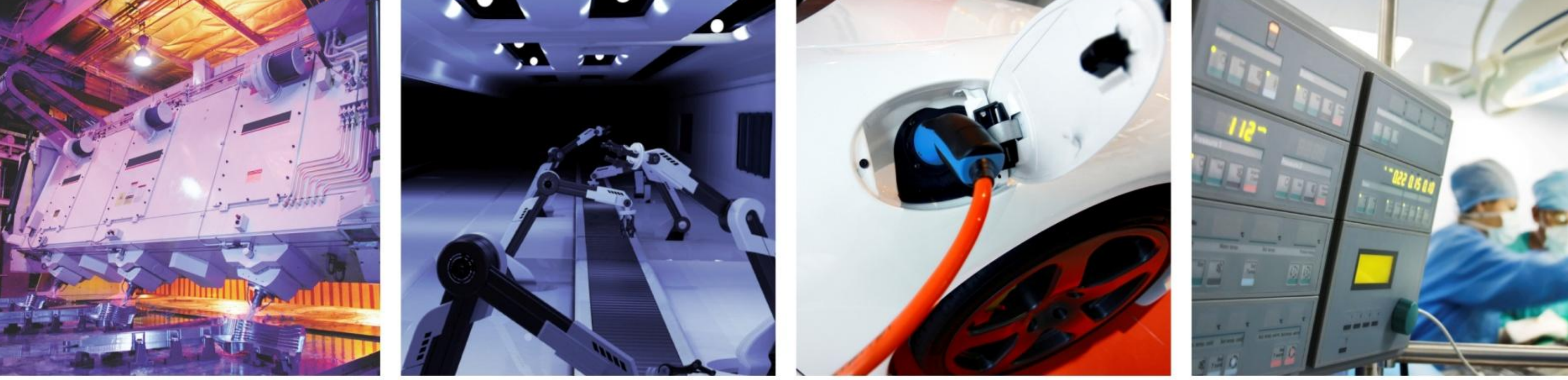

Cyber-Physical Systems: Situation Analysis of Current Trends, Technologies, and Challenges

Smart System Technologies for Manufacturing, Power Grid and Utilities, Buildings and Infrastructure, Transportation and Mobility, and Healthcare

DRAFT
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Prepared by
ENERGETICS INCORPORATED
Columbia, Maryland 21046

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Table of Contents

Introduction

Cyber-physical systems (CPS) are smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components. CPS and the innovative products and technologies they support have the potential to create a source of competitive advantage for the U.S. economy in the 21st century.

The President’s Council of Advisors on Science and Technology (PCAST) in a 2007 report[1] noted that improved methods to develop CPS “are a national priority for Federal R&D,” and are needed to assure high levels of reliability, safety, security, and usability. Because CPS support real-time behavior and must perform with ultra-high reliability, requirements for CPS are more stringent and, in some cases, entirely different than those required for other automated systems.

The PCAST recommended that federal R&D agencies should “strengthen existing programs or create new ones that cross disciplinary boundaries to accelerate work in this area.” A December 2010 PCAST report further reinforces and expands the emphasis on networking and information technology (IT) systems integrated with and acting upon the physical world, particularly as applied to energy, transportation, health care, and homeland security.[2]

In view of recent reports and the potential opportunities for economic growth and competitiveness represented by CPS, the National Institute of Standards and Technology (NIST) is undertaking efforts to explore the technology and measurement barriers in this important field. This situation analysis is an integral part of that effort. It provides a high-level perspective on the scope of CPS in selected sectors, current drivers for CPS development and use, state-of-the-art in technology, broad challenges, and measurement issues. The information presented here was obtained through a comprehensive review of published literature in the field. It will provide background material for expert participants at planned future workshops and roundtable activities designed to gain real-time inputs on the critical measurement challenges and gaps that could impede development of future cyber-physical systems.

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[11] President’s Council of Advisors on Science and Technology, *Leadership Under Challenge: Information Technology R&D in a Competitive World*, PCAST report (Washington, DC: Executive Office of the President of the United States, August 2007), http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-07-nitrd-review.pdf.

[22] President’s Council of Advisors on Science and Technology, *Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology* (Washington, DC: Executive Office of the President, December 2010), http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf.

Scope of the Report

This situation analysis is organized around five sectors of the economy: 1) manufacturing, 2) smart grid and utilities, 3) buildings and infrastructure, 4) transportation and mobility, and 5) healthcare, as shown in Table 1. These sectors were chosen because they are considered prime areas of opportunity for CPS as these systems are already emerging in many applications.

Table 1. Sectors Covered in the CPS Situation Analysis

Smart Manufacturing	Smart, pervasive application of networked information for demand-dynamic economics, integrated computational materials, enterprise and supply chain performance, and broad-based workforce engagement; manufacturing robotics that work safely with people in shared spaces; computer-directed metal-based additive manufacturing.
Smart Grid and Utilities	Systems for more efficient, effective, safe and secure generation, transmission, and distribution of electric power, integrated through the Smart Grid; smart systems applied to water and pipeline systems.
Smart Buildings and Infrastructure	Smart net-zero energy buildings for energy savings while improving indoor air quality; actively monitored, controlled, and optimized buildings, bridges, dams, and other structures.
Smart Transportation and Mobility	Vehicle-to-vehicle communications for enhanced safety and convenience ("zero fatality" highways), drive-by-wire, autonomous vehicles; next generation air transportation system (NextGen); autonomous vehicles for off-road and military mobility applications.
Smart Healthcare	Life-supporting micro-devices, embedded in the human body; wireless connectivity enabling body area sensor nets; mass customization of heterogeneous, configurable personalized medical devices, and natural, wearable sensors and benignly implantable devices.

The following chapters discuss each of the five sectors and include the following:

- An overview of how CPS can be applied in that sector
- Key drivers for CPS technology and use, including major business, societal, political, technological, and other drivers/opportunities
- State-of-the-art in technology and selected research and development efforts
- Broad challenges and barriers, both technical and non-technical
- Measurement problems and impediments that could hinder technology innovation

Smart Manufacturing

INTRODUCTION

Smart manufacturing combines technology, knowledge, information, and human ingenuity to develop and apply "manufacturing intelligence."[3] It comprises the smart use of networked information for demand-dynamic economics; integrated computational materials; enterprise and supply chain performance and broad-based workforce engagement; manufacturing robotics that work safely with people in shared spaces; and computer-directed, metal-based additive manufacturing.

Smart manufacturing allows for the complete optimization of a manufacturing plant, where information can be communicated among industrial machines, in real-time. Examples of smart manufacturing applications include the following:[4]

- Connections between the manufacturing plant floor and the manufacturing supply chain (enterprise business systems, suppliers, and customers)
- Self-monitoring manufacturing equipment that can report its own health and productivity status and communicate with maintenance staff requesting remedial action
- Flexible and adaptable manufacturing equipment that responds to consumer preferences

Cyber-physical systems (CPS) enable smart manufacturing applications via large-scale interconnected systems of heterogeneous components that integrate computation with industrial production processes. These control systems provide independent control of production process through the use of control loops, in which sensors communicate with actuators and processors, interacting with the process throughout the production line.[5] These highly integrated production networks can greatly improve the efficiency of industrial processes.

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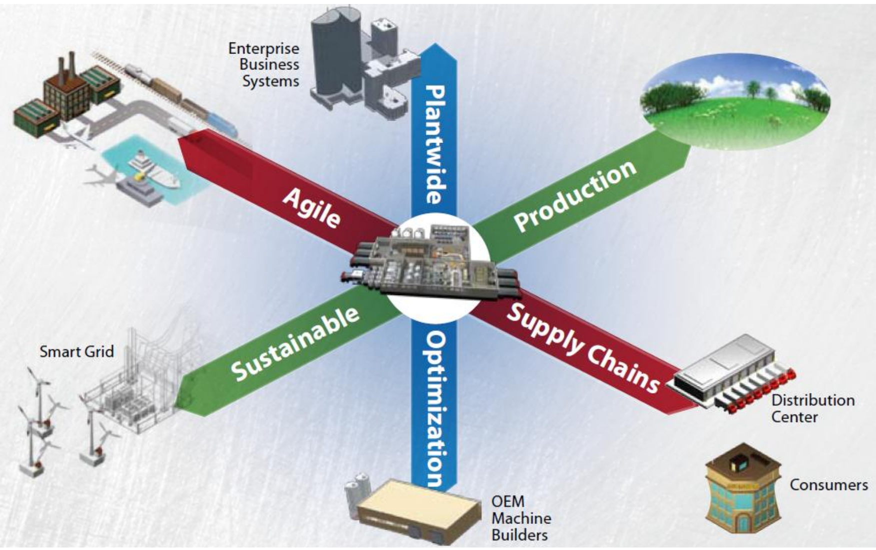
[3] Rockwell Automation., *What is Smart Manufacturing?* (Milwaukee, WI: Rockwell Automation, n.d.), http://www.rockwellautomation.com/news/get/TIMEMagazineSPMcoverstory.pdf.

[4] Keith D. Nosbusch, *Smart, Safe, Sustainable Manufacturing: A New U.S. Industrial Strategy for Competitiveness.* (Milwaukee, WI: Rockwell Automation, July 2009.), http://www.rockwellautomation.com/news/get/KDNSmartSafeandSustainableManufacturning.pdf.

[5] Yunbo Wang, Mehmet C. Vuran, and Steve Goddard, *Cyber-physical Systems in Industrial Process Control* (Lincoln, NE: University of Nebraska-Lincoln, 2008), http://sigbed.seas.upenn.edu/archives/2008-01/Wang.pdf.

Figure 1. Graphical Representation of the Components of Smart Manufacturing



Source: Rockwell Automation. *What is Smart Manufacturing?* *http://www.rockwellautomation.com/news/get/TIMEMagazineSPMcoverstory.pdf*

One example to how CPS can be applied to manufacturing is given by Yunbo Wang et al. in the case of a rice production line. This type of process consists of multiple stages, and each stage has an embedded control system to make control autonomous. Applied CPS for a large-scale system such as this one can provide interactive control and thus improve efficiency and reliability so that the control loops span several stages instead of being restricted to a single stage.[6]

Current and Potential Applications of Smart Manufacturing[a]

- Digital control systems with embedded, automated process controls, operator tools, and service information systems can optimize plant operations and safety.
- Asset management using predictive maintenance tools, statistical evaluation, and measurements could maximize plant reliability.
- Smart sensors could detect anomalies and help avoid abnormal or catastrophic events.
- Smart systems integrated within the industrial energy management system and externally with the smart grid could enable real-time energy optimization.

[a] https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf

KEY DRIVERS

The world's manufacturing sector spearheads innovation and has a powerful multiplier; for every dollar of manufacturing activity an additional $1.40 in related business activity is created, including the product supply chain, product distribution, and other related services.[7] The U.S. manufacturing sector creates high-value jobs, allows for advancements in national defense, improves the domestic economy by increasing exports, and improves the economic growth of related sectors.[8]

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[6] Ibid.

[77] Keith D. Nosbusch, *Smart, Safe, Sustainable Manufacturing: A New U.S. Industrial Strategy for Competitiveness* (Milwaukee, WI: Rockwell Automation, July 2009), http://www.rockwellautomation.com/news/get/KDNSmartSafeandSustainableManufacturning.pdf.

[8] U.S. Manufacturing Competitiveness Initiative., *Ignite 2.0: Voices of American University Presidents and National Lab Directors on Manufacturing Competitiveness* (Washington, DC: Council on Competitiveness, June 2011), http://www.compete.org/images/uploads/File/PDF%20Files/Ignite_2.0_.pdf.

Manufacturing is also a key element to domestic innovation. The U.S. manufacturing sector faces increasing global competition and could benefit from industrial innovation and improved productivity. Although the United States is currently the largest manufacturing economy, the 2010 Global Manufacturing Competitiveness Index places it fourth in manufacturing competitiveness, lagging behind China, India, and the Republic of Korea. That same index forecasts that by 2015, the United States' rank will decline to fifth, as Brazil increases its competitiveness.[9] These advancing economies continue to develop their manufacturing sectors with strong support from their education sector, infrastructure, and government policies that promote business growth.[10]

Some of the benefits of CPS in manufacturing are a reduced time to market; leveraging of dynamic demand-driven economics by enabling agile response to consumer demand; providing companies a global competitive edge while also driving higher export markets; as well as the possibility for integrated energy management and the smart grid.[11] CPS can increase U.S. manufacturing competitiveness by improving the productivity and flexibility of industrial processes, thereby reducing production costs.[12] Advanced factories that are highly automated can have the ability to prevent work-related injuries and can also improve product quality and reliability before the product is transported outside of the factory. Smart manufacturing can even help identify recalls faster and efficiently pinpoint potential problems during inspections.[13] Real-time handling and comprehensive tracking of the factory and supply networks will help guarantee safe and reliable products and processes, increasing both consumer and manufacturing operator confidence.[14]

Importance of U.S. Manufacturing:

- Represents the world's largest manufacturing economy and produces 21% of the world's manufactured products.[a]
- Generates $1.6 trillion of value each year, which represents more than 11% of U.S. gross domestic product.[b]
- Supports about 18.6 million jobs, of which 12 million are employed directly in manufacturing.[c]
- Performs two-thirds of all domestic R&D.[d]

Source: National Association of Manufacturers, *Facts About Manufacturing*, based on the following:

[a] United Nations, Statistics Division (2009), http://unstats.un.org/unsd/snaama/selbasicFast.asp

[b] U.S. Bureau of Economic Analysis, Industry Economic Accounts (2009), http://www.bea.gov/iTable/index_error_GDPindyIO.cfm

[c] National Association of Manufactures, The Facts About Modern Manufacturing (2009), http://www.nam.org/Statistics-And-Data/Facts-About-Manufacturing/Landing.aspx ;U.S. Bureau of Labor Statistics. http://www.bls.gov/data/;

[d] National Science Foundation (2008). *U.S. Businesses Report 2008 Worldwide R&D Expense of $330 Billion: Findings from New NSF Survey, http://www.nsf.gov/statistics/infbrief/nsf10322/*

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[9] Deloitte., *2010 Global Manufacturing Competitiveness Index*. (Washington, DC: Council on Competitiveness, June 2010), http://www.deloitte.com/assets/Dcom-Global/Local%20Assets/Documents/Manufacturing/dtt_2010%20Global%20Manufacturing%20Competitiveness%20Index_06_28_10.pdf.

[10] U.S. Manufacturing Competitiveness Initiative, *Ignite 2.0: Voices of American University Presidents and National Lab Directors on Manufacturing Competitiveness* (Washington, DC: Council on Competitiveness, June 2011), http://www.compete.org/images/uploads/File/PDF%20Files/Ignite_2.0_.pdf.

[1111] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[12] G.,. Tassey, *R&D and Long-Term Competitiveness: Manufacturing's Central Role in a Knowledge-Based Economy* (Gaithersburg, MD: National Institute of Standards and Technology, 2002.), http://www.nist.gov/el/msid/infotest/upload/SIMCAprogram2012.pdf.

[13] Keith D. Nosbusch, *Smart, Safe, Sustainable Manufacturing: A New U.S. Industrial Strategy for Competitiveness* (Milwaukee, WI: Rockwell Automation, July 2009), http://www.rockwellautomation.com/news/get/KDNSmartSafeandSustainableManufacturning.pdf.

