Foundations for Innovation:

Strategic R&D Opportunities for 21st Century Cyber-Physical Systems

Connecting computer and information systems with the physical world

January 2013

Report of the Steering Committee for Foundations in Innovation for Cyber-Physical Systems

STEERING COMMITTEE FOR FOUNDATIONS FOR INNOVATION IN CYBER-PHYSICAL SYSTEMS

This report was prepared through the collaborative efforts of the individuals noted below. It reflects their expert contributions as well as the many insights generated at the *Foundations for Innovation in Cyber-Physical Systems Workshop* held March 13-14, 2012 in Rosemont, Illinois.[1]

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[1] Workshop Report: Foundations for Innovation in Cyber-Physical Systems, January 2013. http://events.energetics.com/NIST-CPSWorkshop/downloads.html

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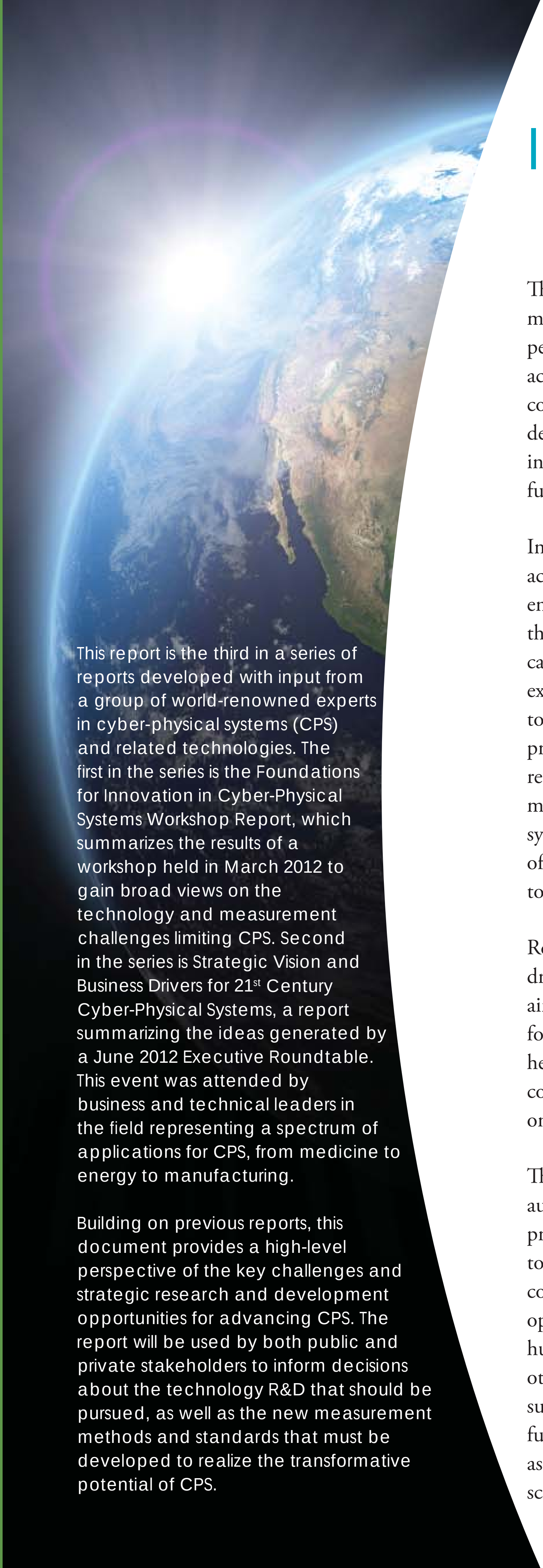

INTRODUCTION

The wide reach of the Internet along with rapid advances in miniaturization, speed, power, and mobility have led to the pervasive use of networking and information technologies (IT) across all economic sectors. Increasingly, these technologies are combined with elements of the physical world (e.g., machines, devices, structures) to create smart or intelligent systems that offer increased effectiveness, productivity, safety, and speed and enable functions not previously possible.

Integrated networking, information processing, sensing and actuation capabilities allow physical devices to operate in changing environments. This makes smart systems possible but also creates the need for a new 'systems science' that can lead to unprecedented capabilities. Tightly coupled cyber and physical systems that exhibit this level of integrated intelligence are sometimes referred to as cyber-physical systems (CPS). All CPS have computational processes that interact with physical components. These can be relatively simple (e.g., a heater, cutting machine) or comprise multiple components in complex assemblies (e.g., vehicles, aircraft systems, oil refineries). The computational and physical processes of such systems are tightly interconnected and coordinated to work together effectively, often with humans in the loop.

Robots, intelligent buildings, implantable medical devices, cars that drive themselves or planes that automatically fly in a controlled airspace—these are all examples of CPS. Today, CPS can be found in such diverse industries as aerospace, automotive, energy, healthcare, manufacturing, infrastructure, consumer electronics, and communications. Everyday life is becoming increasingly dependent on these systems—in some cases with dramatic improvements.

There is a growing trend toward computational intelligence, automation, and control for complicated but well-defined tasks or processes, especially when demands or constraints are not amenable to human intervention. For example, automatic collision systems could detect moving objects and respond faster than a human operator. Unmanned CPS could be used to reduce the risk to human life by detecting mines, exploring volcanoes, or conducting otherwise hazardous tasks. Machines driven by a computer do not suffer fatigue and may be more precise than is humanly possible. In future CPS could make possible concepts only imagined today, such as unmanned tours to the moon, bionic suits, and automated large-scale indoor agriculture systems.

This report is the third in a series of reports developed with input from a group of world-renowned experts in cyber-physical systems (CPS) and related technologies. The first in the series is the Foundations for Innovation in Cyber-Physical Systems Workshop Report, which summarizes the results of a workshop held in March 2012 to gain broad views on the technology and measurement challenges limiting CPS. Second in the series is Strategic Vision and Business Drivers for 21st Century Cyber-Physical Systems, a report summarizing the ideas generated by a June 2012 Executive Roundtable. This event was attended by business and technical leaders in the field representing a spectrum of applications for CPS, from medicine to energy to manufacturing.

Building on previous reports, this document provides a high-level perspective of the key challenges and strategic research and development opportunities for advancing CPS. The report will be used by both public and private stakeholders to inform decisions about the technology R&D that should be pursued, as well as the new measurement methods and standards that must be developed to realize the transformative potential of CPS.

This trend does not remove the importance of human involvement but does change roles and requirements for new skill sets. Furthermore, as CPS become more dependent on computational processes, it becomes increasingly important that they be engineered to be reliable, secure, and safe. Future scientific and engineering advances that extend the connectivity of these systems and deliver greater reliability could open new opportunities to take advantage of the unique properties of CPS.

A CALL TO ACTION

The future applications of CPS are more transformative than the IT revolution of the past three decades. Unparalleled analytical capabilities, real-time networked information, and pervasive sensing, actuating, and computation are creating powerful opportunities for systems integration. Next generation CPS will be able to execute extraordinary tasks that are barely imagined today. These new capabilities will require high-confidence computing systems that can interact appropriately with humans and the physical world in dynamic environments and under unforeseen conditions. Achieving these capabilities presents a complex and multi-disciplinary engineering challenge.

Future CPS have many sophisticated, interconnected parts that must instantaneously exchange, parse, and act on detailed data in a highly coordinated manner. Continued advances in science and engineering will be necessary to enable advances in design and development of these complex systems. Multi-scale, multi-layer, multi-domain, and multi-system integrated infrastructures will require new foundations in system science and engineering. Scientists with an understanding of otherwise physical systems will need to work in tandem with computer and information scientists to achieve effective, workable designs. Standards and protocols will be necessary to help ensure that all interfaces between components are both composable and interoperable, while behaving in a predictable, reliable way.

