-year plan, two years co-funding, three years break ground

Stakeholders and Roles

Government: enable and support programs; specify CPS capabilities/attributes in procurements; help in coordinating educational programs and requirements for continuous certification

Industry: provide specifications for training and certification

Universities: conduct training programs

Figure 6-3. Value Proposition of CPS Research

Research is often described in terms that are highly theoretical and with jargon that is not readily understood or recognized. It is hard to explain the value and substance of the research to the layman or decision-makers, i.e., why it is worthy of investment, who will benefit, how it can be applied, and the time to market.

Measurement Challenges

- Creating technical performance measures for CPS research
- Quantifying benefits for investors and customers
- Typical metrics, such as number of papers, patents, and research awards, may not resonate with stakeholders

Performance Targets

- Baseline of today's performance and quantification of current awareness of CPS research
- Understanding the quantified improvement that are desired or possible

Potential Applications

- Industry adoption of CPS to either generate products using CPS, work to mature or transition CPS technologies, or new start-ups using CPS

Benefits/Impacts

- Quicker, greater, and less expensive industry adoption of research
- Better (technical and non-technical) industry and other stakeholder understanding of what CPS research delivers

Major Tasks

- Encourage self evaluation criteria such as in Heilmeier questions to simply describe research, benefits, risks and why it is being done; embed as part of the research response and include timelines
- Place higher value on tangible industry participation versus letters
- Form technical committee under IEEE or ACM to address the value proposition
- Create technology transition awards

Key Milestones

- Number of industry attendees at CPS meetings greater than some number
- Number of patents from research increases above some threshold
- Increasing number of articles on CPS research outside of traditional journals
- Number of times citations are pulled from Google Scholar or IEEE Explore

Stakeholders and Roles

Government: support for research

Universities: conduct research

Industry: support and conduct research

Industry start ups: recipients of future research

Students: conduct research in engineering and non-engineering disciplines

7.0 Application-Specific Challenges

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.. Many challenges to CPS advancement remain throughout the stages of technology development, from basic science to applied R&D to technology deployment. The workshop identified challenges that are relevant to advancing technologies in the technical topics considered, and these are described in the main chapters of this report. However, challenges also exist that are unique to the application area and/or industrial sector, as outlined below. Prior to the workshop a situation analysis was conducted to identify the state of technology in some of the key application areas, as well as the major challenges, which are summarized in the next section (EI CPS 2012). These are not intended to be all-inclusive of the CPS challenges in these sectors, but representative of some of the major issues.

6.4 Smart Manufacturing

Some of the main challenges associated with the implementation of CPS in include affordability, network integration, and the interoperability of engineering systems.
Most companies have a difficult time justifying risky, expensive, and uncertain investments for smart manufacturing across the company and factory level. Changes to the structure, organization, and culture of manufacturing occur slowly, which hinders CPS technology integration. Pre-digital age control systems are infrequently replaced because they are still serviceable. Retrofitting these existing plants with CPS is difficult and expensive. Incorporating CPS in new plant designs is more feasible. The lack of a standard industry approach to production management results in customized software or use of a manual approach. There is also a need for a unifying theory of non-homogeneous control and communication systems.

6.5 Infrastructure for Smart Grid and Utilities

A grand challenge for CPS is the design and deployment of an energy system infrastructure that is able to provide blackout free electricity generation and distribution, is flexible enough to allow heterogeneous energy supply to or withdrawal from the grid, and is impervious to accidental or intentional manipulations. Integration of CPS engineering and technology to the existing electric grid and other utility systems is a challenge. The increased system complexity poses technical challenges that must be considered as the system is operated in ways that were not intended when the infrastructure was originally built. As technologies and systems are incorporated, security remains a paramount concern to lower system vulnerability and protect stakeholder data. In addition, to operate the infrastructure with CPS technologies, a qualified, innovative, and skilled workforce is needed.

Also affecting CPS integration are numerous non-technical business and policy challenges including policies on the regulation and implementation of smart grid technologies, standards development, and the responsibility of maintaining, operating, and repairing the equipment for power generation and grid connectivity.

6.6 Smart Buildings and Infrastructure

Issues of building ownership (i.e., building owner, manager, or occupants) challenge CPS integration with questions such as who pays initial system cost and who collects the benefits over time. A lack of collaboration between the subsectors of the building industry slows new technology adoption and can prevent new buildings from achieving energy, economic, and environmental performance targets.

Uncertainty in future policies and a near term focus for buildings increase the risk in adoption of advanced building technologies such as CPS. Funds for bridge repair, maintenance, and replacement shrink as costs of construction continue to rise. Although structural health monitoring systems could help determine when a bridge needs maintenance and possibly extend its useful life, these systems would require funding themselves as well as additional maintenance and replacement costs.

Integration of CPS both within the building and with external entities, such as the electrical grid, will require stakeholder cooperation to achieve true interoperability. As in all sectors, maintaining security will be a critical challenge to overcome.

6.7 Smart Transportation and Mobility

Federal, state, and local government budgets have limited resources for advanced transportation improvements and to integrate new CPS into the existing infrastructure. Although certification of these systems is critical, several issues remain, such as what should be certified, who is responsible for certification, and how will the systems be certified. New policies and legislation will be required to launch and sustain new technologies.

Representing human behavior in the design, development, and operation of CPS in autonomous vehicles is a challenge. Incorporating human-in-the-loop considerations is critical to safety, dependability, and predictability. There is currently limited understanding of how driver behavior will be affected by adaptive traffic control CPS. In addition, it is difficult to account for the stochastic effects of the human driver in a mixed traffic environment (i.e., human and autonomous vehicle drivers) such as that found in traffic control CPS.

Increasing integration calls for security measures that are not physical, but more logical while still ensuring there will be no security compromise. As cyber physical systems become more complex and interactions between components increases, safety and security will continue to be of paramount importance.

6.8 SMART HEALTHCARE

Challenges exist in the overall cyber-physical infrastructure (e.g., hardware, connectivity, software development and communications), specialized processes at the intersection of control and sensing, sensor fusion and decision making, security, and the compositionality of cyber-physical systems. Proprietary medical devices in general were not designed for interoperation with other medical devices or computational systems, necessitating advancements in networking and distributed communication within cyber-physical architectures. Interoperability and closed loop systems appears to be the key for success. System security will be critical as communication of individual patient data is communicated over CPS networks. In addition, validating data acquired from patients using new CPS technologies against existing gold standard data acquisition methods will be a challenge. CPS technologies will also need to be designed to operate with minimal patient training or cooperation.

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Acronyms/Abbreviations

ABET	Accreditation Board for Engineering and Technology
CPS	Cyber-physical systems
DARPA	Defense Advanced Research Projects Agency
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
FAA	Federal Aviation Administration
IEEE	Institute of Electrical and Electronics Engineers
IT	information technology
LCA	Life cycle analysis
MBA	master of business administration
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
SRR	Safety, resilience, and reliability
V&V	verification and validation