[14] Smart Manufacturing Leadership Coalition., *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

One of the main drivers in manufacturing productivity is increased automation and advances in information technology, which lead to competitiveness and economic prosperity.[15] Digital computing and communications is increasing in manufacturing plants, allowing for new opportunities for the adoption of smart manufacturing techniques and technologies. Smart manufacturing used in the innovation, planning, designing, operating, and maintaining of manufacturing facilities can support more agile operations and accelerated product and business cycles.[16] Increased integration in manufacturing systems can provide pathways to manufacture materials and products based on global and domestic needs.[17]

As businesses strive to achieve higher levels of sustainability and safety, advances in smart manufacturing can help to meet these goals while increasing performance.[18] By increasing plant efficiency, CPS can also reduce materials waste and reduce energy use and environmental emissions.[19] Manufacturing intelligence can decrease the use of precious resources by increasing efficiency and minimizing the use of energy, water, materials, labor, and time. Improving the sustainability of critical U.S. industries such as clean energy and medicine will help to reduce the impacts on the environment and climate.[20]

The development and implementation of new technology in future U.S. manufacturing can lead to high-value jobs, wealth creation, sustained economic growth, and national security. But in order to do so, there must be a shift from traditional manufacturing of low-cost, volume production to high-value product areas based on innovation.[21] CPS in manufacturing, which take advantage of system simulation, optimization software, and other smart tools and systems will enable more efficient and integrated manufacturing. Competitiveness, efficiency, and sustainability all stand to increase with newly innovated, planned, designed, operated, maintained, and managed smart manufacturing facilities and systems.[22]

Manufacturing industries are being shifted towards just-in-time processing and accelerated introduction of innovative products. Programmable manufacturing facilities produce customizable products as opposed to large quantities of products. In order to keep up with global competition in an environment where energy costs and supplies are uncertain, new CPS technologies must be embraced.[23] Highly optimized manufacturing plants and supply systems will be able to easily adjust to fluctuations or arising customer demands.[24]

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[15] Keith D. Nosbusch, *Smart, Safe, Sustainable Manufacturing: A New U.S. Industrial Strategy for Competitiveness* (Milwaukee, WI: Rockwell Automation, July 2009), http://www.rockwellautomation.com/news/get/KDNSmartSafeandSustainableManufacturning.pdf.

[16] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[17] Ibid.

[18] Ibid.

[19] Rockwell Automation, *What is Smart Manufacturing?* (Milwaukee, WI: Rockwell Automation, n.d.), http://www.rockwellautomation.com/news/get/TIMEMagazineSPMcoverstory.pdf.

[20] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[21] National Institute of Standards and Technology, "Extreme Manufacturing – What are the technology needs for long-term US Manufacturing Competitiveness?" accessed, December 2010, http://www.nist.gov/el/extrememanu.cfm.

[22] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[23] Ibid.

[24] Ibid.

CURRENT STATE OF THE TECHNOLOGY

Manufacturing today occurs in traditional factory-situated shop floors where the focus is on mass production of physical components and the system is typically not completely integrated. Although robotics have become more common and improved productivity of some tasks, workflow automation is hindered by high costs of maintenance and investment. Many aspects of the production process, including design, manufacturing, and supply, are increasingly outsourced to effective labor markets overseas. China, South Korea, Indonesia, India, and Europe continue to invest in research and innovation as well as education of a skilled workforce while the United States falls behind due to lack of technology investments among other factors.[25] Since manufacturing is growing globally and declining in the United States, there is the possibility of a threat to national security.[26]

CPS science and technology can provide many possibilities for innovation in the manufacturing industry through smart products and production and lifecycle design for product safety, security, and sustainability. The scope of areas that benefit from cyber-physical engineering concepts, infrastructure, and tools is broad and includes homes, military logistics and weapons systems, healthcare, clothing, agriculture, food processing and preparation, and automotive and air vehicles. There is a trend towards the demand for products that have safe, dependable, and secure “plug and play” integration of cyber and physical components thus leading towards the possibility of being highly customizable. Mass customization in manufacturing currently only involves minimal flexibility to alter fixed parameters.[27] Manufacturing in the United States should move towards mass customization in order to enable tailoring of products based on real-time customer input while maintaining cost and production efficiency.[28] The increased innovation in materials such as carbon-fiber composites, conductive polymers, metal-ceramic compounds, among others, enables the creation, local sourcing, and production of smart products. [29]

The vision for smart manufacturing is for all aspects of manufacturing to be highly integrated, from plant operation to supply chain. The entire life cycle of a product would be enabled to be tracked, including aspects such as processes and resources, leading to manufacturing environments that are flexible and can optimize performance and efficiency.[30] Advances in CPS can help reduce the time-to-market for products and systems, while promoting innovation, competition, and resilience in supply chains. These advances can allow a more flexible optimization of cost and markets since production could be located near materials, technology skill centers, or consumers.[31] The future workforce of manufacturing will have core knowledge and skills that can be applied to innovation and research.[32]

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[25] Networking and Information Technology Research and Development ., “Winning the Future with Science and Technology for 21st Century Smart Systems” (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.

[26] Ibid.

[27] Ibid.

[28] Alan L. Jacobson, “Working Paper: NIST Extreme Manufacturing Working Paper” (Malibu, CA: HRL Laboratories, LLC, January 2011), http://www.nist.gov/el/upload/Jacobsen.pdf.

[29] Networking and Information Technology Research and Development , “Winning the Future with Science and Technology for 21st Century Smart Systems” (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.

[30] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[31] Networking and Information Technology Research and Development , “Winning the Future with Science and Technology for 21st Century Smart Systems” (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.

[32] Ibid.

Table 2. Evolving CPS Landscape in Manufacturing[37]

	Current	Future
CPS in manufacturing	Computer-controlled machine tools and equipment; robots performing repetitive tasks, fenced off from people	Smarter, more connected processes for agile and efficient production, manufacturing robotics that work safely with people in shared spaces, computer-guided printing or casting of composites
CPS in materials	Relatively few, highly specialized applications of smart materials—predominantly passive materials and structures	Electronics provide versatility without recourse to a silicon foundry; emerging materials such as carbon fiber and polymers offer the potential to combine capability for electrical and/or optical functionality with important physical properties (strength, durability, disposability)

The state of robotics in today's manufacturing industry as designed to be precise and repeatable, operate in only structured environments, and have limited application. Integration of robotics is expensive, and can cost five to ten times the capital cost. In some cases, robotic systems in factories are unsafe for people to be around, leading to a separation between the two types of workers.[33]

Table 2 shows the current and future vision of CPS in manufacturing and in materials.

One possible application of smart manufacturing that shows a shift towards the production of customizable, more accessible manufacturing is the development of three-dimensional (3D) printing and additive manufacturing. A 3D printer creates objects by taking a digital file and then deposits layers of material until the object is completed. Today, there are 3D printers that are used to make prototypes during the design process, or even production of small amounts of products. One of the benefits of 3D printing is the idea of additive manufacturing or that the product is created using only the material that is needed. Also possible is the ability to easily make repairs on-site.[34] Reduction in the amount of material used can help to reduce costs, waste, and weight, while still maintaining quality. Although these printers are not extensively used in traditional manufacturing environments because of cost and time restraints among others, there is the possibility of these types of machines being integrated into manufacturing systems.[35] A 3D printer that is marketed towards consumer use will soon be available for purchase, where objects can be created from scratch or customized from existing designs and then sent to the printer. Also available is a platform where applications or designs for products can be purchased or sold.[36]

There is a current trend in today's manufacturing towards "converged modular automation," in which systems are built of modular cyber-physical components. These components have their own embedded controller and are all connected by a network that allows for a supervisory controller to gather information and for information exchange from peer-to-peer.[38] The advantage of such modular

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[33] Rodney. Brooks, *Extremely Agile, Adaptive, Responsive and Robust Manufacturing*. January 2011.
[34] Networking and Information Technology Research and Development , "Winning the Future with Science and Technology for 21st Century Smart Systems" (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.
[35] "The Printed World" *The Economist*, February 10, 2011., http://www.economist.com/node/18114221.
[36] Christina. DesMarais, "3D Printing Draws Closer to Mainstream with Cubify."," *PCWorld*., January 8 2012., http://www.pcworld.com/article/247481/3d_printing_draws_closer_to_mainstream_with_cubify.html.
[37] Networking and Information Technology Research and Development , "Winning the Future with Science and Technology for 21st Century Smart Systems" (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.
[38] D. M. Tillbury, "Modeling and Verification of Distributed Cyber-Physical Systems: Challenges, Research Needs, and Possible Roadmap" (Ann Arbor, MI: The University of Michigan, October 5, 2006), http://www.truststc.org/scada/papers/paper16.pdf.

automation systems is that they can be more reconfigurable than custom-designed systems, but modules that have embedded controllers are more complex than a typical system and requires additional testing and validation before it can be applied.[39]

A study from the University of Michigan identified the following research needs in the areas of modeling and verification of mechanical and computing systems (direct quote from report):[40]

- Automatically generating models of physical systems that can interface with models of computing system operation
- Specifications of model correctness and uncertainty, and methods for validating these specifications
- Abstraction methods for modules, to manage complexity
- Specifications for re-configurability, and methods to validate these specifications
- Specifications (interface models) that guarantee interoperability
- Certification methods to guarantee conformance with international standards
- Verification techniques for modular CPS

The study also identified a possible roadmap to achieve these needs, describing steps in specific order:[41]

1. Survey of existing techniques for modular design in mechanical and software domains
2. Mapping potential synergies from mechanical and software design domains to cyber-physical systems
3. Definition/identification of ‘challenge problem’
4. Design and construction of testbed, with physical modules distributed at multiple sites (simulations at all sites)
5. Definition of interface specifications for modules
6. Demonstration of module operations, validation of conformance with interface specification
7. Validation of simulation model in normal and fault modes
8. Demonstration of module interoperation in normal mode
9. Demonstration of module interoperation in fault mode, and fault recovery using unified HMI
10. Definition of reconfiguration scenario that was not originally envisioned
11. Demonstration of reconfiguration through adding a new module and/or rearranging existing modules

BROAD CHALLENGES AND BARRIERS

To realize the benefits of smart manufacturing, the exchange of information in manufacturing networks has to be seamless, but such a comprehensive infrastructure is not yet in existence.[42] Some of the main

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[39] Ibid.
[40] Ibid.
[41] Ibid.

challenges associated with implementing CPS include network integration, affordability, and the interoperability of engineering systems.[43] Using a systems view of manufacturing is necessary to gain a better understanding of what effects the changes in one element will have throughout the entire system.[44]

Smart manufacturing is only slowly incremented into portions of the manufacturing markets and does not provide investment incentives. Most companies have a difficult time justifying risky, expensive, and uncertain investments for smart manufacturing across the company and factory level.[45] High costs are prohibitive to small and medium size companies, resulting in a slow adoption of smart manufacturing technologies in the supply chain that impacts the investment return for the companies that do invest.[46] Pre-digital age control systems are infrequently replaced because they are still serviceable, and retrofitting existing plants is more difficult than implementing CPS manufacturing technologies in new plants.[47] There is a lack of industry standard approach to production management, and most companies customize their own software or use a manual approach.[48]

Today's production networks carry out all tasks related to the life cycle of the product, including design, engineering, fabrication, and maintenance functions and are, therefore, becoming increasingly complex and dynamic and require more sophisticated information integration.[49] This increasing complexity is beginning to exceed the ability of both engineers and designers to fully control and optimize their performance. Traditional communication, control, and software theory cannot efficiently provide all the tools needed to analyze large-scale control networks.[50] For example, current network research often focuses on connectivity and coverage issues assuming that network components are homogeneous; but in practical terms CPS consists of both wireless and wired networks characterized with varying capacities and reliability. There is a need for a unifying theory of non-homogeneous control and communication systems. The heterogeneity of each device, in terms of memory, communication, and processing, should be considered in the design of the CPS architecture to optimize real-time communication and reliability.[51]

Changes to the structure, organization, and culture of the manufacturing do not occur quickly, which is something that must change if CPS technologies are to be successfully integrated. New smart manufacturing technologies cannot be introduced incrementally or over a generation, but must be

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[42] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[43] Ibid; President's Council of Advisors on Science and Technology, *Report to the President on Ensuring American Leadership in Advanced Manufacturing* (Washington, DC: Executive Office of the President, June.201), http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

[44] Robert E. Mansfield Jr. ., "Extreme Manufacturing: The Future Manufacturing Enterprise" (Gaithersburg, MD: National Institute of Standards and Technology, December 2010), http://www.nist.gov/el/upload/Extreme-Manufacturing_NISTWorkshop_Jan2011.pdf.

[45] Jim Davis and Smart Manufacturing Leadership Coalition, "A Smart Manufacturing Public-Private Partnership Program" (Los Angeles: University of California – Los Angeles, January 2011), http://www.nist.gov/el/upload/SMLCtwopageprogramstatement1-0.pdf.

[46] Ibid.

[47] Ibid.

[48] Ibid.

[49] Simon. Frechette, "Systems Integration for Manufacturing and Construction Applications" (Gaithersburg, MD: National Institute of Standards and Technology, September 2011), http://www.nist.gov/el/msid/infotest/upload/SIMCAprogram2012.pdf.

[50] Yunbo Wang, Mehmet C. Vuran, and Steve Goddard, *Cyber-physical Systems in Industrial Process Control* (Lincoln, NE: University of Nebraska-Lincoln, 2008), http://sigbed.seas.upenn.edu/archives/2008-01/Wang.pdf.

[51] Ibid.

integrated smoothly and faster than the norm to be effective.[52] There is little communication and collaboration between the manufacturing and information technology communities in both academia and industry, which may be a cause of the slow integration of new systems and technologies.[53]

Because design and engineering processes and their software applications are located throughout the production network, information quality is highly important. A 2004 report published by Gartner Research found that 25% of Fortune 1000 companies have reported issues finding and correcting quality problems, which can cause several billion dollar losses from production delays.[54]

In order for a revival and improvement of U.S. manufacturing to occur, an emphasis must be placed on improving both the education and workforce that can be applied to the industry.[55] Access to skilled workers in manufacturing is limited, and the next-generation workforce must be able to successfully develop and use CPS technologies in manufacturing. These workers will be able to take full advantage of manufacturing technology using their skills and talent.[56] Changes in the education available are needed to help to develop this highly skilled and prepared workforce and to spur advanced research. Other countries, such as China, South Korea, and India, are largely investing in research and innovation for advancements in manufacturing.[57]

MEASUREMENT PROBLEMS AND IMPEDIMENTS

Advancements in measurement science for manufacturing are necessary before highly integrated CPS can achieve significant advances. Complex, first- to-market products should be quickly, safely, and cost effectively brought to market by manufacturing processes and equipment. Interoperability of systems in manufacturing remains a challenge yet can help streamline production processes using data and virtual modeling that is consistent across the supply chain. Measurement science will allow for improvements in advanced manufacturing and CPS by increasing the versatility, autonomy, and re-tasking of robots and automation technologies; enabling real-time monitoring, control, and performance optimization of systems in factories; facilitating integration of engineering information systems to improve product and process performance; and enabling rapid and cost-effective production of complex products.[58]

To successfully design and implement CPS and integrate applications, there is a need for new measurement science. A deficiency in measurement science for the standardization and communication of

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[52] Robert E. Mansfield Jr., “Extreme Manufacturing: The Future Manufacturing Enterprise” (Gaithersburg, MD: National Institute of Standards and Technology, December 2010), http://www.nist.gov/el/upload/Extreme-Manufacturing_NISTWorkshop_Jan2011.pdf.

[53] Jill. Jusko, “Workshop Tackles ‘Extreme’ Manufacturing.” *Industry Week*. January 14, 2011, http://www.industryweek.com/articles/workshop_tackles_extreme_manufacturing_23665.aspx.

[54] Gartner Business Intelligence Report (ISBN 0-9741571-1-2), 2004.

[55] Engineering Laboratory, “National Workshop on Challenges to Innovation in Advanced Manufacturing,” National Institute of Standards and Technology, accessed January 2010, http://www.nist.gov/el/advmanuwkshp.cfm.