This report is a call to action. It outlines a set of strategic R&D opportunities that must be addressed to enable advanced CPS to reach their potential and deliver broad societal benefits in the future. The United States (U.S.) is a global leader in cyber technologies and well-positioned to gain a competitive advantage in CPS. Work in CPS is moving rapidly forward on a global scale. In the European Union, the ARTEMIS program has proposed spending $7 billion on embedded systems and CPS by 2013—with a view to becoming a global leader in the field by 2020. Japan is capitalizing on its traditional strengths in this field to make technology advances, and currently hosts the largest tradeshow in the world on embedded systems. The great potential of CPS is motivating countries such as India and China to forge ahead into the field. The opportunity is now for the U.S. to establish competitive leadership through the ability to develop next generation systems that you can trust your life with.

> "Advanced sensing, measurement, and process control, including cyber-physical systems… has applicability across almost all industry domains. These technologies are critical for enhancing tradability… megatrends of energy and resource efficiency, better safety, and higher quality also depend highly on advances in sensing and automatic process control."
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> Recommendation #2, Increase R&D Funding in Top Cross-cutting Technologies, from the Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing (PCAST, 2012)

REAPING THE BENEFITS OF CYBER-PHYSICAL SYSTEMS

Development and use of advanced CPS will generate unique opportunities for economic growth, create skilled jobs for the long term, and help ensure the health, safety, and security of the nation while improving quality of life. CPS are drivers for innovation in a broad range of industries and can lead to new products or unlock new markets (see Table 1). By the end of the decade, embedded networking and computing components are projected to account for more than half of the value share in diverse sectors, including automotive, consumer electronics, avionics and aerospace, manufacturing, telecommunications, intelligent buildings, and health and medical equipment. A recent report estimates that the technical innovations of CPS could find direct application in sectors currently accounting for more than $32.3 trillion in economic activity, and with the potential to grow to $82 trillion of output by 2025—about one half of the global economy (GE, 2012).

U.S. manufacturing competitiveness will increasingly rely upon CPS technologies for advanced robotics and computer-controlled manufacturing processes linked to automated design tools, along with integrated, broad-based, and dynamic management of production lines, factories, and supply chains. Equally broad-based performance metrics will be needed to enable integration of economic, productivity, energy, and sustainability objectives.

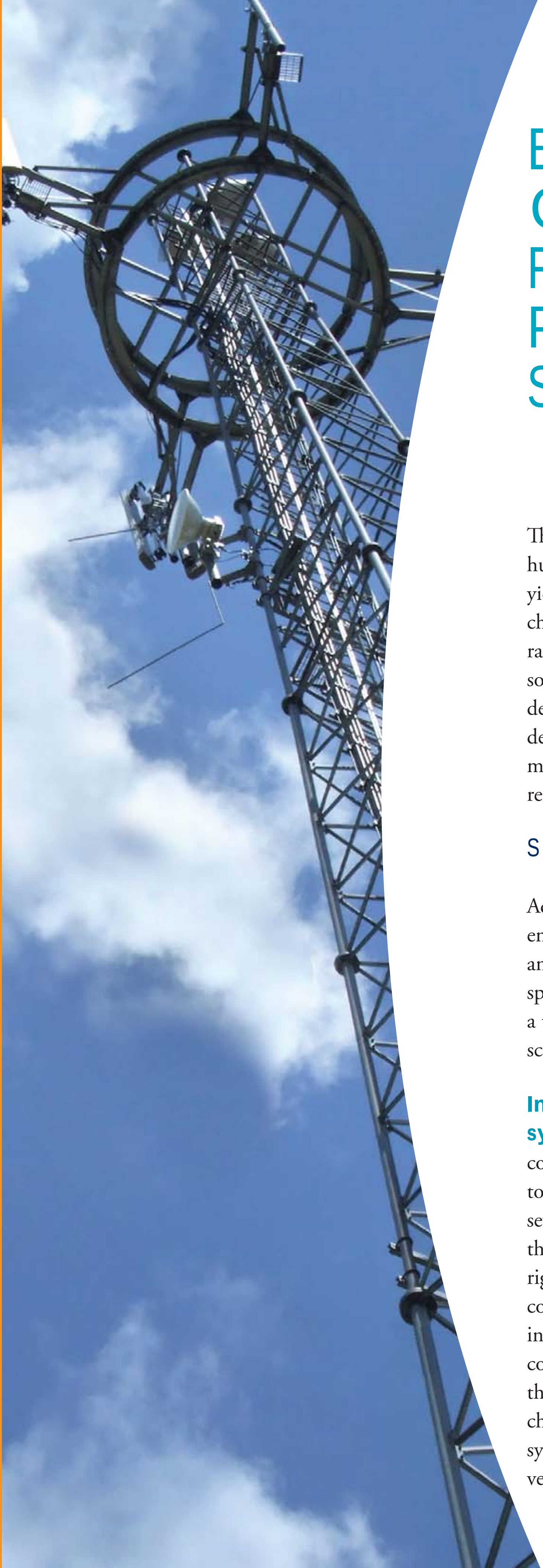
CPS are critical to national efforts to reduce energy use while increasing performance, reliability, and efficiency across economic sectors—via the smart grid, smart transportation systems, smart manufacturing, and smart buildings infrastructure.

CPS is already facilitating a broad shift from hospital-based to home-based health care and expanding independent living opportunities for seniors. By extending the reach of quality care beyond traditional hospitals, CPS-based medical devices and systems are enabling more individualized health care and improved patient outcomes. As advances are made, CPS can lead to new capabilities to diagnose, treat, and prevent disease.

In national defense, CPS now delivers superiority in virtually all weapons systems, including manned and unmanned aircraft, ground vehicles, robotic platforms, surface and underwater vessels, and the overarching systems that integrate the nation's fighting forces. In homeland security and law enforcement, CPS is used in diverse roles from bomb disposal and emergency response robotics to sensor networks providing advance warning of catastrophic events.

TABLE 1. APPLICATIONS OF CYBER-PHYSICAL SYSTEMS

Innovative Products or Applications	Cyber-Physical Systems	Impacts
Smart Manufacturing and Production		
• Agile manufacturing • Supply chain connectivity	• Intelligent controls • Process and assembly automation • Robotics working safely with humans	• Enhanced global competitiveness • U.S.-based high tech manufacturing • Greater efficiency, agility, and reliability
Transportation and Mobility		
• Autonomous or smart vehicles (surface, air, water, and space) • Vehicle-to-vehicle and vehicle-to-infrastructure communication	• Drive by wire vehicle systems • Plug ins and smart cars • Interactive traffic control systems • Next-generation air transport control	• Accident prevention and congestion reduction (zero-fatality highways) • Greater safety and convenience of travel
Energy		
• Electricity systems • Renewable energy supply • Oil and gas production	• Smart electric power grid • Plug-in vehicle charging systems • Smart oil and gas distribution grid	• Greater reliability, security, and diversity of energy supply • Increased energy efficiency
Civil Infrastructure		
• Bridges and dams • Municipal water and wastewater treatment	• Active monitoring and control system • Smart grids for water and wastewater • Early warning systems	• More safe, secure, and reliable infrastructure • Assurance of water quality and supply • Accident warning and prevention
Healthcare		
• Medical devices • Personal care equipment • Disease diagnosis and prevention	• Wireless body area networks • Assistive healthcare systems • Wearable sensors and implantable devices	• Improved outcomes and quality of life • Cost-effective healthcare • Timely disease diagnosis and prevention
Buildings and Structures		
• High performance residential and commercial buildings • Net-zero energy buildings • Appliances	• Whole building controls • Smart HVAC equipment • Building automation systems • Networked appliance systems	• Increased building efficiency, comfort and convenience • Improved occupant health and safety • Control of indoor air quality
Defense		
• Soldier equipment • Weapons and weapons platforms • Supply equipment • Autonomous and smart underwater sensors	• Smart (precision-guided) weapons • Wearable computing/sensing uniforms • Intelligent, unmanned vehicles • Supply chain and logistics systems	• Increased warfighter effectiveness, security, and agility • Decreased exposure for human warfighters and greater capability for remote warfare
Emergency Response		
• First responder equipment • Communications equipment • Fire-fighting equipment	• Detection and surveillance systems • Resilient communications networks • Integrated emergency response systems	• Increased emergency responder effectiveness, safety, efficiency, and agility • Rapid ability to respond to natural and other disasters



BROAD CHALLENGES FOR CYBER-PHYSICAL SYSTEMS

The interconnection of networking, computing, physical, and human components reaches most engineered systems and yields revolutionary new capabilities. The underlying technical challenges also have a great deal of commonality reflecting a range of fundamental scientific, engineering, institutional, and societal issues. Barriers arise throughout all stages of technology development, from basic science through applied R&D, demonstration, manufacturing, and deployment. Addressing the most critical of these will help ensure that in the future CPS are reliable, safe, producible, and secure.

SCIENTIFIC AND TECHNICAL CHALLENGES

Advancement in CPS requires a new systems science that encompasses both physical and computational aspects. Systems and computer science has provided a solid foundation for spectacular progress in engineering and information technology; a type of new systems science is now needed to address the unique scientific and technical challenges of CPS.

Integrating complex, heterogeneous large-scale systems. Future CPS will contain heterogeneous distributed components and systems of large numbers that must work together effectively to deliver expected performance. There are several challenges to achieving this today. A fundamental issue is the lack of common terminology, modeling languages, and rigorous semantics for describing interactions—physical and computational—across heterogeneous systems. Achieving the interoperability and compositionality of various components constructed in different engineering domains and sectors, without the benefit of unifying theories and standards, presents a major challenge. A lack of clear ownership of the interface between systems (e.g., between code, hardware, and multiple equipment vendors) also contributes to interoperability and integration problems. In addition to standards, interoperable systems need to ensure that timely outputs, outcome agreements, resilience, data transfers, and technical security protocols are addressed seamlessly within and between components. This includes aggregating and sharing data within systems as well as across systems and components.

Interaction between humans and systems. Current models for human and machine behaviors are not adequate for designing CPS when humans and machines closely interact. One of the challenges is modeling and measuring situational awareness—human perception of the system and its environment and changes in parameters that are critical to decision-making. This is particularly necessary for complex, dynamic systems, such as those used in aviation, air traffic control, power plant operations, military command and control, and emergency services. In such systems situational awareness can involve large and unpredictable combinations of human and machine behavior. Inadequate situational awareness and limited ability to model the human component in large complex systems has been identified as one of the primary factors in accidents related to human error (Nullmeyer et al, 2005).

Dealing with uncertainty. Complex CPS need to be able to evolve and operate reliably in new and uncertain environments. An increasing number of these systems will also demonstrate emergent and unknown behaviors as they become more and more reliant on machine learning methodologies. In both cases, uncertainty in the knowledge or outcome of a process will require new ways to quantify uncertainty during the CPS design and development stages. Current methods for characterization and quantification of uncertainty are limited and inadequate. This is exacerbated by the limits of reliability and accuracy of physical components, the validity of models characterizing them, network connections, and potential design errors in software. Ongoing debate also surrounds the expectations for quantifying uncertainty, that is, attaining perfect results given the uncertainty of the physical world and approximations in design.

Measuring and verifying system performance. The difficulty of verifying performance, accuracy, reliability, security, and various other requirements impedes development and investment in CPS. Today's capabilities for verification and validation (V&V) of CPS are limited, time consuming, and costly, particularly when compared to development time. Two major challenges are the creation of methodologies to further the capabilities of V&V of complex systems, and the development of test beds and datasets to support a principled approach to the validation of complex CPS. If the design phase is more reliable, testing can become more informed and require less time. The evaluation challenges will become increasingly difficult at the larger scales and higher complexity expected for future CPS, which will have massive and interconnected sensor, actuator, and component networks.

Robots can be designed to accomplish tasks that were not possible before. At left, researchers at the National Renewable Energy laboratory are using new robots to fabricate and analyze thin-film solar photovoltaic cells with greater precision and speed than ever before possible. When working with silicon, the robot can build a semi-conductor on a six-inch-square plate in about 35 minutes—while analyzing anomalies and light absorption and preparing the next plates. The robot is able to complete tasks that previously required as many as five laboratories.

Credit: NREL 17161/Pat Corkery (NREL, 2010)

Metrics are essential for the evaluation of many aspects of CPS, from design to testing, deployment, and operation. Key areas where scientifically-based metrics are needed include complexity, adaptability, safety, security, privacy, resilience, reliability, and manufacturability. One major challenge is to design metrics with sufficient flexibility to be applicable to a wide variety of systems. Determining how to use metrics effectively presents another challenge. For example, if metrics for privacy are defined, then design methods for achieving privacy objectives must also be developed. There are also challenges in modeling privacy requirements so that a system can be validated against these requirements.

System design. The design of CPS is hampered by the limited ability to design at a systems-level. There are many factors impeding system-level design, such as the lack of formalized high fidelity models for large systems, insufficient ways of measuring performance, and inadequate scientific foundations (e.g., no 'science of systems'). A key factor is compositionality[2] and modularity in the design approach. Compositionality in CPS is impacted by the strong interdependencies of software and systems engineering and often limited by poor system design. For example, CPS development could be greatly facilitated if system components could be developed and verified in isolation and the system-level properties inferred from the properties of its parts. Designers of CPS aspire to this modular and compositional approach both in design and verification. However, it is only currently possible in narrow domains and with restricted, simple properties. Scientific and technical challenges to achieving compositionality include a lack of mathematical and system science foundations, formalized metrics, evaluation techniques, and methods for dealing with cross-cutting properties in the design space. Furthering the mathematical methodology for design space exploration is critical for allowing a principled approach to design complex architectures that are modular.

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[2] Compositionality in this sense means that system-level properties or performance can be derived from the local properties of individual components.