[56] Smart Manufacturing Leadership Coalition, *Implementing 21st Century Smart Manufacturing: Workshop Summary Report* (Los Angeles: Smart Manufacturing Leadership Coalition, 24 June 2011), https://smart-process-manufacturing.ucla.edu/about/news/Smart%20Manufacturing%206_24_11.pdf.

[57] Networking and Information Technology Research and Development , “Winning the Future with Science and Technology for 21st Century Smart Systems” (Arlington, VA: Networking and Information Technology Research and Development, 2011), http://www.nitrd.gov/subcommittee/hcss/documents/CPS_OSTP_ResponseWinningTheFuture.pdf.

[58] Engineering Laboratory, “Strategic Goal: Smart Manufacturing, Construction, and Cyber-Physical Systems,” National Institute of Standards and Technology, accessed November 2011, http://www.nist.gov/el/smartcyber.cfm.

system engineering requirements can result in costly production delays.[59] Increasing the efficiency of production networks requires the optimization of production processes from concept to production. Current standards for process integration and technologies used in their implementation have not been able to achieve the needed seamless integration of information exchange in production networks.[60] There is a need for new information interpretation and exchange standards and new modeling languages, which require new validation methods and tools for their implementations and new approaches to preserve the quality of engineering knowledge across processes and production partners.[61]

Model validation is expensive and time consuming and sometimes even cost prohibitive for one-of-a-kind manufacturing systems.[62] NIST has developed tools and conformance-testing methods, which have been effective in reducing the implementation costs of existing standards, but many of these standards remain incompatible and hinder integration.[63] The maturity of integrated production networks across different industries varies, as does the rate of tool use and adoption of standards.[64] In addition, computer-aided design (CAD) models of the factory undergo several changes during the construction phase, rendering the original CAD models inaccurate and complicating future reconfiguration efforts. The current trend towards modular automation components facilitates the cost effectiveness of high-fidelity models and their validation, because the components are built in quantity and applied to various designs. Therefore, the validation costs can be justified and amortized, facilitating future configurations.[65]

Modeling and simulation capabilities as well as infrastructure are not standard across multiple industry segments, but should be developed and accessible to all sizes of enterprises.[66] Currently, virtual designing and modeling are infrequently used, yet provide the possibility to reduce the amount of trial and error and prototyping during the development of a product.

It is important to consider the tradeoffs when selecting between commercial-off-the-shelf, open-architecture control technologies and more expensive proprietary offerings. These proprietary offerings may not have available reconfiguration or upgrade paths, which could present problems in the future; on the other hand, the open-architecture solutions may be more affordable but inspire less confidence in the production line.[67]

The conformance of CPS with international standards presents another issue. There are several “open” standards for networks and logic programming, but most do not guarantee interoperability and international safety standards. For automation modules to properly work together, they must communicate

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[59] Simon Frechette, “Systems Integration for Manufacturing and Construction Applications” (Gaithersburg, MD: National Institute of Standards and Technology, September 2011), http://www.nist.gov/el/msid/infotest/upload/SIMCAprogram2012.pdf.

[60] Ibid.

[61] Ibid.

[62] D. M. Tillbury, “Modeling and Verification of Distributed Cyber-Physical Systems: Challenges, Research Needs, and Possible Roadmap” (Ann Arbor, MI: The University of Michigan, October 5, 2006), http://www.truststc.org/scada/papers/paper16.pdf.

[63] Simon Frechette, “Systems Integration for Manufacturing and Construction Applications” (Gaithersburg, MD: National Institute of Standards and Technology, September 2011), http://www.nist.gov/el/msid/infotest/upload/SIMCAprogram2012.pdf.

[64] Montana Mallett and David C. Stieren, “MBE Supplier Capabilities Assessment & Potential Certification Development.” (presentation, MBE Education & Training Summit, Battle Creek, MI, May 2010), http://model-based-enterprise.org/Docs/MBE_Summit_Presentation.pdf.

[65] D. M. Tillbury, “Modeling and Verification of Distributed Cyber-Physical Systems: Challenges, Research Needs, and Possible Roadmap” (Ann Arbor, MI: The University of Michigan, October 5, 2006), http://www.truststc.org/scada/papers/paper16.pdf.

[66] Jim Davis and Smart Manufacturing Leadership Coalition, “A Smart Manufacturing Public-Private Partnership Program” (Los Angeles: University of California – Los Angeles, January 2011), http://www.nist.gov/el/upload/SMLCtwopageprogramstatement1-0.pdf.

[67] D. M. Tillbury, “Modeling and Verification of Distributed Cyber-Physical Systems: Challenges, Research Needs, and Possible Roadmap” (Ann Arbor, MI: The University of Michigan, October 5, 2006), http://www.truststc.org/scada/papers/paper16.pdf.

with a standard protocol. Each individual automation module needs its own human-machine interfaces (HMI), but when they form a connected system, standard techniques are needed to build and operate a unified HMI that controls the entire system.[68]

Data collection is an important aspect of achieving demand-dynamic smart manufacturing, yet there are challenges in both gathering and interpreting data. One challenge with data collection in manufacturing is developing models to help evaluate the data, thus leading to intelligent behavior and innovation. These models must be able to process large amounts of data in real-time. Not all data that is collected will provide useful knowledge about processes or machinery and must be checked for consistency, reliability, accuracy, and applicability.[69] Also, data needs to be managed as an operating asset and be easy to share within a company as well as between different companies in a more automated manner.[70] There is a lack of standard methods to transfer data and models within a supply chain. Data sharing between companies leads to many issues, including intellectual property rights, confidentiality, and security.[71]

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[68] Ibid.

[69] Engineering Laboratory, “National Workshop on Challenges to Innovation in Advanced Manufacturing.,” National Institute of Standards and Technology, accessed January 2010, http://www.nist.gov/el/advmanuwkshp.cfm.

[70] Jim Davis et al.., *Smart Process Manufacturing: An Operations and Technology Roadmap* (Arlington, VA: National Science Foundation, November 2009), http://oit.ucla.edu/nsf-evo-2008/documents/SmartProcessManufaturingAnOperationsandTechnologyRoadmapFullReport.pdf.

[71] Engineering Laboratory, “National Workshop on Challenges to Innovation in Advanced Manufacturing,” National Institute of Standards and Technology, accessed January 2010, http://www.nist.gov/el/advmanuwkshp.cfm.

- Jacobson, Alan L. “Working Paper: NIST Extreme Manufacturing Working Paper.” Gaithersburg, MD: National Institute of Standards and Technology, January 2011. http://www.nist.gov/el/upload/Jacobsen.pdf.
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Smart Grid and Utilities

INTRODUCTION

Many aspects of our lives, including finances, transportation, and emergency services, depend on the reliable production, transfer, and distribution of energy, including electricity, oil, and natural gas.[72] Today's electric grid is a complex system of systems, with many different stakeholders and customers. The National Academy of Engineers has named the development of "electrification," which includes today's electric system, as the greatest engineering achievement of the twentieth century.[73] The water supply and distribution system is also listed as a great engineering achievement; the supply of safe, clean, and reliable water is important to health, quality of life, and emergency services. Yet even though these systems are great achievements, they need to be modernized in order to increase their efficiency and reliability. Existing infrastructure is aging and control systems can be highly improved.

Cyber-physical systems (CPS) stand to have a significant impact on large-scale, computer-mediated physical distributed systems such as the electric grid and water distribution systems. The cyber and physical components integrated in the system have many interactions the can affect the entire operation, but are poorly understood. The electric grid and other utilities can use CPS technologies to help the system become smarter and more efficient.[74] The infrastructure for both the electric grid and water distribution systems is aging and face technical and reliability problems. The Environmental Protection Agency reports that there are 240,000 water main breaks per year in the United States, and as a system ages the number of main breaks increases.[75] New technologies, including those in CPS regarding sensors and control, may help to increase the effectiveness of water utility distribution systems.

The electric power industry in the United States is a $737 billion industry, representing 3% of real gross domestic product (GDP). About 70% of industries, U.S. businesses, and consumers are served by shareholder-owned electric companies. The electric industry is spending about $75 billion per year in investments, which include upgrades for the smart grid.[76] The U.S. water industry is estimated to have revenues upwards of $150 billion per year. Water utilities increasingly rely on wireless and automated

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[72] Networking and Information Technology Research and Development Program (NITRD). *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.

[73] National Academy of Engineering. "Greatest Engineering Achievements of the 20th Century." 2012. http://greatachievements.org/

[74] National Science Foundation (NSF). *Report: Cyber-Physical Systems Summit*. 2008.

[75] Environmental Protection Agency (EPA). "Water Distribution Systems." 2012.

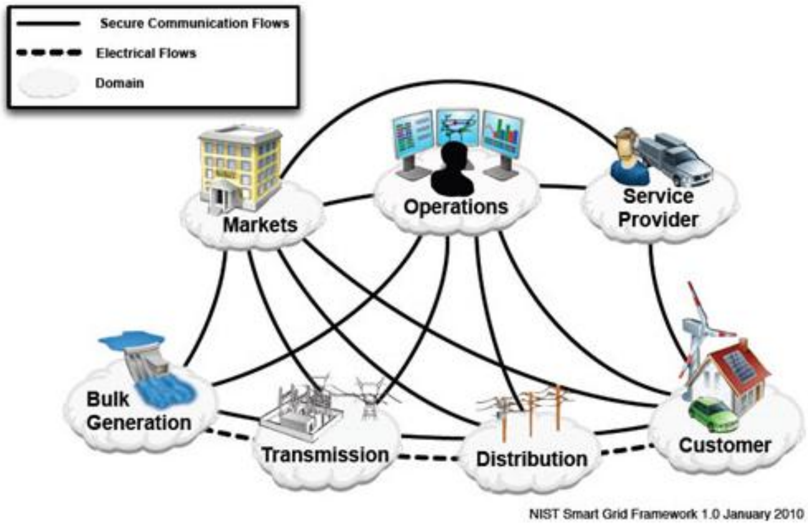
[76] Edison Electric Institute. *Key Facts About the Electric Power Industry*. 2011.

systems for their control operations, distribution, and monitoring, to which CPS technologies could be applied to increase the security, efficiency, and reliability.[77]

Investment in modernizing the electric grid is an area of focus for the United States in order to increase efficiency and reliability, reduce blackouts and cost, and improve the security of the electricity system. Also, modernizing the grid is necessary to enable it to integrate the use of clean energy technologies, such as renewable sources.[78] The new energy technology sector will both depend on and provide jobs for a highly skilled and innovative workforce.[79]

Production of electricity is dominated by fossil fuels, but renewable sources of energy are increasingly used to generate electricity. In 2010, electricity was generated from 24% natural gas, 10% renewables, 45% coal, 20% nuclear, and 1% oil and other liquids. Electricity demand is expected to increase 23% by 2035 due to higher demand of electricity-consuming products (electronics, cars) among other factors.[80] Cyber-physical systems can help to meet this demand by helping the electric grid become more efficient and successfully integrate the increasing renewable sources of electricity into the grid.

Figure 2. Relationships and Interactions within the Smart Grid



Source: NIST & the Smart Grid
http://www.nist.gov/smartgrid/nistandsmartgrid.cfm

KEY DRIVERS

Increases in electricity demand in the residential sector are due to factors such as population growth, a rise in disposable income, and population shifts to warmer regions.[81] Although the increase in demand for electricity has slowed in the decades since the 1950s, it is still estimated that demand will increase by

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[77] Adam, Nabil. U.S. Department of Homeland Security (DHS). *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.

[78] The White House. *Strategy for American Innovation: Invest in the Building Blocks of American Innovation*. 2011.

[79] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.

[80] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview.* 2012.

[81] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2011.* 2011.

23% between 2010 and 2035.[82] CPS in the smart grid and smart utilities can help the reliability and efficiency of the system, while enabling suppliers to have real-time situational awareness. As electricity and utilities become more connected and networked, there will be opportunities to optimize and reduce costs and the need for cyber security and monitoring efforts.[83]

The ability of the U.S. electric system to provide reliable and continuous access to electricity and to respond to increases in demand contributes to our high quality of life. Electricity is currently a product that is delivered on demand and cannot be stored easily or economically, so it is necessary for electricity suppliers to be able to have enough capacity available to meet the maximum demands.[84] Using automated control, autonomous systems, and digital information, the smart grid will increase the reliability and quality of the power supply and reduce the extent and frequency of power outages.[85]

One of the trends in sectors such as electricity and water is increased automation. While automation allows for less interaction by operators, it is not entirely reliable; however, it can increase safety and reduce costs while eliminating some aspects of operator error. CPS applications can help increase the reliability, security, and confidence in automation systems in the electric and water sectors.[86]

The three primary stakeholder groups in the smart grid are consumers, utilities, and society. Consumers play a more active role in managing their energy consumption using variable, real-time pricing and will even be able to install infrastructure to provide electricity to the grid. Electricity supply from utilities will be more reliable as efficiency increases and they will be able to better manage emergency interruptions. Stakeholders, such as those that are most affected by power outages, will benefit from more reliable energy supply as will other stakeholders, such as regulators, vendors, and integrators.[87] In the water sector, stakeholders include a wide range of operators, owners, and consumers, as water systems span large geographical regions and any disruption or problem can affect large quantities of people. About 160,000 public water systems serve 250 million people in the United States.[88]

Improvement in energy efficiency is a strong driver towards the research and development of the smart grid and other smart utilities. Renewable energy and smart grid research has a high public interest, making it a strong priority for policy makers.[89] Increasing the efficiency in the interactions between elements of the systems can also help reduce costs for utilities and consumers. A grid that is more efficient using CPS and other technologies can reduce total energy use and losses, reduce peak demand, and provide end users the ability to reduce their energy usage.[90]

Environmental issues are also a cause for advances in CPS technologies within the smart grid and utilities. Coal's share of electricity generation is estimated to decrease from 45% in 2010 to 39% by 2035, while the share from natural gas is estimated to increase from 24% to 27% in the same time period.[91] The

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[82] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview*. 2012.
[83] Electric Power Research Institute (EPRI). *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[84] Edison Electric Institute. *Key Facts About the Electric Power Industry*. 2011.
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[86] Krogh, Bruce et al. *National Workshop on Beyond SCADA: Networked Embedded Control for Cyber-Physical Systems (NEC4CPS).* 2007.
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[88] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[89] Baheti, Radhakisan and Helen Gill. *Cyber-physical Systems.* 2011.
[90] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[91] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview.* 2012.

increased use of renewable energy to generate electricity accounts for 33% of overall growth between 2010 and 2035 due to various federal and state policies and requirements.[92]

The current level of electricity demand has a significant effect on energy-related carbon dioxide emissions since a large portion of electricity is generated from coal. Electricity generation in the United States is responsible for 40% of human-caused carbon dioxide emissions.[93] Concerns about greenhouse gas emissions are moving electricity generation away from coal. With the projections of increased use of renewable energy and modest growth in demand, electricity-related carbon dioxide emissions will grow 4.9% between 2010 and 2035.[94] CPS can help to reach these projections of slowing the rise of carbon dioxide emissions as demand for electricity increases.

As more consumers begin to use electric vehicles, the smart grid will have to adapt to increased loads as well as being able to integrate these vehicles as part of the grid. These vehicles will provide both opportunities and challenges as to how the smart grid can provide charging when necessary or even use the vehicles as storage when possible. CPS engineering and advancements in smart transportation will thus affect those in the smart grid, allowing for innovation in function and capability in both energy and transportation systems.[95] Integrating electric vehicles into the smart grid will also help reduce the number of gasoline-powered vehicles that contribute to emission.[96]

CURRENT STATE OF THE TECHNOLOGY

The U.S. electric power grid is a large, complex "system of systems." Power generation, transmission, and distribution systems operate on local, regional, and national levels. The entire grid consists of three interconnected networks divided into 152 regional control areas.[97] The grid encompasses 3,200 electric utility companies, 17,000 power plants, and covers six million miles of distribution lines.[98] Although the complicated system is dependable and effective, many improvements can be made using the application of CPS to develop a more efficient, reliable smart grid.

The electric grid today is driven by consumer demand—and it is generated as it is consumed. Electricity cannot be stored easily or economically, leading to little storage capacity for producers. The current system of managing generation while responding to demand is inefficient for generation systems today, especially when the systems are unable or slow to switch on or off in response to demand.[99] Control in power plants is primarily used to ensure that there is stability during normal operation. Each utility company uses automatic generation control (AGC) to regulate power imbalances that are not easily predicted, yet there is no online coordination between the utilities.[100] Control mechanisms for power flow are inefficient and expensive and do not allow for flexible routing of power flow.[101] If the system could predict or model future demand using CPS engineering and technologies, providers would be able to better prepare for peak loads without overestimating them.

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[92] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview.* 2012.
[93] Arnold, George W. *NIST presentation: Overview of NIST's Smart Grid Program*. 2011.
[94] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview.* 2012.
[95] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[96] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[97] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[98] Arnold, George W. *NIST presentation: Overview of NIST's Smart Grid Program*. 2011.
[99] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[100] Ilic, Marija. *Complex Power Grids: From Grid-Centric Reliability to Meeting Grid-enabled Users Needs.* Presentation at 2011 CPS PI Meeting.
[101] Krogh, Bruce et al. *National Workshop on Beyond SCADA: NEC4CPS.* 2007.

The U.S. electric power system is currently 99.99% reliable, yet it is still susceptible to interruptions and disturbances that amount to high costs.[102] These interruptions can be caused by unintentional incidents, such as excessive peak loads or natural accidents, or by intentional incidents, such as targeted cyber attack. Disturbances can cause destruction of critical process components and failures that stop generation and distribution of electricity to consumers in localized or widespread areas.[103] While some of these system failures are localized to small regions, others can cause cascading power failures in larger regions, such as in the widespread power outage in the northeast United States and Canada in 2003.[104] While an increased networking of the control of utility systems has many benefits, it also exposes the systems to possible attacks.

In order for the water system to become more flexible and reliable, systems that allow for more secure automation and provide real-time operational information are needed. CPS architectures that are able to adapt to a changing environment while remaining secure can help to improve the sector's resilience. The water systems will use the CPS technologies to quickly regain operation after an interruption, allow for self-repair and configuration, and real-time monitoring.[105]

While a majority of electricity is currently generated from coal, natural gas, and nuclear power, electricity produced from renewable resources is estimated to increase to 16% in 2035.[106] Although renewable sources provide "clean" sources of electricity generation, they sometimes provide intermittent or variable sources of energy.[107] CPS technologies and engineering will provide the next-generation control architectures and platforms needed to optimize the electricity system as it is called on to integrate a variety of energy sources, including intermittent renewables

CPS technologies can also be used to help manage user consumption. For example, applying CPS to the advanced metering infrastructure may enable more effective management of consumption by providing the ability to schedule power utilization based on information from the meters.[108] Smart meters provide information for the development of technologies that can enable demand management, distribution automation, substation intelligence, distributed generation, and information technology. The objective of these technologies is to increase energy efficiency through optimization, control, and a reduced peak load.[109] CPS technology will provide the tools for real-time, resilient, safe, and secure control of energy systems, resulting in highly integrated, dependable, and flexible energy technologies.

The American Recovery and Reinvestment Act of 2009 (Recovery Act) provides funding of $4.5 billion to increase the rate of modernization of the electric grid, specifically through the Smart Grid Investment Grant and Smart Grid Demonstration programs.[110] There has been increased use and installation of smart meters and advanced metering infrastructure (AMI), which is helping modernize the U.S. electric grid by reducing peak and overall electricity use.[111] In June of 2011, funding from the Recovery Act had already facilitated the installation of five million smart meters. These smart meters provide information about

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[102] National Academy of Engineering. "Greatest Engineering Achievements of the 20th Century." 2012. http://www.greatachievements.org/?id=2998
[103] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[104] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[105] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[106] U.S. Energy Information Administration (EIA). *Annual Energy Outlook 2012 Early Release Overview.* 2012.
[107] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[108] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[109] Baheti, Radhakisan and Helen Gill. *Cyber-physical Systems.* 2011.
[110] U.S. Department of Energy (DOE). Smartgrid.gov. "Overview of Programs, Studies and Activities."
[111] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.

electricity use to utility companies and allow consumers to monitor their real-time energy use.[112] AMI is only a small step towards the development of smart grid and utilities, as there are still structural issues remaining in the current power system.[113] Advances in CPS technologies can also help improve interoperability and cyber security—other top priorities of these smart grid demonstration programs.

Table 3. Evolving CPS Landscape in Energy[114]

	Current	Future
Energy	Centralized generation, Supervisory Control and Data Acquisition Systems for transmission and distribution	Systems for more efficient, effective, safe and secure generation, transmission, and distribution of electric power, integrated through the smart grid; smart ("net-zero energy") buildings for energy savings; systems to keep nuclear reactors safe

A smart grid of the future will be more flexible and resilient and have the ability to provide real-time pricing and response, reduce the time and extent of power outages and disturbances, reduce congestion, and better utilize resources. No longer will the network be considered to be centralized and distribution only, as generation will also come from homes and other distributed sources.[115] The system must be able to integrate alternative technologies, including solar, thermal, wind, and water-based generators; smaller scale nuclear generation; and generation from alternative fuels. In addition, an increase in electricity storage capacity will be necessary to help the grid be better able to handle peak loads. Integrating buildings that have cogeneration of heat and power as well as electric vehicles into the grid will present challenges, but also provide opportunities.[116]

BROAD CHALLENGES AND BARRIERS

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, in addition to other properties.[117] This infrastructure will provide energy that is more efficient, reliable, and stable while meeting consumer demand. In addition to being blackout free and eliminating power surges, the infrastructure must be flexible, allowing heterogeneous participants to consume energy from and supply energy to the grid. The energy system infrastructure must be secure and impervious to accidental or intentional disruptions or manipulations. It will be important for the architecture, control, and implementation to be modified and adapt to future technologies as well.[118] In order to operate the next-generation energy and water systems and infrastructure that take advantage of CPS technologies, there also needs to be a qualified, innovative, and skilled workforce.[119]

Sources for electricity generation today are typically centralized, but will become more distributed as sources become more varied. Among these include the increase in renewable sources for electricity generation, including solar, wind, and others. Technical challenges arise with the increase of distributed

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[112] U.S. Department of Energy (DOE). "Energy Secretary Chu Announces Five Million Smart Meters Installed Nationwide as Part of Grid Modernization Effort." 2011.
[113] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[114] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[115] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[116] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.
[117] Rajkumar, Ragunathan et al. *Cyber-Physical Systems: The Next Computing Revolution.* 2010.
[118] National Science Foundation (NSF). *Report: Cyber-Physical Systems Summit*. 2008.
[119] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems*. 2011.

sources of power generation. Incorporating power generated from distributed resources into the grid requires new controls as well as complex balancing schemes.[120] For example, power generated from wind is growing rapidly, yet it supplies an irregular stream of electricity. This type of source, along with other distributed sources, causes an additional stress on the current grid.[121] Energy storage technologies are currently not effective enough to support a higher penetration of renewable sources and there is only an ill-defined hierarchy for integrating the sources into the grid.[122] Coordination of and interaction between varying distributed resources will pose many new challenges.[123]

One of the challenges of applying CPS engineering and technology to the electric grid and other utilities is integrating these technologies into the existing infrastructure. Improvements and changes are being applied to the existing power grid system, which must transition into the smart grid of the future.[124] There will need to be changes in how the system is managed as power generation comes from more distributed that need to be continually integrated into the existing infrastructure. Unforeseen complications and challenges will arise as these distributed sources are connected to the grid on the regional and national level.[125] Generation, storage, and distribution will have to remain dependent and stable even as sensing and actuation technologies are added to sections of the existing grid.[126] Automation and connectivity applications in water-sector systems provide obvious improvements, but they are added to older infrastructure. This increased complexity of the system poses technical challenges and effects that must be considered as the system is operated in ways that were not intended when the infrastructure was originally built.[127]

As technologies and systems are incorporated as part of the modernization of the grid, security remains a paramount concern in terms of lowering the vulnerability of the smart grid and water sector systems.[128] Any disruptions to these sectors affect other sectors, making their secure operation a necessity. The energy and electric sectors are networked and complex, with increasing interactions between generation, transmission, and distribution processes, resulting in numerous access points. Control systems should have integrated protection, detection, and response mechanisms to be able to survive natural disasters, human error, and cyber attack without loss of function.[129] Privacy of various stakeholder data will need to be protected as the grid becomes more interconnected.[130]

Increased connectivity within the system allows for better interoperability and communication, yet security risks increase as more entities are provided access. Although there are many benefits to placing smart meters in residences, this provides another risk for cyber attack. These and other components and subsystems in the smart grid should be securely integrated using security mechanisms, authentication techniques and protocols, and timely and secure communication and control networks. Increased complexity, integration, and automation in the water sector allow for the possibility of security breaches or cyber attacks.[131]

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[120] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[121] Rajkumar, Ragunathan et al. *Cyber-Physical Systems: The Next Computing Revolution.* 2010.
[122] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[123] Rajkumar, Ragunathan et al. *Cyber-Physical Systems: The Next Computing Revolution.* 2010.
[124] Rajkumar, Ragunathan et al. *Cyber-Physical Systems: The Next Computing Revolution.* 2010.
[125] NSF. *Report: Cyber-Physical Systems Summit*. 2008.
[126] NSF. *Report: Cyber-Physical Systems Summit*. 2008.
[127] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[128] U.S. Government Accountability Office (GAO). *Electricity and Modernization.* 2011.
[129] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[130] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[131] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.

One of the technical challenges that face the smart grid is how to better store excess energy. Instead of the current model of utility companies providing electricity on demand for consumers in a downhill, one-way fashion, the smart grid must be able to handle increased generation from renewable sources as well as directly from customers or electric vehicles. The grid must be able to flexibly respond to changes in supply and demand.[132]

Since there are many different stakeholders in the smart grid, there are numerous business and policy challenges that arise. Different states will have their own policies on regulating and implementing smart grid technologies, including advanced metering. Some states are considering passing legislation that gives the customer the option to opt out of the installation of smart meters in their residence.[133] Standards are developed based on the consensus of multiple stakeholders. While this is effective, it is taking a considerable amount of time.[134] Other challenges to consumers providing power to the grid include the legal and policy implications as to who is responsibility for maintaining, operating, and repairing the necessary equipment.[135]

MEASUREMENT PROBLEMS AND IMPEDIMENTS

In systems as complex and networked as the smart grid and other utilities, there are measurement problems and challenges in various areas that continue to emerge as CPS and other technologies are integrated.

Data capture, transmission, and retention methods that are reliable and effective must be developed. If there is a delay or disruption of the delivery of data from sensors or actuators, this can present multiple challenges to control systems that will rely on real-time data. Data transmission is reliable but not entirely trustworthy, as it is still affected by problems such as memory overflow, network overload, and slow processing speed, all of which can cause possible vulnerabilities. There must be methods to ensure that data cannot be corrupted or manipulated through a cyber attack.[136] Current data management methods work well for small amounts of data but fail or become ineffective for larger data sets that will come from distribution automation and customer information. Other challenges in data management include data identification, validation, updating, time-tagging, and consistency across databases.[137]

Another challenge with data comes from not being able to effectively collect it from geographically distributed sources of energy. The ability to collect more accurate data from these geographically dispersed sources would provide producers with a more effective ability to generate and route power. Without this data, it would be difficult to obtain a real-time, global picture of the state of the entire system. [138] New platforms must be developed that can convert various data into valuable information.[139]

Although there are currently large-scale simulation test beds for the power grid, these will not suffice as more CPS technologies are integrated. Tomorrow’s test beds should be broadly accessible and encompass aspects that extend beyond the grid, including communication and computing layers and the fuel supply

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[132] NITRD. *Winning the Future with Science and Technology for 21st Century Smart Systems.* 2011.
[133] U.S. Energy Information Administration (EIA). *Smart Grid Legislative and Regulatory Policies and Case Studies.* 2011.
[134] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[135] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[136] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[137] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[138] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[139] Ilic, Marija. *Complex Power Grids.* Presentation at 2011 CPS PI Meeting.

chain.[140] Including the ability to integrate adaptation, control, and other intelligent elements into the test beds for utilities can help achieve outcomes such as the following:[141]

- Fine-grained optimization of efficient energy generation, storage, transmission, and use
- Multi-regional or multi-national coordination, pricing, and control of power supply and demand
- "Just enough" generation and use of energy
- Definition and management of energy needs, costs, and emissions

Development and use of predictive tools can help increase the efficiency and reliability of the power industry as well as that of other industries. Current practices are only reactive because action can only be taken after a problem occurs, such as an outage caused by severe weather conditions. Developing anticipatory control will make the grid smarter and better able to deal with imminent problems. Advances beyond the current information technology, real-time access to data from wired and wireless devices, and a coordination network that can realize impacts of future events are necessary to enable predictive control for the grid.[142]

Tools that could predict and coordinate power needs and costs based on weather, time and day of the week, energy future costs, or other criteria in a highly distributed system are not yet available.[143] In order to help increase performance while ensuring robustness, tools need to be developed that can help quantify the boundary of acceptable operating conditions. Tools such as these could increase the efficiency and capacity of the grid while ensuring secure operation.[144] In the water sector, there is a lack of performance metrics and tools that can successfully evaluate the operation and control systems. These metrics and tools should be able to identify critical cyber and physical components and systems as well as the effects of increased interconnectivity.[145]

It will be a challenge to develop and establish a modeling framework that is sufficiently accurate; not too complex; and that captures interdependencies between the grid, technologies, and systems. Data collection will be useful when developing and verifying models, but the data will constantly be changing as the system status changes.[146] There is a need to develop other models, theories, and tools that consider the continuous and discrete aspects of the energy supply system, including the integration between the cyber and physical components. As more components are integrated into the system, the numbers and types of interactions increase and the components have various types of safety and security verification. Verification and validation of these interactions will be a challenge, especially as the automation, connectivity, and accessibility of control processes increase.[147]

When the system is in an abnormal condition, operators in utility plants are overwhelmed by the number of alarms. Operators must make decisions about how to react within very little time. As the smart grid is developed, there must be a method developed that can evaluate, prioritize, and respond to the alarms to reduce confusion. Currently, there is no diagnostic software than can provide operators suggested courses

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[140] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[141] NSF. *Report: Cyber-Physical Systems Summit*. 2008.
[142] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[143] NSF. *Report: Cyber-Physical Systems Summit*. 2008.
[144] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[145] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.
[146] Ilic, Marija. *Complex Power Grids.* Presentation at 2011 CPS PI Meeting.
[147] Adam, Nabil. DHS. *Workshop on Future Directions in Cyber-Physical Systems Security*. 2010.

of action for abnormal conditions.[148] Software needs to be developed that is user friendly and can detect the causes of technical problems and provide effective actions to operators.[149]

Software applications, including programs, algorithms, calculations, and data analysis, are essential to the successful operation of the smart grid. This software must be able to handle increasingly complex problems as CPS technologies and applications are integrated into the grid.[150] Other types of software should be developed to be adaptive and able to alter objectives based on changing conditions.[151] Also, there needs to be more situational awareness displays and analysis tools.[152]

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[148] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.
[149] Ilic, Marija. *Complex Power Grids.* Presentation at 2011 CPS PI Meeting.
[150] EPRI. *Report to NIST on the Smart Grid Interoperability Standards Roadmap*. 2009.
[151] Ilic, Marija. *Complex Power Grids.* Presentation at 2011 CPS PI Meeting.
[152] Krogh, Bruce et al. *Beyond SCADA: NEC4CPS.* 2007.