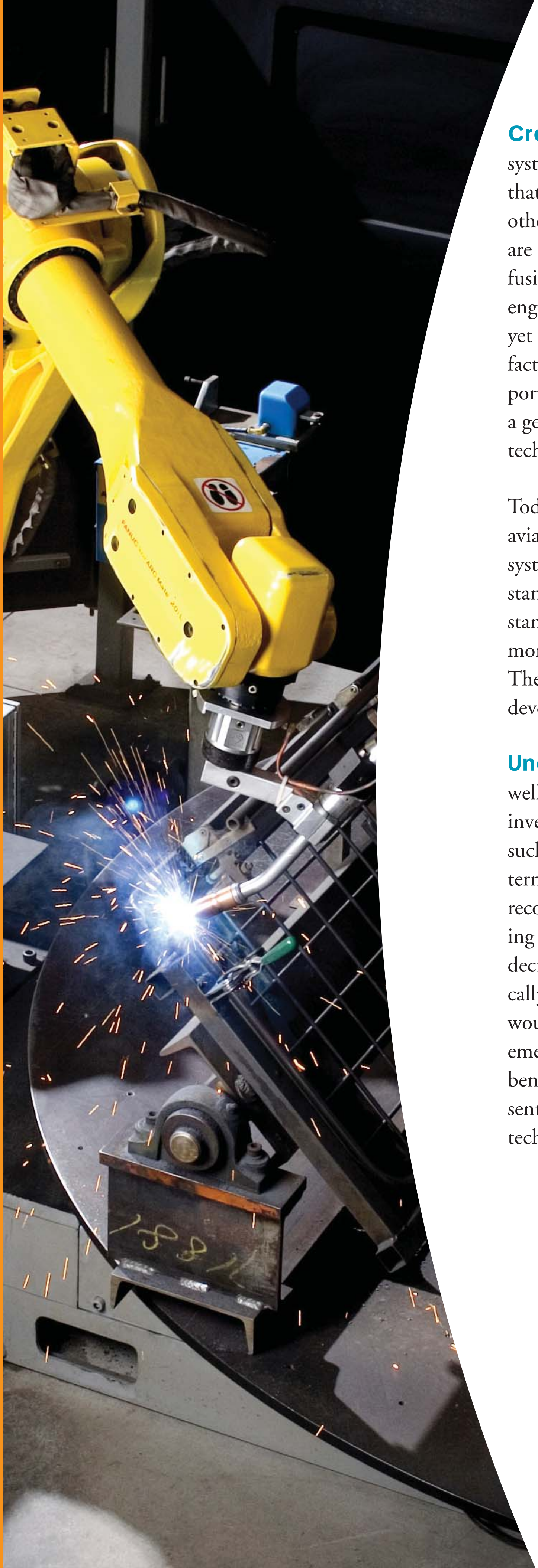
INSTITUTIONAL, SOCIETAL, AND OTHER CHALLENGES

Trust, security, and privacy. Assuring that systems are trustworthy, secure, and protect the privacy of information creates both technical and policy challenges. Cyber-security is a critical aspect of CPS on many levels, including the protection of national infrastructure, privacy of individuals, system integrity, and intellectual property. Recent foreign-based intrusions on U.S. computer systems, both government and commercial, illustrate the current vulnerabilities of the Internet and the rationale for addressing the global security of cyberspace (GAO, 2010). While cyber-security is a strong national priority and much progress has been made to ensure protection from cyber-attacks, CPS security raises a host of new challenges. For example, the combination of cyber and physical vulnerabilities may lead to attack models that are fundamentally new, hard to analyze, and carry substantial risk in maintaining physical integrity of critical systems.

Challenges to secure CPS include modeling the security threat, developing a formal approach to CPS vulnerability assessments, and designing evolutionary and resilient architectures to handle rapidly evolving cyber and physical threats. Along with security, maintaining privacy and confidentiality is an important aspect. Patients depending on implanted medical devices, for example, want protection of their identity and critical health information that could be exposed via the connection of their devices to monitoring networks. Industry requires protection of intellectual property as well as sensitive business and demographic information. Assuring the confidentiality of information and controlling the access and use of data are challenging, especially as the systems that collect, manage, and analyze information are rapidly evolving and in some cases need to operate in a distributed or relatively open environment.

Effective models of governance. The rapidly emerging global networks of CPS in energy, air traffic, transportation, cloud-based services and many others call for new governance models—both domestic and global—for providing standards, protocols, and oversight of systems that operate both in physical and cyber space. These new governance models are being explored but are not yet formalized. Governance could provide structured control and regulation for these systems and reduce liabilities that arise because of unwanted intrusions or other vulnerabilities. Governance is being discussed in many organizations, ranging from expert forums to treaty-based, decision-making bodies within governments. There is growing debate around these issues, with some pushing for increased intergovernmental oversight while others contend that the private sector can self-regulate via development of appropriate economic incentives, rules, and controls.

Many factories have robots as well as humans working in them; but the two do not always work well together. At the Massachussets Institute of Technology (MIT), researchers have come up with an algorithm that may make it easier and safer for humans and robots to work side-by-side, giving robots the tools to learn the preferences of a human coworker.
(MIT, 2012)



Creation of CPS business models. The extreme systems integration inherent in CPS is a disruptive technology that changes the status quo, creates new industries, and eliminates others. Transformation of traditional industries into those that are CPS-based is a complex, high risk process because it requires fusing the business models of the IT industry with those of engineering-based industries. These fused business models are not yet well-established and can be difficult to convey. A contributing factor is that economic and other data that could be used to support a business case are not well documented for CPS. The lack of a generic, proven business model can inhibit investments in new technologies and systems, in spite of the benefits.

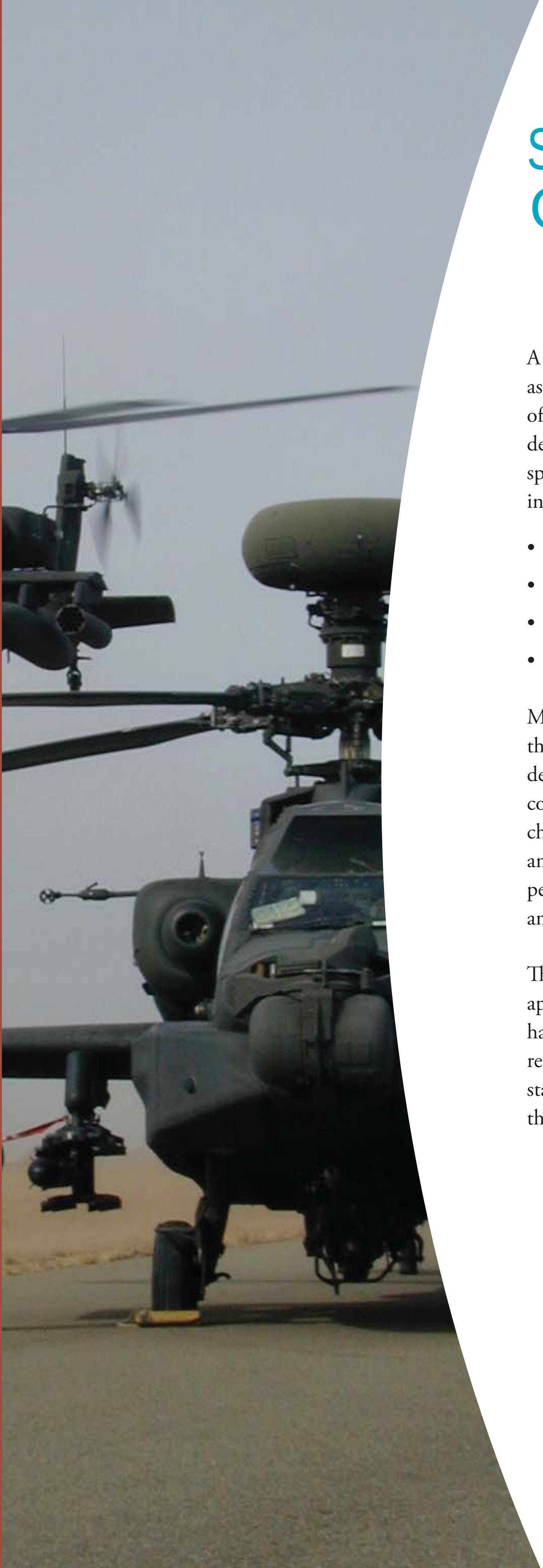
Today's examples of successful CPS business models include the aviation industry, which has incorporated cyber-physical avionic systems in modern airplanes. In this case, the industry understands the safety implications and has developed stringent safety standards and certification processes. As CPS become larger and more complex, the issues of business risk and liability also increase. There is an opportunity to mitigate this risk by sharing the cost of developing precompetitive and infrastructure technologies.

Understanding the value of CPS. CPS will benefit from well-developed infrastructure, which requires significant upfront investment. The value of CPS needs to be better understood for such investments to occur. R&D on CPS is often described in terms that are theoretical or include vocabulary that is not readily recognized. As a result, understanding the substance and applying the results of CPS R&D can be challenging for businesses, decision-makers, and end-users. Less academic and more strategically insightful ways of presenting CPS research, benefits, and risks would facilitate quicker and less expensive industry adoption of emerging technologies as well as improved understanding of the benefits and applications of CPS research. Some studies have presented methods to successfully articulate the value of CPS-related technology (BAH, 2010) but overall this remains a challenge.

Multi-disciplinary education and collaboration. The science and engineering of CPS are cross-disciplinary in nature, requiring expertise in computer science, mathematics, statistics, engineering, and the full spectrum of physical sciences—even extending into the arts such as ethics and psychology. Working across disciplines can be challenging, as it requires experts with highly diverse backgrounds to communicate on a common basis. In academia, there is a lack of concentrated, multi-disciplinary CPS education and research, as efforts have focused on the cyber or physical domains rather than a combination of the two. Significant challenges exist in creating multi-disciplinary CPS programs within the existing university structure, which has historically been divided into conventional disciplines (e.g., computer science, engineering, chemistry). Academia has previously confronted and successfully addressed similar challenges, resulting in the creation of new, vibrant industries such as bio-engineering.

Skilled workforce. CPS are sophisticated, advanced technology systems that require knowledge and training to design, develop, implement, and use. They require new skills and a new workforce. Creating and maintaining a skilled workforce to support future CPS is a significant challenge in its own right. CPS technology is a rapidly changing field and mechanisms for training and continuing education will be needed, as well as qualified instructors that stay abreast of emerging developments. Rigorous tools for workforce training in CPS are not currently available but could be highly effective in creating and maintaining a future workforce.

Research programs in CPS across the nation are leading to new discoveries and technologies while helping to educate a multi-disciplinary future workforce. A considerable portion of this research is conducted through U.S. government programs. For example, at the National Science Foundation (NSF) the CPS program provides support to universities to develop the core system science needed to engineer complex cyber-physical systems and fosters a research community committed to advancing research and education in CPS. At the Defense Advanced Research Projects Agency (DARPA), research is ongoing in several areas that will accelerate progress in CPS. These include adaptive vehicles, construction of high-assurance cyber-physical systems, and advanced model-based design methods for cyber-physical systems. Within agencies, research in CPS is underway on mission-oriented applications, such as the smart grid, intelligent buildings, and advanced medical devices. The activities in CPS across federal agencies are coordinated by the Networking and Information Technology R&D (NITRD) Senior Steering Group on CPS and the High Confidence Software and Systems Coordinating Group. This group fosters close communication and liaison among agencies, academia, and industry to address CPS R&D needs and facilitate interagency program planning in this field.



STRATEGIC R&D OPPORTUNITIES

A number of strategic R&D opportunities have been identified as critical to accelerating progress in CPS and overcoming some of the important challenges. These are illustrated in Table 2 and described in depth on the following pages. They cover the full spectrum of CPS design, development, implementation, and use, including:

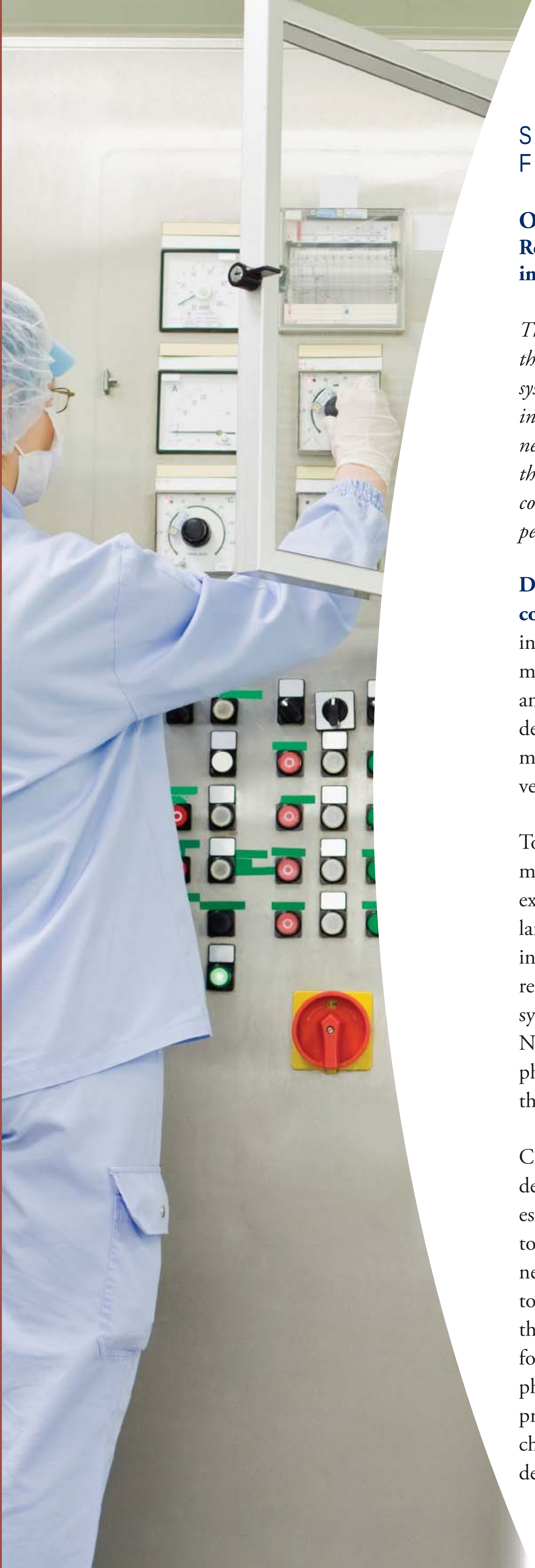
- Science and engineering foundations
- System performance, quality, and acceptance
- Applied development and deployment
- Workforce for continuing innovation in CPS

Measurement science and technology advances are woven throughout these opportunities and impact all stages of CPS development, from fundamental science and discovery to commercialization and deployment. For example, the major challenges of interoperability, interactions between humans and machines, understanding uncertainty, and evaluating performance all have strong roots in measurement science and technology.

The strategic R&D opportunities are recurring themes that appear in multiple technology areas and consequently would have far-reaching impact if addressed. They represent the priority research that has been identified as essential to advancing the state of CPS and reaping the potential benefits to society and the nation.