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- U.S. Government Accountability Office (GAO). *Electricity and Modernization*. 2011. http://www.gao.gov/new.items/d11117.pdf

Smart Buildings and Infrastructure

INTRODUCTION

Next-generation technologies and methods integrated into building systems could allow building energy use to be seamlessly predicted, monitored, controlled, and minimized across the dimensions of performance, scale and time.[153] Homes and businesses could be connected with the smart grid, where their energy monitoring and control systems predict usage and then negotiate energy consumption and prices with the utility company.[154] The cyber and the physical worlds must be tightly integrated to enable many of these concepts to work effectively in buildings.

Achieving net-zero energy (NZE) buildings, for example, where the building can produce as much (or more) energy than it consumes, requires highly integrated systems of cyber and physical components. The smart buildings of the future will also include co-generation of heat and power with sophisticated controls.[155] Research in cyber-physical systems (CPS) provides opportunities for improvement in the efficiency and performance of commercial and residential buildings as well as other structures, such as bridges and dams.

The National Academy of Engineering acknowledges restoring and improving urban infrastructure as one of the grand challenges of engineering in the 21st century.[156] The nation's infrastructure continues to age while demands increase due to a higher volume of cars, trucks, and buses. Budgets to maintain or replace these systems are already strained. There is a critical need to develop technology that can accurately assess the health and safety of bridges, buildings, and other structures to be able to prioritize the allocation of limited resources to retrofit and replace these systems, thus prolonging their useful lifetimes and reducing accidents. CPS research, including areas such as sensors for bridge structural health monitoring, could be applied to other infrastructure areas such as power, communications, water/ wastewater systems as well as other critical structures including nuclear power plants, offshore structures, dams, levees, refineries and other chemical plants.

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[153] National Science and Technology Council (NSTC) Committee on Technology. "Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings." Oct 2008.
[154] NITRD "Winning the Future."
[155] NITRD (Networking and Information Technology Research and Development Program). "Winning the Future with Science and Technology for 21st Century Smart Systems."
[156] National Academy of Engineering. "Grand Challenges for Engineering." 2008.

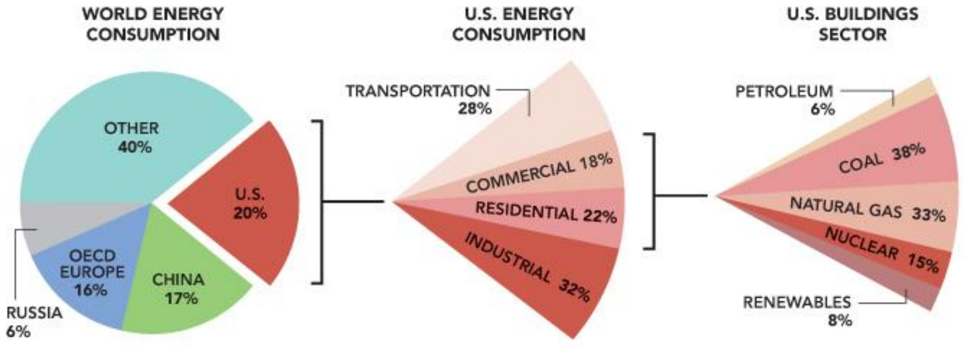
KEY DRIVERS

Energy Efficiency

The buildings sector, including both residential and commercial, accounted for 40% of U.S. primary energy use in 2008–higher than both the transportation and industrial sectors, as shown in Figure 3. Buildings sector energy use in the United States also accounted for 8% of the total world energy consumption in 2008. Of this energy use, 76% came from fossil fuels, 15% came from nuclear generation, and 8% was provided by renewable sources.

A majority of the energy consumption of buildings occurs for the end uses of space heating, water heating, and lighting.[157] The Energy Independence and Security Act (EISA) of 2007 creates a national goal for all commercial buildings built after 2030 to be net-zero energy buildings, and all buildings built before 2030 should be retrofitted to achieve net-zero energy use by 2050.[158] In order to reach these goals, advances in buildings technologies must come about. As noted earlier, cyber-physical systems can facilitate development of NZE buildings and reduce the impact of the buildings sector on total U.S. energy consumption. Implementing smart environment-aware technologies in buildings to achieve even a modest improvement in efficiency of 20% could yield significant benefits.[159] Integrating technologies into buildings to create smart systems has the potential to deliver savings of up to 70% of building energy use compared with conventional building design; renewable energy could be used to supply energy onsite at the home and close the gap to achieve NZE.[160]

Figure 3. Buildings sector energy consumption[161]



Environment and Carbon Emissions

The buildings sector accounts for 40% of carbon dioxide emissions in the United States.[162] Global emissions from buildings are expected to grow, especially as the populations from countries such as India and China become more urbanized. In the United States and Canada, much of the floor space that will be in use already exists, making retrofits of existing buildings an important part of reducing emissions.[163]

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[157] United States Department of Energy. “Buildings Energy Data Book, Chapter 1: Buildings Sector.” Mar 2011.
[158] United States Congress. Energy Independence and Security Act of 2007. 4 Jan 2007.
[159] Sztinpanovits, Janos et al. “Industry-Academy Collaboration in Cyber Physical Systems (CPS) Research White Paper.” 31 Aug 2009.
[160] NSTC. “Federal R&D Agenda.”
[161] U. S. DOE. “Buildings Energy Data Book.”
[162] U. S. DOE. “Buildings Energy Data Book.”
[163] The Climate Group. “Smart 2020: Enabling the low carbon economy in the information age.” 2008.

Although greenhouse gas emissions are the highest in the buildings sector, according to some studies these represent the greatest potential for reduction of emissions, especially with the implementation of net-zero energy buildings.[164] It is important to consider that the largest carbon savings in the buildings sector by 2030 will come from retrofitting existing inefficient buildings. As buildings become more efficient during their operation, the construction and disassembly of buildings will remain a significant problem. The development of new building materials that have minimal environmental impacts is needed where recycled materials cannot be used. [165] Smart systems that improve building life or for manufacture of new building materials could play a role.

Aging Infrastructure

The aging infrastructure of the United States' transportation system poses incredible technical and economic challenges, with bridges remaining a main concern. In 2008, approximately one in four of the nation's 600,000 bridges was structurally deficient or functionally obsolete, and the number of deficient urban bridges was increasing. The average age of a bridge in 2008 was 43 years. Most bridges are only designed to last 50 years and were not designed for the increases in traffic volume that they are experiencing today. Problems of congestion cannot be overcome unless bridges are expanded or renovated to keep up with increasing volume of light and heavy vehicles. Yet the costs of construction continue to rise, leaving challenges in how to fund the massive costs of new bridges.[166] CPS applications could help to accurately assess the health and safety of bridges, thus enabling more informed and effective allocation of limited resources. New technologies that provide a better understanding of the maintenance requirements of infrastructure can even extend their useful lives. Smart bridge technology today is limited to groups of discrete sensors that provide limited knowledge about large and complicated systems.[167]

Health and Safety

The collapse of the Interstate 35 West Bridge in Minneapolis on August 1st, 2007 sparked a closer look at the condition of the nation's bridges. Although there have only been about 47 deaths due to bridge failures in the United States over the past 20 years, any bridge failure is viewed as unacceptable.[168] Travelers often do not consider themselves at risk when crossing a bridge; they expect for bridges to be functional and safe. CPS research can help ease the burden that states face in trying to keep up with maintenance and help to ensure that there are no preventable accidents involving bridges.

Natural disasters such as earthquakes, hurricanes, and flooding can also cause structural damage to bridges or buildings. Advances in CPS could provide the ability to determine the extent of damage these structures suffer after this type of event and could help to prevent collapses or other types of structural failure.

In buildings where people are constantly present, such as homes, hospitals, schools, workplaces, and factories, building occupant health and safety is a primary concern. Most people spend a majority of their time indoors, where the air quality can be poor compared to outdoors. As buildings become more intelligent and energy efficient, conditions to support the occupants' health, safety, and productivity should be maintained or improved. In fact, as building technologies are applied to achieve net-zero

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[164] NSTC. "Federal R&D Agenda."
[165] NSTC. "Federal R&D Agenda."
[166] American Association of State Highway and Transportation Officials (AASHTO). "Bridging the Gap: Restoring and Rebuilding the Nation's Bridges." Jul 2008.
[167] French, C. et al. "Report on the NSF Bridge Workshop."
[168] AASHTO. "Bridging the Gap."

energy, they should arguably improve these factors and thus increase occupant comfort and safety. Indoor air quality is one area that must be considered as buildings become highly integrated and more energy efficient, since it is linked to occupant health, safety, and productivity.[169] Compromising indoor air quality could increase costs by decreasing the productivity of employees or students. CPS that detect, monitor, and provide feedback or control of indoor air quality or potentially dangerous conditions are one approach to this challenge. Other factors that can affect building occupant health and should be taken into consideration include pollutants, dampness, humidity, and airborne diseases.[170]

CURRENT STATE OF THE TECHNOLOGY

Buildings Technologies

Modern buildings are systems of components consisting of interacting heat exchange, airflow, water, safety, access/security, and movement control subsystems. These subsystems are increasingly coupled using embedded sensing and control systems where state information from one system is directly used to make operational decisions in another subsystem.[171] Integration of different controls and aspects of buildings can help to increase overall building performance by improving control and efficiency while reducing costs. Certain areas of building control are already becoming more connected. For example, coordinating the heating, ventilating, and air conditioning (HVAC) system with other systems in buildings, such as lighting or fire alarms, allows for safer and smarter operation. Some examples of integration in buildings include allowing the fire alarm/life safety system to control elevators or safety exit lighting, or enabling the HVAC system to use air ducts for smoke control and removal in the event of a fire.[172]

In a recent report, the National Science and Technology Council (NSTC) Committee on Technology noted the importance of submetering of building energy and water usage. Submetering represents an area where further research in CPS would be applicable and could help in achieving NZE buildings. Meters are already used in buildings to measure energy and water consumption, although usually on a monthly basis and for a building as a whole. Submetering allows for the possibility of gathering continuous data for individual areas, systems or equipment. Integrating submetering with building automation systems, and the development and implementation of technologies including sensor systems that can evaluate the data collected could lead to greater energy conservation and efficiency. The technical details of submeters themselves as well as the software, data networks, and services must be considered, allowing for applications of research in cyber-physical systems. [173]

Although net-zero energy buildings are not yet required, there are already some that have been designed and constructed. According to U.S. Department of Energy, Energy Efficiency and Renewable Energy’s Building Technologies Program, in 2008 there were ten NZE balance commercial buildings in the United States.[174] Numerous NZE residential buildings have already been constructed, with some notable examples.[175] The National Renewable Energy Laboratory (NREL) Research Support Facility (RSF) in Golden, Colorado is a good example of a smart building that is a highly integrated CPS. The RSF is a

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[169] Persily, A. K. and S. J. Emmerich. “Indoor Air Quality in Sustainable, Energy Efficient Buildings.” 15 Aug 2010.
[170] NSTC. “Federal R&D Agenda.”
[171] Kleissl, Jan and Yuvraj Agarwal. “Cyber-Physical Energy Systems: Focus on Smart Buildings.” 2010.
[172] CPS Security.
[173] “Submetering of Building Energy and Water Usage.”
[174] http://zeb.buildinggreen.com/
[175] http://www.wbdg.org/resources/netzeroenergybuildings.php

222,000 square foot commercial building that was designed to be ultra efficient and achieve NZE status using photovoltaics. Design of the RSF required a “whole building” integrated process, as well as considerations of every aspect of office environment and energy use. There are many examples of technologies that are used in the RSF where cyber and physical components are tightly integrated–energy use is continuously studied and adjusted, automatic windows can be electronically lightened or darkened to control sunlight and heat flow, and carbon dioxide sensors respond to occupancy and control ventilation when needed. Even various factors of human behavior were taken into consideration in order to decrease the amount of energy used per worker and create a redesigned office space.[176]

Smart Sensors and Structural Health Monitoring

Smart sensors are examples of technology that exists today and will expand and become even smarter in the future to play an essential role in CPS. Structural health monitoring (SHM) is an emerging field in civil engineering which allows the possibility of continuous or periodic assessment of the condition of civil infrastructure. Current sensors can discretely monitor factors such as strains, accelerations, deformations, and corrosion potential.[177] SHM could provide the information to assess the condition of bridges, buildings, dams or other structures and help to determine when preventative maintenance is necessary, thus preventing structural failure or costs. Smart sensors, which are typically low cost and battery powered, and have an on-board microprocessor and sensing capability, are a viable option for the sensors to be used in SHM projects.

The European research project Wireless Sensor and Actuator Networks for Critical Infrastructure Protection (WSAN4CIP) has recently successfully demonstrated cost-effective wireless sensor systems for monitoring of electricity distribution and water networks. These types of systems are designed to secure and better manage different types of critical infrastructure. In the test case for a power distribution network, examples of what the secure wireless sensor system can provide include information about and locations of disruptions of power, as well as automatic filming of locations if an intruder is detected. In the drinking water network test case, the system was shown to provide data about water pressure to help indicate if there is a disruption, as well as detection of intruders via open door contacts.[178]

There are numerous bridges which have implemented structural health monitoring systems using sensor networks. One example of a wireless SHM system that is currently being implemented is on the Jindo Bridge in South Korea, a joint project between the University of Illinois at Urbana-Champaign, the University of Tokyo, and the Korean Advanced Institute of Science and Technology. Original sensors were installed in 2009 and more were added in 2010, resulting in a system of sensors along the bridge that measures a total of 659 channels of data. These sensors prove data about various physical states of the bridge and will email the research team if anomalies are detected. The wireless smart sensor nodes are even self-powered by sunlight and wind; the network monitors the battery levels of the sensors. Although the sensor system on the Jindo Bridge is not the first of its kind, it is much cheaper to deploy than systems that have been established on other bridges. This system of wireless sensors runs costs around $100 per sensing channel compared to others such as the $15,000 per sensor system installed on the Bill Emerson Memorial Bridge in Missouri.[179]

In addition to sensor systems, there are other areas of emerging technology involving cyber-physical systems in civil infrastructure. One emerging idea is the possibility of using unmanned air vehicles

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[176] http://www.nytimes.com/2011/02/15/science/15building.htm, http://www.nrel.gov/sustainable_nrel/rsf.html
[177] French, C. et al. “Report on the NSF Bridge Workshop.”
[178] http://www.wsan4cip.eu/news/view/article/wireless-sensors-for-infrastructure-protection.html
[179] “Wireless Monitoring of Civil Infrastructure Comes of Age.”

(UAVs) to "inspect" infrastructure such as bridges and dams. The UAV hovers alongside the bridge or other structure and takes close-up, high quality images which can then be analyzed to determine the structural health. Although still in early development, this technology could provide valuable information that would normally not be able to be obtained during a normal inspection without having to close lanes on a bridge or requiring an inspector to be present.[180]

Going beyond typical sensor systems, there is the possibility of the development of a material that could detect the formation of a crack in a structure. Researchers at Princeton University are developing a sensor composed of an organic laser deposited on a sheet of rubber that changes color when it is stretched. This sensor, which covers a larger area than traditional sensors, could help inspectors by determining small changes in strain that are undetectable to the eye.[181]

BROAD CHALLENGES AND BARRIERS

Building Ownership

Issues of ownership can present a challenge for the emergence of more effective and integrated CPS in buildings. The building industry and consumers are motivated by different and sometimes conflicting factors, making financial incentives for new technology a challenge. Investing in building technologies and systems to achieve energy efficiency can have high first costs, and there can be a division between who makes the initial investment and who pays the cost or reaps the benefits over time. This impacts the decision to invest in the first place.