TABLE 2. STRATEGIC R&D OPPORTUNITIES FOR CYBER-PHYSICAL SYSTEMS

Robust, Effective Design and Construction of Systems and Infrastructure	**Science and Engineering Foundations**
Develop cost-effective system design, analysis, and construction	
Create domain-specific frameworks for design	
Manage the role of time and synchronization in architecture design	
Enable natural, more seamless human-CPS interactions	
Develop systematic inter-process and inter-personal communication for sensors and actuators	
Improved Performance and Quality Assurance of Computational and Physical Systems	**System Engineering**
Create methods for system-level evaluation, verification, and validation of cyber-physical systems	
Develop science-based metrics (e.g., security, privacy, safety, resilience, adaptability, flexibility, reusability, dependability)	
Effectively characterize and quantify reliability amidst uncertainties	
Effective and Reliable System Integration and Interoperability	**Applied Development and Deployment**
Create universal definitions for representing ultra-large heterogeneous systems	
Build an inter-connected and interoperable shared development infrastructure	
Develop abstraction infrastructure to bridge digital and physical system components	
Dynamic, Multi-Disciplinary Education and Training	**Workforce for Continuing Innovation in CPS**
Establish multi-disciplinary CPS degrees and resources	
Pursue dynamic training and certification in CPS	



SCIENCE AND ENGINEERING FOUNDATIONS

OPPORTUNITY
Robust, effective design and construction of systems and infrastructure

The development of CPS requires a new systems science foundation that can effectively integrate the elements of complex computational systems and processes with physical systems. Building blocks for design involve modeling, synthesis, simulation, and verification capabilities, new design tools and frameworks, ontologies and modeling languages that cross discipline boundaries, methods that enable scalability from concept to operation, and the means to ensure a range of functional, performance, safety, security, and reliability requirements.

Develop cost-effective system design, analysis, and construction methods—Before making large investments in a prototype CPS, it is important for designers to create a model to understand the dynamics of the many subsystems and their interactions, including the environment in which the deployed system must operate. Approaches are needed to develop models that are robust, semantically precise, reduce design and verification costs, and are reusable assets.

Today, building formalized, high fidelity models using mathematically based, formalized modeling languages is expensive, time consuming, and lacking tools and methods for large heterogeneous systems such as CPS. Such models should include an appropriate level of abstraction for the properties relevant to the system being designed, and be able to simulate system behavior under a range of conditions and assumptions. New, formal modeling methods are needed to create robust, physically relevant simulations that accurately recreate scenarios that CPS systems will experience in operation.

Creating more detailed models based on first principles is desirable but increases the number of parameters that must be estimated for model calibration—and the measurements required to fit these parameters can be difficult to obtain. Methods will be needed to recognize dominant parameters and apply abstractions to remove those that are less relevant from the model. For CPS this is especially important in developing models that are useful for studies at the systems level. Such models would evidence the phenomenological behaviors that emerge from the detailed first principles but balance abstraction and approximation, while characterizing these in light of the purpose they serve in system design.

The development and broad application of rigorous modeling tools could reduce the cost and duration of the design process, while improving design quality, performance, resilience, and dependability. Ultimately, domain-specific CPS design tools are required for aerospace, defense, transportation, medicine, and other industries that are built on standardized, configurable, and reusable tool suites for safety-critical and high-reliability systems.

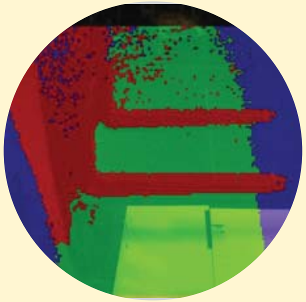
In addition to system modeling, major challenges include designing to conflicting requirements of system components (which can cause unintended consequences), a lack of tools or framework for co-designing heterogeneous components and systems, a lack of design standards to enable interoperability, and a lack of foundations to enable compositionality. Co-design is a particularly critical factor in the development of systems that face extreme demands and require high levels of performance, safety and reliability. Interoperability is a challenge that is exacerbated in CPS where there are large, complex, highly networked systems and components originating from multiple domains and disciplines.

Create domain-specific frameworks for design—Engineering methods for co-design and new standards are needed that offer a common semantic foundation for modeling languages for exchange and translation across domains. Creating domain-specific design frameworks that are built on generic but customizable methods and tools would contribute substantially to reducing time to market, development costs, and the complexity of the design process. Finally, the design and implementation of CPS needs to be understood as a process that includes not only evaluation and co-design, but incorporates the ability to build sophistication as the levels of need advance.

Manage the role of time and synchronization in architecture design—Management of time and synchronization is a complex yet critical issue for real-time CPS. Generally speaking, synchronization is the coordination of events that must occur to operate a system and the coordination of time between the cyber and physical dimensions of CPS. In computer science, for example, synchronization refers to the coordination of simultaneous threads or processes to complete a task. With a mobile device, synchronization occurs when the device communicates with applications on a personal computer or server (e.g., syncing or docking the device). For a vehicle system or manufacturing unit, time management occurs in reference to physical processes that have actual physical consequences. Today, timekeeping technologies such as Global Positioning System satellites and the Network Time Protocol provide real-time approximation of Coordinated Universal Time (world time standard) and are used for many synchronization applications.

Poor timing and synchronization can result in data loss, downtime, and performance failure. Major challenges include effective timing and synchronization of multiple tasks, developing a unified, common view of time, measuring time and time scales,

Standards for Autonomous Vehicles



3D measurement of overhanging obstacles in the path of an AGV or industrial vehicle

Credit: NIST

There is a growing acceptance of either partially or fully autonomous mobile equipment in the manufacturing area. However,in manufacturing facilities people and mobile equipment frequently move through the same cluttered and constantly-changing environment. Standards are essential to reduce the potential for injury and ensure a safe environment. The ability to control multiple autonomous vehicles from different manufacturers with different sensing capabilities is also a challenge.

and communicating time characteristics to system components or sensors. Overcoming these challenges could impact any data driven, real-time application. Simply put, effective time management will make it easier for applications to run in a time-correct manner. Tackling these challenges may require multi-layered architecture for time management.

Enable natural, more seamless human-CPS interactions—A better model of human strengths and weaknesses and the 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 optimized for human interventions will help manage risks and safety as systems move toward mixed-initiative modes of operation. They could also make humans more comfortable with and accepting of machine interactions.

Cognitive models are needed for human-machine behavior that can be validated and become adaptable to interactions as they occur. Cognitive models should also consider the growing number of autonomous CPS and that human-machine interactions are increasingly participatory. The requirement to couple unpredictable human behavior with the predictable, hard-wired behavior of machines and physical systems creates inherent difficulties in developing such models.

Develop systematic inter-process and interpersonal communication for sensors and actuators—A core component of CPS is the interpretation of data from various sources. CPS can contain highly connected and massive networks of sensors, actuators, and other devices that collect and act on many types of data. It is inherently difficult to measure the behavior of complex systems that contain multiple pathways for data interpretation, planning, and control.

The need to measure human interactions adds another level of complexity and uncertainty. A structured design and process integration method is needed to systematically relate multiple signals and symbols for inter-process and interpersonal communications across domains and applications. This would enable the development of less expensive plug-and-play sensors, create opportunities for modular, plug-and-play CPS, and lead to structured design and integration tools that reduce the cost and time to market of new systems.

SYSTEM PERFORMANCE, QUALITY, AND ACCEPTANCE

Opportunity
Improved performance and quality assurance of computational and physical systems

Development and acceptance of CPS in real-world applications will require assurances that these systems will perform as expected. Assessing both performance and quality involves V&V of the functioning of the entire system as well as individual components. The ability to infer the performance and quality of the entire system from its components can be advantageous—a property that is often referred to as compositionality—but is challenging to achieve in practice. The ability to compare performance and quality consistently across systems is essential but will require standardized, science-based metrics for safety, security, resilience, and other key parameters. Predicting operational performance and quality characteristics of CPS with high confidence (i.e., quantified assessment) is especially important for systems that operate autonomously or that directly impact human health and safety.