There are also conflicting interests for the various stakeholders of a building during its delivery and post-delivery life (e.g., design, construction, and operation stages) which may hinder the adoption of intelligent building technologies. Deciding whether the building owner, manager or occupants have ownership of energy use will likely affect whether or not intelligent building technologies are adopted.[182]

Industry Structure and Culture

The current lack of collaboration between the subsectors of the buildings industry, including the architecture, construction, remodeling, operation and maintenance, and demolition subsectors can prevent new buildings from achieving energy, economic, and environmental performance targets and also inhibit the adoption of advanced technology.[183] The structure and culture of the building industry is also generally somewhat slow to change and adopt new technologies.

Training, Education, and Awareness

Increased training and education is necessary to better inform all levels of stakeholders about energy issues and the advantages of high performance buildings, as well as a lack of public awareness about NZE concepts and their benefits. Human behavior, especially how humans and buildings interact, can play a major role in CPS research. Consumers may need incentives such as ease of use or aesthetics in order to fully embrace and adopt future building technologies. The implementation of intelligent building

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[180] "Civil Infrastructure Inspection and Monitoring Using Unmanned Air Vehicles."
[181] "Light-Emitting Rubber Could Sense Structural Damage."
[182] NIST. "Measurement Science Roadmap for Net-Zero Energy Buildings Workshop Summary Report." Mar 2010.
[183] NSTC. "Federal R&D Agenda."

technologies will need to create an optimal work and living environment, be use-friendly and facilitate changes in occupant behavior to achieve greater energy efficiency and performance.[184]

Regulation and Policy

Uncertain, inconsistent, or insufficient policies and regulations for buildings can create greater risk in adoption of advanced technologies in buildings. Most policies are focused on the near term, where encouragement of long-term thinking may be necessary. There is uncertainty in future policies that could encourage support for research and development.[185] In some cases, existing building codes and regulatory frameworks can form barriers to innovation in the construction of NZE or high performance buildings.[186]

For bridges, factors such as cost, policy, and prioritization sway decision-making over the needs of a particular bridge, especially when resources are limited.[187] Since local, state, city, and federal transportation budgets are relatively limited, replacement of the most structurally deficient and functionally obsolete bridges is not a feasible option. Funds for 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.

Building Efficiency Controls

Often buildings do not perform as well as their design specifications for efficiency, and efficiency decreases as buildings age. After a building is constructed, a greater level of monitoring and automatic controls than what is available today will likely be needed to achieve high efficiency in practice. Successful control systems will require well-established protocols and conventions for data compatibility and equipment interoperability, which are currently lacking. Software that will allow for the installation of reliable, sophisticated systems is lacking in part due to the fragmentation of the buildings industry.[188] Also, a lack of dynamic simulation models and robust optimization techniques for discontinuous systems has impeded advancement of control systems.[189]

Integration/Complexity

Integration is necessary for cyber-physical systems in buildings and infrastructure and is challenging. As components of infrastructure become more integrated, complexity will increase along with the possibility of higher variances and emergence of other problems. As CPS for buildings, bridges, and other structures emerge, they will likely be highly technical. Yet the end user, such as a building manager or occupant, must be able to easily use and be provided meaningful information from these complicated systems. Intelligent building or structural health monitoring systems will need to take into consideration the level of knowledge and training of the various end users, and thus be intuitive.[190]

As noted, low- or zero-energy buildings cannot be achieved by individual technologies but require a highly integrated system of diverse technologies and components. Improved performance can be achieved

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[184] NIST. “Measurement Science Roadmap Report.”
[185] NIST. “Measurement Science Roadmap Report.”
[186] NSTC. “Federal R&D Agenda.”
[187] French, C. et al. “Report on the NSF Bridge Workshop.”
[188] Zero Energy Commercial Buildings Consortium (CBC). “Next Generation Technologies Barriers & Industry Recommendations for Commercial Buildings.”
[189] NIST. “Measurement Science Roadmap Report.”
[190] NIST. “Measurement Science Roadmap Report.”

by buildings systems that integrate services including energy management, fire and security, transportation, fault detection and diagnostics, optimal control, real time purchase of electricity, and the aggregation of building stock.[191] Also, cybernetic building systems will be integrated with entities not only within the building, but outside as well, such as with the Smart Grid.[192] For buildings, the main challenge to system integration starts with the design process. Lack of communication and cooperation between the designers, builders, managers, and occupants have resulted in buildings where systems operate mostly independently or even against each other, preventing buildings from achieving optimization.[193]

For structures such as bridges, integration will play an important role for cyber-physical systems such as structural health monitoring. A range of monitoring sensors and systems, protocols, end users, and end-user-targeted data and information will be involved for bridges during their construction and lifetime. Each bridge will need a unique approach to a monitoring system which will likely involve different sensor types. The complexity of the solutions itself presents a challenge for integration. Improvement is needed in sensors and data systems as well as how the different components are integrated, which will involve hardware and software experts, machine learning and pattern recognition experts, electrical and structural engineers, and the owners and operators of the infrastructure systems for which the monitoring technologies are being developed.[194]

Security

Security plays a paramount role and presents numerous challenges for smart buildings and bridges. As buildings and infrastructure become more integrated and the number of components increases, the opportunity for security risks increases as well. These security risks range from accidental or those caused by human error to malicious. For example, a failure in a fire alarm system may cause the HVAC system to shut off or sprinklers to go on while occupants are in a building, causing unintended damage to equipment or inconvenience to the occupants. If hackers gain access to an HVAC system in a critical building such as a hospital, they could cause potential harm to hospital staff, patients, and visitors. Security policies and mechanisms must be properly designed, configured, and enforced, yet there is a lack of models and approaches that take both security and safety into consideration.

In order to overcome the risks of security in CPS in buildings and infrastructure, certain challenges must be faced. Security considerations include intrusion detection, access control enforcement, and network security. Increased integration and connectivity of systems in a building allows for convenient and useful remote access for authorized users but poses the risk of infiltration by unauthorized users. As buildings become a part of the Smart Grid, there are even more opportunities for vulnerabilities in the system. To protect CPS in increasingly integrated buildings and infrastructure from security threats, there is a need for the development of tools and techniques that consider the possible security scenarios and thus ensure that integration does not have negative effects. These verification and validation methods will be especially be important for structures such as hospitals and chemical plants where exploitation could lead to harm to people or the environment. The development of a unified framework for analyzing safety and security and methods to verify and validate the effectiveness of security mechanisms in building systems could counter some of these security problems.[195]

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[191] NIST Measurement Science.
[192] NIST. “Embedded Intelligence in Buildings Program.” 15 Dec 2011.
[193] Zero Energy Commercial Buildings Consortium (CBC). “Analysis of Cost & Non-Cost Barriers and Policy Solutions for Commercial Buildings.”
[194] French, C. et al. “Report on the NSF Bridge Workshop.”
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MEASUREMENT PROBLEMS AND IMPEDIMENTS

Achieving Net-Zero Energy in Smart Buildings

Challenges in measurements for intelligent buildings are numerous, and must be overcome before NZE buildings can reach fruition. New metrology for smart building technologies should include performance metrics and measurement methods, tools to predict performance, protocols to achieve desired performance, evaluation and assessment of the performance of technologies, systems, and practices, and performance-based standards and practices.[196] System complexities and interactions in a building should be captured while innovation in the design and manufacturing of individual components and systems is supported.[197] Today systems in intelligent buildings are unable to effectively communicate, interact, share information, make decisions, and perform smoothly and reliably because of a lack of measurement methods.[198]

Measurement science is needed to support intelligent buildings systems that can detect and respond to faults, operational errors, and inefficiencies to ensure that buildings perform as expected and performance does not decrease.[199] Challenges include but are not limited to the following: data and methods for assessing the performance of buildings, tests and test beds for the evaluation of controls technology and fault detection approaches, best practice guidelines for intelligent design and operation of buildings, measurements to support automation of commissioning processes, and low-cost, reliable energy metering systems.[200] Overcoming these challenges in measurement science could lead to enhancements in communication protocol standards that enable the practical use of integrated systems such as lighting and energy management and achieve increased comfort safety, energy efficiency, and secure, real-time communication of information within the building system. This will be essential for applications such as interconnection between the building and the Smart Grid.[201]

There are currently no standard methods for both collecting and sharing operational data for intelligent buildings, making it difficult to compare and analyze data. There are also no protocols for integrating large quantities of sensor data, and the lack of a standard format for transferring data prevents easier analysis. Data requirements and analysis methods must be determined for more effective performance assessment of a building as a whole, as opposed to assessment of subsystems of components. When using collected data to assess a building's performance, there is a challenge in identifying the critical parameters for building design, the level of accuracy that is needed for the data, and the ways to measure these parameters in real buildings.[202]

To ensure the accuracy of performance measurements before the implementation of intelligent buildings technologies, there is the need for "cyber infrastructure," or physical, virtual, and hybrid test beds. Current testing methods are performed in controlled laboratory environments and are not able to consider the complexities of highly integrated systems.[203] A new test bed could emulate an entire building, with the possibility to test the performance of integrated systems under normal or hazardous operating conditions

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[196] NSTC. "Federal R&D Agenda."
[197] NIST Measurement Science.
[198] NIST Measurement Science.
[199] NSTC. "Federal R&D Agenda."
[200] NIST. "Measurement Science Roadmap Report."
[201] NIST. "Embedded Intelligence in Buildings."
[202] NIST. "Measurement Science Roadmap Report."
[203] NIST Measurement Science.

to determine how they will react to instances such as equipment failures.[204] Other benefits of a test bed include being able to speed up and standardize evaluation and validation, provide a basis of comparison, and reduce need for duplicative test beds. Buildings will not become more intelligent until there are best practice guidelines for intelligent system design, operation, and maintenance, leading to the development of algorithms that respond to exterior (e.g. weather conditions) and interior sources (e.g. occupancy sensors).[205] Test beds could enable more energy efficient building operation through the development of information models and software tools that improve the design and commissioning process and increased use of embedded intelligence that can detect and respond to problems and optimize the control and performance of building systems.[206]

Sensors for Monitoring Bridges and Other Structures

The development of more robust and advanced smart sensors could help provide valuable information about the health of various structures, including bridges, tunnels, buildings, and water distribution systems. While “smart bridge” technology is emerging, current systems that use discrete sensors are inadequate to completely monitor the large, complicated systems that suffer local abnormalities.[207]

Sensors can provide valuable insight on the structural health and condition of bridges or buildings, but full scale, effective networks of sensors on bridges (or other types of civil infrastructure) will not become common until challenges are overcome. The continual improvement of wireless sensors is essential because they will reduce the need of also installing costly and bulky wires. It must be determined what the sensors will measure about the bridge (e.g., strain, cracking, corrosion, scour, environmental conditions). Based upon the requirements, sensors must be developed to address certain environments or conditions. Examples include sensor technology for underwater or extreme temperature environments, sensors that can self-monitor their health or sensors that can measure the aging effects of materials. Sensors with the ability to accurately detect and predict the rate of something like corrosion would be especially useful for areas of the bridge that cannot be monitored visually.[208]

One of the main difficulties in implementing a sensor network for structural monitoring is that damage is normally localized, meaning that the sensors must be densely allocated over the whole structure and be able to detect very small changes in a large system in a timely manner in order to be most effective. There are challenges in reconciling the sensor placement, especially when considering the high cost of deploying large sensor networks. In a system of sensors, it is likely that one or more sensors will fail, and the remaining sensors must be able to compensate for that failure. The design lifetime of the sensors and system as a whole present a challenge, because most structures such as bridges are designed for lifetimes of 50 to 100 years or possibly longer. How long will the sensors last and then how and when will they be replaced to ensure continuity? Hardware and software upgrades should be easily implemented over the lifetime of the structure, and these costs of replacement and maintenance should be considered.[209]

There are numerous other challenges and concerns that must be eliminated to achieve effective, reliable, and economical structural health monitoring using sensor systems. There are many different types of sensors that measure different properties at different rates, some of which were not designed for applications such as bridge monitoring but may be of use (e.g., traffic or security cameras). Also, just

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[204] NIST. “Embedded Intelligence in Buildings.”
[205] NIST. “Measurement Science Roadmap Report.”
[206] NIST. “Embedded Intelligence in Buildings.”
[207] French, Catherine et al. “Report on the NSF Bridge Condition Monitoring and Prognostication Workshop.” Nov 2008.
[208] French, C. et al. “Report on the NSF Bridge Workshop.”
[209] French, C. et al. “Report on the NSF Bridge Workshop.”

because something can be measured does not mean that the measurement will necessarily be useful for the purpose of determining structure health. Ideally, all data gathered by sensors should be useful.

The development of "active" sensors that excite and measure structural response at various locations could enhance the capability of detecting small changes, resulting in more effective monitoring. Smart sensors should have more computing power to be able to handle large amounts of data, while not becoming too expensive. There is the need to demonstrate the effectiveness of SHM systems, but there are generally no real world structures on which to test them. Laboratory testing is necessary in the development of these systems but not sufficient to gauge how they will react on an actual bridge.[210]

Sensors for Surveillance and Monitoring

The smart buildings of the future will ideally be equipped with a variety of sensors, ranging from visual, infrared, thermal, magnetic, and others. Using such a suite of sensors, it could be feasible to monitor the location of anyone in the building, using some device that the person will wear or just by using visual sensors that develop models of a specific person as the person enters the building. Challenges remain in the interpretation of the sensory data, so that the "building" can monitor the activities of all (or a subset of) the individuals inside the building. Thus, it will become feasible to detect the person who tries to forcefully open a door, as well detect that the elderly resident of apartment X21 cannot get up from the couch and needs help. Sensors for surveillance and monitoring of building also relate to healthcare and are discussed in Chapter 5.

The sensory suite and the associated network should be taken into account from building design and not afterward, as is current practice. A cultural barrier stems from the current practices of building design and surveillance networking, which have little interaction.

Data Acquisition and Interpretation

Today's sensors do not directly measure damage or performance; they provide data from which these properties must be determined. Since sensors and other systems in bridges, buildings, and other structures gather large quantities of data, there is the need to organize, process, and obtain meaningful results from that data in a timely and effective manner. Interpretation of data is done for the purpose of making it easier for the end user to come to conclusions and is especially dependent upon the end user's level of knowledge and training. Challenges remain in methods of data acquisition and interpretation. An increase in the amount of sensors will also increase the amount of data that is gathered and must be analyzed in order to gain meaningful information about the structure, and networking becomes more difficult. Not only will the amount of data increase, but there will be different types of data and sensors will supply various sizes of data sets. The data from both the sensors and human inspectors should be linked and analyzed together.

Many challenges arise from the gathering, transmitting, and processing of large quantities of data. Decisions must be made about whether sensors should perform pre- and post-processing before transmitting data, or should the processing occur at a central node. If sensors were able to distinguish between useful and "bad" data caused by noise or other interference, then unnecessary transmitting or processing of unhelpful data could be prevented. For structural health monitoring systems that are put into place on existing bridges, there is a challenge in establishing a baseline to which the newly collected data can be compared. New bridges do not have this problem because data will have been gathered since their construction. Existing structures have unknown levels of stress and deterioration, so there may be a

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[210] French, C. et al. "Report on the NSF Bridge Workshop."

challenge in establishing baseline measurements and parameters. Analytical or numerical models of the structure, sensing system, and what is trying to be detected will help determine how the information that is gathered is translated into knowledge about the state of the structure yet are not currently developed.[211]

For intelligent control in buildings, there is also the lack of information models and standards that capture measurement and other issues that arise. There are limitations to the few sensors that are available, and there are no methods or standards for data collection and transfer, and further modeling based upon the data. Once information is gathered from sensors, there must be models or methods to be able to identify poorly performing buildings. Without a way to present the data in a manner that is comprehensible and useful to the end user, there is no effective way to make decisions.[212]

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Smart Transportation and Mobility

INTRODUCTION

Transportation cyber-physical systems (CPS) already play a role in the daily life and economy of the United States. This role is expected to increase in the future as higher levels of transport autonomy, safety, and convenience are achieved. The complexity of transportation systems as a whole, as well as smaller components such as vehicles, is growing at an exponential rate. Next-generation transportation systems must be highly networked and dynamic, while maintaining high system performance and low cost. Everyday tasks or events, such as commuting by automobile, train, or airplane, depend on complex yet reliable and seamless interactions between the vehicles' computer systems and physical systems while under control by human operators or end users. Today's transportation systems are being designed to be more competitive within their respective industries by adding more complex features and capabilities to increase energy efficiency and safety. Also, CPS advances in transportation can be applied in the military to maintain the edge in fighting capability. The ability to affordably design and adopt energy-efficient transportation CPS supports U.S. economic, national security, and environmental objectives.[213]

The major markets where transportation CPS can be applied include ground transportation or intelligent transportation systems (ITS), or air transportation, mainly the Next Generation Air Transportation System (NextGen), which can be thought of as large-scale CPS. The cyber or computer components of automobiles, aircraft, and other vehicles have been increasing and will continue to play a larger role in these systems. By 2015, as much as 40% of an automobile's value will be in cyber-physical components (electronics, sensors and actuators, and embedded software). The air transportation sector is also heavily dependent on cyber-physical components and composes a significant portion of U.S. exports.[214]

The cost of aircraft is moving increasingly toward software and systems and away from structures, aerodynamics, and propulsion.[215] For example, in the late 1980s, software for the 747-400 required 10 megabytes of memory; in the early 1990s, software for the Boeing 777 required 100 megabytes of

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memory and 10 million source lines of code (SLOC). It is expected that developing aircraft such as the 787 will require even higher levels of software size and system complexity. Automobiles today have about 10 million SLOC and consist of 1–10 networks—figures that are expected to increase to hundreds of millions of SLOC and tens of internal and external networks to accommodate increasing technological needs.[216]Advances in CPS will be needed to ensure the safety and security of these increasingly complex and networked automobiles and aircraft. One example of a CPS in transportation is an aircraft whose smart sensor fabrics and onboard networking enables self-monitoring of its systems and structural health while performing real-time diagnostics and coordination with ground stations.[217]

Research in CPS is necessary to transform the national airspace system (NAS), which is the safest in the world yet is operating under a loosely integrated network of systems, procedures, and infrastructure, much of which is decades old.[218] Since national airspace is already crowded, events such as severe weather can cause significant delays and result in loss of both money as well as energy. Better management of air traffic can result in a more efficient system, increasing the on-time performance of flights as well as reducing energy consumption which may result from delays. One main focus for increasing the efficiency and safety of the United States' air transportation system is in the development of NextGen. NextGen, a transformational effort for air traffic control led by the FAA, envisions how the nation's aviation system will operate in 2025 and beyond. NAS was already operating at near capacity in 2004, and it is expected that the demand will grow two-to-three fold over the next 20 years. NextGen will transform how the U.S. air transportation system is operated and managed. This will improve safety, speed and efficiency and mitigate the environmental impacts of air transportation, while accommodating increased demand.

CPS will be critical to developing and implementing NextGen in the United States as well as worldwide. Areas where CPS can be applied, and that will require both new technologies and the transformation of existing technology include satellite navigation and control of aircraft, advanced digital communications, advanced infrastructure for greater information sharing, and enhanced connectivity between all air transportation system components. Reliable, seamless integration of the technological (e.g., computer-based) and physical elements of the system will continue to be essential for the safe operation of air transportation. This requirement will become even more essential in next-generation systems in which the level of automation in all parts of the systems increases, ranging from aircrafts to ground infrastructure, communication systems, and air traffic controller decision support tools.[219]

Fifteen years ago, the U.S. Department of Transportation (DOT) launched the Intelligent Vehicle Initiative, which focused on preventing crashes by helping drivers avoid mistakes. Europe has also paid more attention to road safety in recent years; the European Road Safety Action Program aimed to reduce road fatalities by 50%% by 2010.

The reason behind this shift in focus is human life. According to DOT, more than 42,000 people die each year in the United States as a result of 6.8 million accidents (www.itsdocs.fhwa.dot.gov//). Highway injuries also have a strong impact—3 million Americans were injured in 2001. Survivors often sustain multiple injuries and require long hospitalizations. The cost is more than $230 billion a year—representing a greater share of the nation's health care costs than any other cause of illness or injury. The

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[216] Poovendran et al. "2008 HCTCPS Workshop Report."
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situation is even worse in developing countries. In 2003, more than 104,372 Chinese died as a result of traffic accidents—on average, 286 people around the world die each day.

The ITS market covers the use of smart technologies such as electronics, communications, and information processing technology that are designed to improve aspects of surface transportation and create safer, smarter, and interconnected transport infrastructure. The DOT ITS Program seeks to "research and facilitate a national, multi-modal surface transportation system that features a connected transportation environment around vehicles of all types, the infrastructure, and portable devices to serve the public good by leveraging technology to maximize safety, mobility, and environmental performance."[220]In this system, vehicles and infrastructure would "talk" to each other and share key information such as real-time traffic, location, or speed. If a vehicle could "see" other vehicles around it, drivers could know when there is a car in a blind spot when changing lanes, or be alerted of upcoming roadway hazards or congestion. In such a system, drivers would be able to check a range of commuting travel options before leaving home, such as travel times, costs, traffic, and environmental footprints.[221]

KEY DRIVERS

Congestion

Both the nation's air and ground transportation spaces are crowded, and CPS can provide solutions or methods to deal with congestion in the future. Congestion is a major problem for ground transportation. In 2010, commuters dealt with a cumulative delay of 4.8 billion hours—or an average of 34 hours per auto commuter for the year, with levels as high as 74 hours for the Washington, D.C. metro area. This excess travel time due to congestion, plus the 1.9 billion gallons of wasted fuel, represents a cost of $101 billion.[222] One cyber-physical system solution for ground transportation is the use of radio communications to report traffic and navigation information to individual vehicles. This empowers the driver to decide upon alternate routes based on data. On a larger scale, this could lead to real-time traffic management, in which the overall traffic system changes and adjusts based on the activities of individual vehicles.[223] In this scenario, vehicles could communicate with the traffic infrastructure to exchange time-critical and less-time-critical traffic and route condition updates to help alleviate congestion.[224] Congestion has also been increasing in aviation, especially for busy metropolitan airports. As air transportation becomes more crowded, systems such as NextGen hope to reduce congestion by increasing efficiency.

Safety Reduction and Accident Prevention

Safety is one of the most important drivers for transportation -CPS and is a priority for all transportation sectors. According to the Centers for Disease Control and Prevention, preventable injuries and deaths from motor vehicle crashes in 2005 led to more than $70 billion in costs.[225] CPS in transportation aim to reduce avoidable crashes that cause unnecessary deaths, injuries, and property damage. Across the avionics, automotive, and railroad sectors, the ultimate goal is to eliminate fatalities and accidents. The

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current state of automobile safety focuses on features within the vehicle; aircraft safety relies on well-defined protocols and procedures with heavy human intervention. In the future, cyber-physical systems of networked vehicles and transportation infrastructure could exchange safety-critical messages and information to increase the level of safety. Aircraft will have higher situational awareness in the air and on the ground. Vehicles approaching an unsafe or congested roadway would be given advance notice, allowing operators to make safer and timely decisions to avoid a hazardous condition or congestion.[226] Current driver-assist systems show some potential for increasing safety. Greater advances could provide significant improvements in accident avoidance and mitigation.[227] For ground transportation, there is the potential that combined vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication systems can potentially address over 80% of -vehicle target crashes each year.[228]

Environmental Issues

The potential benefits of transportation CPS include reducing pollution caused by idling vehicles, stop-and-go traffic, and delayed aircraft, as well as by more energy-efficient automotive and aviation vehicles and transportation in general. The NextGen effort will address the environmental impacts of aviation by reducing noise and emissions as well as by improving energy efficiency, and is projected to save 1.4 billion gallons of aviation fuel and reduce carbon dioxide emissions by 14 million tons by 2018.[229] Emissions from car tailpipes are the largest human-made source of carbon dioxide, nitrogen oxides, and methane. Greenhouse gas emissions are the greatest when cars are moving in congested and free-flowing conditions.[230]

Renewable fuels as well as electric, hybrid, and more-fuel-efficient vehicles can also be applied to transportation systems to increase sustainability. While CPS research does not contribute directly to the development of renewable fuels, it can play a major role in making the integrated system that utilizes these fuels more efficient and economical to operate. CPS can also be used to increase the efficiency of automobiles and aircraft by using wireless technologies to reduce wires in vehicles or by reducing the number of onboard computers, thus reducing fuel use.[231]

Convenience/Connectivity

Convenience and connectivity are both social and technological drivers in the development and advancement of systems.CPS. The average American commuter spends 89 minutes in ground vehicles, 127 minutes on a domestic flight, or 50 minutes in a train. .The amount of time spent in transport systems has transformed the amenities that are available to travelers. Cars now have personalized options such as climate control, Bluetooth and Facebook connectivity, and real-time traffic navigation. Buses may offer wireless connectivity and travelers can check the bus location in real time using a smartphone. Some airplanes are also Wi-Fi ready and allow travelers increasingly varied personal entertainment options.

Highly connected vehicles provide information, entertainment, and convenience options for the driver, but also improve the ease with which software can be corrected or updated and diagnostics can be

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[231] Poovendran et al. "2008 HCTCPS Workshop Report."

performed.[232] Consumers expect wireless access to the internet when driving, flying, or riding the train. The ideal future transportation CPS would therefore allow the consumer to remain connected, while also personalizing vehicles and providing comfort and convenience.

Connectivity can also be applied between vehicles and infrastructure. The connectivity of vehicles to infrastructure could greatly reduce traffic, which would reduce emissions and make commutes more convenient and efficient for travelers. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) systems are applications that demonstrate the potential of CPS in transportation. By connecting vehicles with other vehicles as well as with the transportation infrastructure, there is potential for lower accident rates and a major market for electronics suppliers and software companies. It is likely that almost every passenger vehicle sold in 2020 will have V2V systems and that these systems will ultimately lead to autonomous driving. Although the connected car is just emerging, future possible communication links could enable innovation in applications and services that will benefit drivers, passengers, automotive manufacturers, and society in general.[233]

Autonomy

Recent reports indicate that the trend toward autonomy is growing in all transportation sectors.[234] The evolution of autonomous transportation systems promises to save lives, increase throughput, and even reduce fuels costs. Whether this takes the form of a self-parking or self-driving vehicle, or a military aircraft automatically completing a mission, the future vision of autonomy can potentially improve safety, efficiency, security, and convenience. An example is automated parking assistance, which is already available in many new model vehicles. Unmanned aerial vehicles (UAVs) are already used in military operations in Iraq and Afghanistan and have been used in civilian airspace to collect data.

CURRENT STATE OF THE TECHNOLOGY

Decision makers, industry officials, and experts in the United States agree that intelligent transportation systems and connected vehicle technologies are the future of travel, and will improve safety, efficiency, and the economy.[235] Today, humans play an active role in both automotive and aviation operations. People drive vehicles while sensor systems alert the driver to various dangerous situations (lane changes, crash ahead). Although modern aircraft have a larger amount of automation, pilots still play an essential role in control and UAVs have yet to make a significant presence in NAS. However, CPS are increasingly being applied to make it easier, safer, and more convenient for humans to operate and use transportation systems.

Connected Vehicle Technologies

The main focus in ITS research that is particularly related to CPS is connected vehicle technologies, specifically V2V and V2I communications. Examples of V2V applications in vehicles include blind spot/lane change warnings, forward collision warnings, electronic emergency brake lights, intersection movement assistance, do not pass warnings, and control loss warning. Examples of V2I applications

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[232] Juliussen and Robinson. “Is Europe in the Driver’s Seat?”
[233] Juliussen and Robinson. “Is Europe in the Driver’s Seat?”
[234] Poovendran et al. “2008 HCTCPS Workshop Report.”
[235] 18th World Congress on Intelligent Transport Systems. “America’s Transportation Leaders Agree that Intelligent Transportation is the Future of Travel.” 21 Oct 2011.

include traffic signal violation warnings, stop sign violation warnings, pedestrian crossing information, and left turn assistance.[236]

One example of a technology that could be applied to future systems with V2V communications is an algorithm being developed by the Massachusetts Institute of Technology. The algorithm predicts when a driver will run a red light, allowing the possibility that this information could be used to alert other drivers in the intersection, thus reducing the probability of a collision.[237]

DOT has joined with the Crash Avoidance Metrics Partnership to develop and test V2V safety applications with prototype vehicles, and it has been gathering data to assess usability and safety. Safety Pilot Driver Clinics, for example, will help determine driver response and acceptance of V2V communications technologies. A Safety Pilot Model Development is also planned and will include as many as 3,000 vehicles, including cars, trucks, and buses that have a mixture of integrated safety applications as well as aftermarket devices. The vehicles will communicate using Dedicated Short Range Communications technology that broadcasts over a dedicated frequency of 5.9 gigahertz. Results from this program will inform the National Highway Traffic Safety Administration (NHTSA) as it decides whether or not to take regulatory action concerning V2V and V2I communications systems.[238]

Examples of Current Autonomous Vehicles

Google Car
Google has developed numerous autonomous Toyota Priuses that have already driven more thanover 190,000 miles in city traffic, busy highways, and winding country roads. The Google Car drives autonomously using a large laser mounted on top of the vehicle, four radars, global positioning system aidGPS, and many other sensors to measure and react to the surrounding environment while avoiding obstacles and obeying traffic laws.

DARPA Urban Challenge
In 2007, the Defense Advanced Research Projects Agency held the Third3rd Urban Challenge, in which competing autonomous vehicles had to drive in an urban environment among other autonomous vehicles as well as those driven by people.

Grand Cooperative Driving Challenge
The first Grand Cooperative Driving Challenge was held in the Netherlands in May 2011. Autonomous vehicles competed and had to communicate with each other while navigating urban and highway environments to perform cooperative driving.

Multi-Vehicle Cooperative Driving and Intersection Control Research

Individual-vehicle-control research concentrates on guaranteeing driving safety. As previously noted, increased traffic congestion is now making multi-vehicle-control research an important topic for research in CPS. Twenty years ago researchers started examining lane changing- and lane-merging-control problems. A solution to those problems comes from the path planning literature, which studies how to generate a collision-free driving path or trajectory under the given vehicle dynamics. On the basis of these studies, researchers now consider cooperative driving with inter-vehicle communication to be a more promising answer to the problems of traffic jams and collisions.

Japan's Association of Electronic Technology for Automobile Traffic and Driving was the first to introduce cooperative driving in the early 1990s. Using appropriate inter-vehicle communication to link vehicles, cooperative driving lets vehicles safely change lanes and merge into traffic, improving traffic control performance. Since then, many other studies have addressed the feasibility and benefits of

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[236] http://www.nhtsa.gov/DOT/NHTSA/NVS/Crash%20Avoidance/Technical%20Publications/2010/811381.pdf
[237] http://web.mit.edu/newsoffice/2011/driving-algorithm-1130.html
[238] U.S. DOT RITA. "Connected Vehicle Research."

cooperative driving—for example, California's Partners for Advanced Transit and Highways project (www.path.berkeley.edu), the European Union's Chauffeur project, and Japan's Demo 2000 Cooperative Driving System.