Create methods for system-level evaluation, verification, and validation of CPS—Evaluating the performance of CPS against system requirements is needed to facilitate acceptance, investment, and practical use of these systems. Some classes of CPS will require extensive and sustained investment (e.g., smart transportation, smart grid) and a solid understanding of potential performance to move technologies forward. System-level evaluation can be performed with V&V methods, especially for safety and trustworthiness requirements, but without standardized requirements, V&V is customized and costly. V&V is also challenged by an inability to effectively evaluate the whole system (how well components work in concert) since the performance of individual components (i.e., cyber, physical, and cyber-physical assemblies) does not necessarily translate to overall system performance. The difficulty of evaluating integrated components which interact in multiple temporal, spatial, and power scales also adds to the challenge. Cost effective methods of verifying and validating CPS could help decrease the cost of system integration, while increasing system reliability.

Foundations and infrastructure are currently lacking for evaluation and V&V of emerging CPS, but could be developed by leveraging methods and tools already in use in other systems. An integrated approach will be needed to enable greater understanding of the interactions between components, the role and impact of interfaces, and emerging system properties.

Autonomously operating systems (those with little human interaction or decision making) require certification processes that attest to assured system performance. Certification is a judgment that a system is adequately safe, secure, or meets other criteria for a given application in a set environment. To be valid, this judgment should be based on as much explicit and credible evidence as possible, with a foundation in good metrics including ways to measure complexity.

However, certification of complex, heterogeneous systems is extremely difficult, particularly in the design phase. Currently, system architecture, design, integration, and design space exploration are only robust enough to allow for building systems first, then testing and certifying. A challenge is to create methodology to enable compositional certification, which includes certification of components separately without the need for re-certifying after the system components are integrated.

The U.S. Department of Transportation (DOT) is exploring use of short-range communication in "smart" cars to improve vehicle safety. Intersection-connected vehicles can improve safety at busy intersections.

Credit: U.S. Department of Transportation

Another challenge is integrating design artifacts and analyses as evidence (including partial and historic) into the certification process.

Develop science-based metrics for system qualities (e.g., security, privacy, safety, resilience, adaptability, flexibility, reusability, dependability)—A universal set of science-based metrics is needed to evaluate and predict how CPS will perform with respect to key system-level properties such as security, privacy, safety, resiliency, and dependability. Dependability in this case means that a system is highly reliable when running, but also capable of effectively predicting, recognizing, and quickly covering from unforeseen events. While it is technically challenging to develop scientifically-based measurements for these broad concepts, they are fundamental to developing and deploying dependable CPS.

Metrics are needed for all phases of CPS development, from the early design stages through prototype, testing, deployment, operation, and operation regimes (e.g., before and after system changes or failures). Design-phase metrics will enable engineers to build in safety, resilience, and dependability in the early stages of development. During the testing stage, metrics can help confirm that prototypes exhibit the desired characteristics. In deployment and operation, metrics can measure and monitor system behavior and provide indications of emerging issues. The use of science-based metrics will lead to greater system reliability and safety, and allow for fewer, lower-impact failures. Metrics could also be formulated to specify a minimum level of reliability and a maximum level of uncertainty. Metrics are also essential to supporting business models and investment because they will enable clear definition of questions of liability.

Effectively characterize and quantify reliability amidst uncertainties—Reliable CPS must behave with some degree of certainty, even in a dynamic, unpredictable environment. Characterization and quantification of reliability provides information on how a system responds to expected and unexpected events, and aids in understanding the potential risks to system operation. The numerous heterogeneous components, disparate characteristics of the physical versus cyber elements, and operational uncertainties found in CPS complicate the characterization of reliability. Failures could occur in both cyber and physical components and affect other system components in complex ways. For example, multiple car accidents experienced by a smart traffic control system could unexpectedly overload the information processing capacity and its ability to respond in real time.

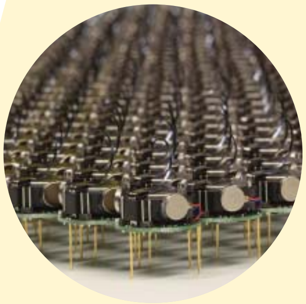
Today, formal methods for determining reliability are lacking for most CPS and need to be developed. Such methods should be able to adapt to changing inputs, be able to compose disparate systems, and provide reproducible results. Effective characterization and quantification of reliability will ensure that systems are robust and resilient, and provide better understanding of potential risks to system operation.

SYSTEMS OF ENGINEERING

Opportunity
Effective and reliable system integration and interoperability

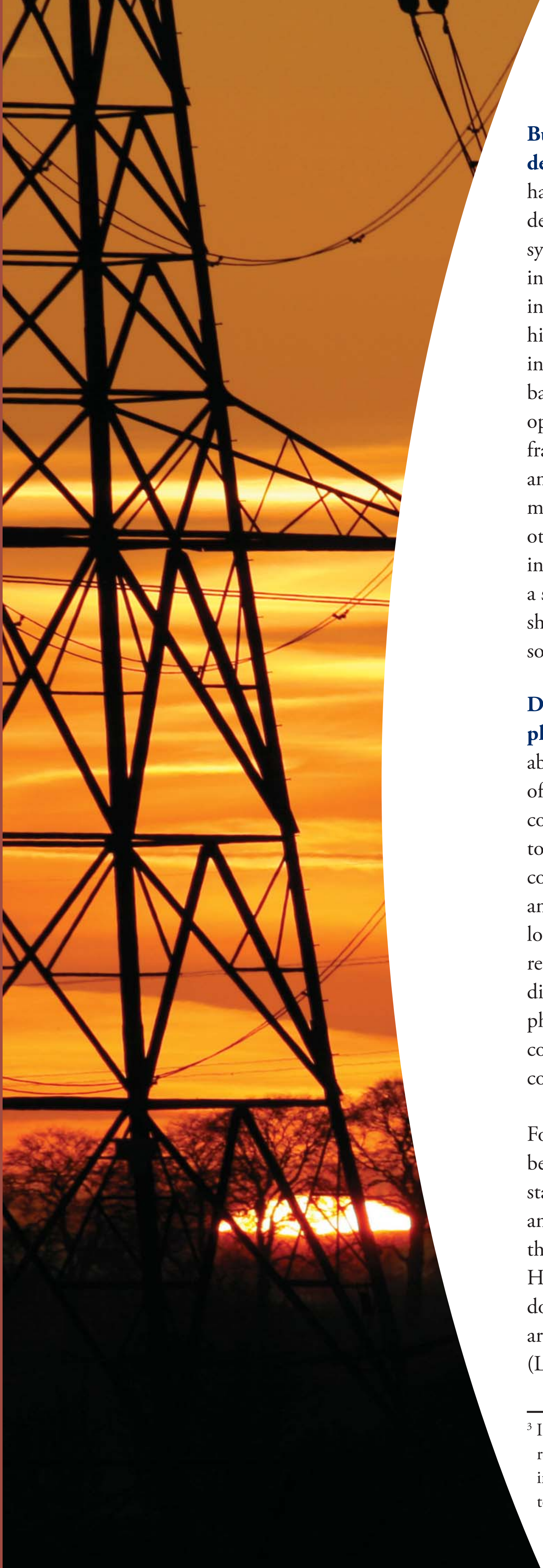
A unique characteristic of CPS is that they integrate computing and communication capabilities in the sensing and actuation functions of multiple components in the physical world. For CPS to operate dependably, safely, securely, efficiently, and in real time, some if not all components, whether cyber or physical, must be able to interact and communicate. These tightly coupled interactions require a high level of system integration and interoperability. System interfaces must be compatible and interactions should be governed by well-defined specifications; simulations of these interfaces should also use semantically precise modeling languages and vocabularies. In addition, individual components, as well as the total system, must be able to interact seamlessly with and respond to human operators and interventions.

Create universal definitions for representing ultra-large heterogeneous systems—Standard methods and shared conceptualization are needed for aligning the description of large, heterogeneous groups of system components, characteristic of many CPS, including specifications for technology, human elements, time, and space. Standard methods should include ways to universally and visually represent overall system behavior and performance of the integrated components. The objective of shared conceptualization is to provide standard definitions and/or ways for readily translating or mapping between systems that can be embraced by both industry users and suppliers of technologies and subsystems. Developing agreements and methods to align CPS is complicated by the heterogeneity and disciplinary isolation of vocabularies and modeling languages for different aspects of large, heterogeneous systems. Challenges include an inability to measure the presence and correctness of complete system requirements and behavior of components within the context of the overall system. The key parameters that need to be universally defined must also be identified; this will require cross-disciplinary interactions among the cyber and physical sciences communities. If successfully developed, a consistent set of definitions could lower currently high integration and development costs, and provide a means to clarify top to bottom system behavior.



Credit: Michael Rubenstein, Harvard School of Engineering and Applied Sciences. (Harvard, 2012)

Computer scientists and engineers at Harvard University have created bug-like ‘Kilobots’ that can interact and coordinate as a team, making it easier for researchers to test collective algorithms on hundreds or even thousands of tiny robots. In one demonstration 25 Kilobots displayed team- or swarm-like behaviors such as foraging, formation control, and synchronization. The robots are modeled after insects like ants and bees that participate in coordinated group behaviors such as food foraging, transporting large objects, and nest building. Support for this work was provided by the National Science Foundation and the Wyss Institute.



Build an inter-connected 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 successfully integrating their systems with external systems to ensure high levels of performance and functionality. Building an infrastructure foundation that is interoperable, contains a balance of open source and proprietary information, and operates under the same standards will provide a protected framework from which interoperability issues are minimized and system development could be profitable. For example, the manufacturers of autonomous cars will have to work with each other as well as with the developers of the traffic regulating infrastructure to develop functional products. Building from a standard foundation would save time and cost through the sharing of critical information, while avoiding the liability of a solely proprietary product.

Develop abstraction infrastructure to bridge digital and physical system components—Innovative approaches to abstractions[3] and architectures that enable seamless integration of digital and physical systems for control, communication, and computation are needed for development of CPS. These need to support and facilitate cost-effective integration. Recently, computers and networks have pushed ahead into monitoring and controlling a variety of physical processes including feedback loops. In these systems, issues arise from the safety and reliability requirements of the physical components that are qualitatively different from those of the computing components. Because physical components are qualitatively different from software components, standard abstractions that are only physical or only computational fail when used in CPS.

For example, in communication networks, interfaces have been standardized between different layers of the network stack to allow heterogeneous systems to operate in a plug-and-play manner. This has created many opportunities for the proliferation of innovative technology and the Internet. However, today's science and engineering knowledge base does not include similar standardized abstraction layers and architectures to support integration and interoperability in CPS (Lee, 2012).

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[3] In computer science, abstraction is the process of finding an alternate representation that embodies less detail but maintains the properties of interest of the original representation. As such, an abstraction is always relative to a set of properties.

The objective is to develop a collaborative, open, and highly-evolvable abstraction framework and infrastructure that spans multiple domains and applications. The outcomes would be a greater confidence in the integration of cyber and physical components, the ability for system-wide and compositional evaluation, and greater openness of systems.

WORKFORCE FOR CONTINUING INNOVATION

Opportunity

Dynamic, multi-disciplinary education and training

Building and sustaining a workforce capable of developing, innovating, and operating future CPS will require significant enhancements in engineering curricula, renewed emphasis on systems sciences and engineering, and an increased emphasis on multidisciplinary research. Dynamic training programs for engineers, operators, and users of these systems will create pathways for keeping the workforce on top of new developments as they emerge.

Establish multi-department CPS degrees and resources—University systems have historically been divided into traditional disciplines (e.g., computer science, electrical engineering). To build and sustain a future workforce for CPS will require the incorporation of multi-disciplinary and targeted educational programs within the existing university structure. A prototype program could be developed in coordination with the National Academy of Engineering, the Accreditation Board for Engineering and Technology, and university organizations supporting research in CPS. Development of new textbooks and courses relevant to the curricula would need to occur in parallel. The objective is to create a more formal teaching and training approach in CPS leading to a new generation of scientists and engineers qualified and interested in working in this field. CPS educational programs will also appeal to students with an interest in new media by providing opportunities for gaining knowledge in emerging IT modalities.

Pursue dynamic training and certification in CPS—CPS is a dynamic field that requires continuous education and retraining. A number of approaches are possible, including development of CPS degrees, certifications, and accreditations, onsite training programs, or robust internships that allow for multi-disciplinary training. For example, a joint industrial and academic certification committee could be formed to develop a prototype test certification and accreditation for CPS training.

Credit: Midwest Center for Structural Genomics

Twenty years ago, it took a week to purify a single protein. Today, robotic chromatography systems are making it possible to dramatically reduce the time needed for protein purification. Above, Irina Dementieva, a biochemist, and Youngchang Kim, a biophysicist and crystallographer, work with the first robot of its type in the U.S. to automate protein purification.

CONCLUSION

The potential of CPS to change every aspect of life is enormous. Concepts such as autonomous cars, robotic surgery, intelligent buildings, smart electric grid, smart manufacturing, and implanted medical devices are just some of the practical examples that have already emerged. These systems all rely on a computational core that is tightly conjoined and coordinated with components in the physical world.

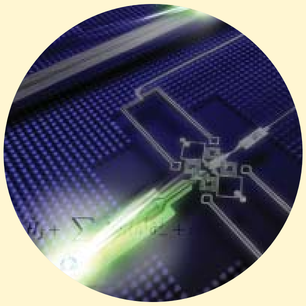
As systems evolve they will shift the reliance on human decision making into new, more strategic aspects and will increasingly rely on operationalizing human knowledge through computational intelligence. This can yield many advantages, such as the computational core detecting and responding faster than humans, being more precise and less prone to fatigue than humanly possible, or expanding the capabilities of the system beyond the operator's skills. As we become more dependent on CPS, the challenge is to design systems that are dependable and reliable—systems we can trust our lives with.

This report is a call to action. Progress has been made, but there are many challenges ahead. Overcoming these challenges creates exciting opportunities to ensure that the U.S. is a technology leader in the field of CPS with a globally competitive edge. Significant challenges outlined in this call to action include:

- **Robust, effective design and construction of systems and infrastructure**—key to designing dependable systems from the ground up and reducing cost and time to market;
- **Improved performance and quality assurance**—essential for spurring future investment, acceptance, and use of innovative systems that promise to provide revolutionary improvements to conventional practice;

- **Effective and reliable system integration and interoperability**—required for highly connected and networked components to work together effectively as a total system; and

- **Dynamic, multi-disciplinary education and training**—will make possible sustained growth and innovation and spawn a new generation of entrepreneurs, as well as the next generation of cyber-physical systems.



Credit: NIST, illustration by Michael Kemper

Artist's rendition of superconducting quantum cable, which could enable future quantum computers to search databases and perform other tasks at exponentially higher speeds than today's most powerful computers.

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