The latest efforts extend cooperative driving technology to road intersections, which involve issues that are more complex than lane changing and merging problems. For example, researchers have analyzed how inter-vehicle peer-to-peer communications help vehicles near an intersection collaborate with each other. They view each vehicle as an individual agent and estimate the proper driving schedule through planning (and perhaps negotiation). Then they modify virtual-vehicle mapping and the trajectory planning method to handle the collision-free requirements and vehicle (dynamic and geometric) constraints. For example, one can imagine that each vehicle approaching the intersection transmits its movement information and driving plan to the repeater installed at the intersection's center. The repeater then transfers this information to other vehicles and to the network.

Research along this path is restricted by the different technologies available in different vehicles, but it could accelerate if automotive manufacturers agree on a communication protocol.

Intelligent Sensing for Cyber-Physical Smart Cars

As noted earlier, technology trends in consumer automobiles are moving toward increased autonomy. Early developments in -CPS for vehicles include traction and stability control, cruise control, and anti-lock braking systems that increase safety. Communication between vehicle components provides information such as velocity, acceleration, and traction for the purposes of navigation, infotainment, and other uses. These systems do not take control of the vehicle, but they provide information to the driver who ultimately makes a decision on how to act. Safety behaviors such as shaking the steering wheel to gain the driver's attention cannot alter the situation but can provide necessary information to the driver to enable action. Systems that perceive the environment outside the car as well as the environment inside the car are of particular importance. Specific examples of these intelligent systems are discussed below.

The state of the art considers three kinds of intelligent-vehicle sensing, namely *out-vehicle environment, in-vehicle environment, and vehicle state.*

Out-vehicle environment sensing involves collecting information about the driving environment. Specific topics include extracting lane boundaries when they are not clearly marked or in adverse weather conditions; detecting other vehicles that are nearby and estimating their kinematics (position, speed, and acceleration); recognizing traffic signs and traffic lights; detecting unexpected traffic participants (such as pedestrians); and sensing obstacles of all kinds. Sensing the environment out of the vehicle is a very challenging task, especially when weather changes are taken into account. Researchers have tried conventional vision-based pedestrian detection but this is a difficult task because pedestrians wear clothes in different styles and colors and may carry items such as bags, objects, or hats of different shapes. In addition, ambient illumination conditions (the sun hides behind the clouds for a moment) introduce distortions in the process. To deal with these problems, current research on the problem uses images fused from multiple wavelengths. For example, research may use thermopile or infrared sensors and may fuse the images acquired from different sensors to increase robustness. There is also current research on recognizing the weather, such as subspace methods to judge rainy weather by detecting raindrops on the windshield. There is also current work on integrating lane detection and vehicle localization, as well as vehicle departure monitoring. Localization is also an important functionality for navigating intelligent vehicles. However, the data obtained from the global positioning system (GPS) and cameras is often uncertain or even momentarily unavailable (in urban areas, for example). Current approaches combine

GPS absolute localization data with data computed by a vision system to provide accurate vehicle position and orientation. Usually, one integrates the position and orientation data into a global reference using a map of the environment and then estimates localization parameters using a particle filter.

Vehicle-state sensing is of a lower level and concentrates on measuring a vehicle's movement and monitoring its actuators. Examples include detection of vehicle position, velocity, and acceleration; engine pressure and temperature; tire pressure; temperature; friction coefficients; and similar variables.

In-vehicle environment sensing involves collecting information about the driver and the passengers; i.e., behavior monitoring. Specific topics include monitoring the driver's eye movements, vigilance, and tiredness; the interaction inside the car; and so forth. Sensing inside the vehicle is equally important to out-vehicle sensing. The driver's diminishing vigilance level has become a serious problem in traffic safety. NHTSA estimates that in the United States, drowsy drivers cause 100,000 accidents each year, resulting in more than 1,500 fatalities and 71,000 injuries (www.aaafoundation.org/). Among different approaches in this field, monitoring the driver's head position has received considerable interest. This could be used to infer the driver's fatigue level (especially when combined with a driver-eye-gaze tracking system) and implement a "smart" airbag.

Several researchers have proposed novel ideas for inferring driver fatigue. New ideas come from a psychology perspective that defines monotony as an exogenous contributing factor of fatigue. An integrated fatigue detection system uses driver-head-pose and eye-gaze tracking as well as road monotony analysis. NHTSA also pointed out that although airbags saved more than 6,000 lives by the end of 2000, they also killed more than 200 occupants through inappropriate deployment (www.iihs.org/safety_facts/qanda/airbags.htm). In response, NHTSA issued a set of regulations mandating smart airbags that can adapt intelligently to the occupant. The head position algorithm must be robust to lighting conditions and uncontrolled driver postures. Infrared cameras can help eliminate the disturbance of poor lighting conditions. Different signal processing algorithms can help deal with occlusions and the presence of other competing head-like objects in the scene (such as hands).

There are different challenges in sensing out of the vehicle and in the vehicle. The major difference is that the illumination environment inside the car can be potentially controlled, while the outside illumination environment is subject to the weather conditions. The challenges for the inside car analysis are related to the analysis of human behavior and teams of engineers and psychologists are needed to address these problems in the future. Regarding out-of-vehicle sensing, the current trend of letting "the sensors do the work"—using sensing across the spectrum (e.g., infrared, thermal imaging)—is useful but restricted by the difficulty of the motion segmentation problem. Specifically, the humans or other vehicles that will be detected are usually also moving. Several ambiguities can arise such that it is not possible to detect humans or other vehicles because of the "special" way in which they are moving. To address these issues, one would require an approach in which information fusion from a variety of sensors eliminates ambiguities.

Advanced user interfaces are also needed to convey to the driver the multitude of information that the system captures. Intelligent assistance systems can show drivers more information—for example, using smart-tire-monitor sensors to display the status of the wheels, or the space around the car, etc. As a result, information visualization, display placement, and viewing methods are currently topics attracting attention in the broad engineering community and the Human Machine Interaction disciplines. The newest ideas propose interfaces for maximization of information representation. The idea is to collapse many of the separate dashboard controls, displays, and systems into a single multifunction display. A more challenging idea is to switch the representation of information to match different driving situations depending on context (e.g., city versus highway driving). Alternatively, it is easy to overload the average human driver with information. Thus, it is important to investigate this topic together with psychologists and ergonomists.

Aviation

NAS, which is currently used to manage air traffic, is generally thought of as safe and effective but not as coordinated and efficient as .possible. For this reason, the Federal Aviation Administration (FAA) has envisioned NextGen replacing NAS. While NextGen will not be fully implemented until 2025, substantial benefits are already emerging. For example, in 2010 the FAA approved the use of Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B provides both air traffic control and pilots on ADS-B-equipped aircraft with a constantly updated display of real-time traffic and other information such as speed, altitude, and aircraft type. ADS-B also provides weather information, allowing for heightened situation awareness. ADS-B technology will be required for aircraft in most airspace by January 1, 2020.[239]

Another developing technology in NextGen is performance-based navigation (PBN). PBN allows for more efficient design of airspace and procedures, which leads to improved safety, airspace access, and predictability of operations, as well as reduction in delays, fuel use, emissions, and noise. The PBN framework defines aircraft performance requirements and provides a basis for the design and implementation of automated flight paths, airspace design, and obstacle clearance, and is not constrained by the location of ground navigation aids. The two main components of PBN are Area Navigation (RNAV), which enables more flexibility for point-to-point operations, and Required Navigation Performance (RNP), which monitors the navigation performance of the aircraft and alerts the crew if any requirement is not met during an operation. Both RNAV and RNP allow the aircraft to determine whether it can safely qualify for an operation based on the specified performance level. While the use of PBN is not yet widespread, its benefits are already being seen at some airports. In Atlanta, arrivals that utilized PBN procedures saved hundreds of thousands of gallons of fuel, and carbon dioxide and air pollutants were reduced by thousands of tons.[240]

The use of UAVs is also indicative of an increase in autonomy in defense applications. UAVs are used frequently in military airspace and have even been introduced into civilian airspace for data collection purposes.[241]

BROAD CHALLENGES AND BARRIERS

There are a number of broad challenges, both technical and non-technical, that must be overcome before the envisioned smart transportation systems of the future can come to fruition. The challenges today are greater than those faced in the past and will continue to grow as individual systems evolve, operate with greater autonomy and intelligence, and operate as part of a networked system of systems. The challenges will also increase in complexity as future generations of unmanned air systems begin operating in national airspace.[242]

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[239] FAA. "NextGen Implementation Plan."

[240] FAA. "NextGen Implementation Plan." http://www.faa.gov/news/fact_sheets/news_story.cfm?newsid=8768

[241] Poovendran et al. "2008 HCTCPS Workshop Report."

[242] Winter. "CPS in Aerospace."

Resources for CPS

Even though transportation infrastructure is already aging, it is too expensive to completely replace, which creates the need to integrate new CPS into the existing infrastructure. Federal, state, and local government budgets leave little room for funding for advanced transportation improvements. Resources and capacity are lacking for cities and states to implement new highway and transit transportation infrastructure. To see more integrated transportation systems, a shift in competition may be required. The design, planning, and operations of transportation have been affected by competing interests, incompatible technologies, and disparate systems, limiting the ability to create a coordinated regional vision for required infrastructure.[243]

Governance and Certification

The tools and techniques used in transportation to certify and develop safe, reliable products are effective for present-day systems, but they might not be economically or technically feasible for more complex, larger future systems. Challenges exist in implementing certification of new ITS or individual technologies, including determining what should be certified, what entity is responsible for certification, and how the certification should be accomplished. Issues for the DOT Intelligent Transportation System Connected Vehicle Research (which can also be applied to other areas of transportation CPS) include uncertainty about what policy or legislation will be required to successfully launch and sustain new technologies. Another issue is determining what entities will potentially own and govern connected vehicle research systems, components, and data. Also in question is what elements need to be governed and how to address public concerns for privacy.[244]

Human-in-the-Loop/Autonomy

Even though there is a trend toward increasing autonomy in transportation, it is critical and necessary to ensure that human interaction remains a consideration, and to continue to keep humans involved. Humans play active and passive roles in transportation and have varying degrees of capabilities. Representing human behavior in the design, development, and operation of CPS is thus a challenge. To meet certain goals, such as zero fatalities, a better understanding of human-cyber interaction is needed to incorporate human behavior into models for these systems. Incorporating human-in-the-loop considerations into the design and operation of transportation -CPS is critical to dependability and predictability. New autonomous control systems will need to operate faultlessly alongside human systems. Measures are needed to determine how safe this interaction will be, without sacrificing the benefits of autonomy.[245]

Safety and Security

Safety is a paramount concern for any transportation system. As technology levels in vehicles drastically increase, the emphasis on safety and security must keep pace. One of the grand challenges that the automotive sector is working to achieve is “zero fatality” highways. It is expected that increased automation can help to achieve safety goals, but not without some challenges. There is a possibility that integrated technologies will create more distractions for drivers, potentially causing safety issues.

Security is an especially important challenge for transportation CPS because of the central role these systems will continue to play in critical infrastructures and safety-critical applications, which makes them

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[243] Transportation for America, ITS America et al. “Smart Mobility for a 21st Century America.” Oct 2010.
[244] USDOT RITA. “ITS Strategic Research Plan.”
[245] Poovendran et al. “2008 HCTCPS Workshop Report.”

an attractive target for cyber attacks.[246] The implementation of NextGen would require a highly integrated network over various aspects of the aviation travel sector. In the past, some parts of the network were physically separated in order to ensure the highest level of security. Increasing integration calls for security measures that are not physical, but more logical, while still ensuring there will be no security compromise. To ensure high levels of security for a highly integrated network, breakthroughs in security technology must be made that can be applied worldwide over various systems.[247] Security threats will be a continuous concern and challenge in transportation CPS. The systems will be constantly changed and updated, creating more opportunities for weaknesses or faults to be potentially exploited.[248] As CPS become more complex and interactions between components increase, safety and security will continue to be of paramount importance.

MEASUREMENT PROBLEMS AND IMPEDIMENTS

There are a number of measurement issues related to CPS for transportation. For example, protocols are needed to set boundaries for interaction between vehicles (and humans, and groups of vehicles) as they relate to high-level decisions. In addition, a wide variety of system components must be able to communicate effectively (i.e., be interoperable). Timely standards and certification processes will also be required to adopt new systems.

Interoperability

Creating the transportation system of the future with breakthrough safety, advanced features, affordability, and dramatic reductions in energy consumption will require greater capability to handle multisystem complexity. Increased interactions and complexity between subcomponents, components and infrastructure, and components and humans and the environment could result in undesired or unintended behaviors that current tools and techniques are not designed to handle.[249]

Some of the greatest challenges exist in the interactions between different modules and components. Embedded systems are composed of heterogeneous components designed and implemented by different suppliers.[250] As the number and features of these components increase, interoperability becomes a greater barrier. The challenge is to ensure interoperability between heterogeneous modules and components that have been provided by different vendors. Interoperability between different generations of vehicles is also a challenge, as well as the fact that software updates will have to be provided to vehicles in the future as requirements change. While sometimes viewed as a secondary issue, ensuring interoperability between cyber-physical tools and technologies for new and legacy systems is a necessity.[251]

Measurement of Complex Systems

It becomes a challenge to measure the performance of CPS exactly because they are the amalgam of several components in a network. The problem resembles in many ways the measurement of behavior, and it could be possible to adopt similar paradigms. For example, CPS have inputs that are signals and have outputs that are decisions or motions. Between the signal analysis and the output decision or motion

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[246] NITRD. “Winning the Future.”
[247] Winter. “CPS in Aerospace.”
[248] Adam. “Workshop on Future Directions in CPS Security.”
[249] Poovendran et al. “2008 HCTCPS Workshop Report.”
[250] Amici, Al et al. USCAR Briefing to NSF.
[251] Poovendran et al. “2008 HCTCPS Workshop Report.”

lies a vast array of competences (procedures, software, firmware) that facilitate the analysis. At the same time, these procedures and data structures become indispensible tools in the evaluation of CPS.

Verification, Validation, and Certification

Verification, validation, and certification is a primary problem for future transportation CPS. Current methods and techniques for verification and validation are challenged by the scale of emerging systems, greater demand for advanced capabilities, and the combination of discrete and continuous aspects in CPS. Aerospace systems are becoming more software intensive, and the size of software is increasing exponentially, reaching 100 million and likely to exceed one billion lines of code. There is a similar trend in the automotive field. As the level of software increases, so does the cost of verification and validation. As a result, software verification is becoming one of the leading components of system cost.[252]

As systems become more integrated, verification and validation will become an even larger challenge. Scalability is also an issue when verification and validation must be applied to larger systems of systems, as the components and interactions increase and become more complex. The challenge is to ensure the vehicle will operate correctly before it is physically tested.[253] Verification and validation techniques that apply to both humans and the environment they interact with must be developed. Future transportation CPS will be evolutionary, and software changes could occur often. This will necessitate the ability to integrate or replace new subsystems and technologies without having to recertify the entire system to avoid repeating high costs.[254]

Shared Resources/Mixed Criticality

As transportation CPS become more complex, it will be necessary for the system to assess criticality. This means, for example, not allowing a lower criticality process (e.g., passenger entertainment) to inhibit a higher criticality process (e.g., flight control communications). Systems that are mixed-criticality typically comprise hardware, operating system, middleware services, and application software all on a single computing platform. In this arrangement, system safety-critical and non-safety-critical data coexist on a shared network.As vehicles and infrastructure age, ideally they would be easily upgraded to compensate for changes in criticality or function. Many of these systems rely on human decisions, which are informed by data from the computing and communication components of the vehicles. Automated vehicles also make functional decisions based upon this data, often located on the same processor. Thus a failure in the onboard reasoning or high-processing capability could damage the vehicle or surroundings. New system development approaches are needed for mixed criticality CPS in which less-tested, lower-criticality code can safely exist on the same processor as the more safety-critical, well-tested code.[255]

Modeling

CPS are incredibly complex, making it difficult to create formal models. CPS are high-dimensional, span multiple time scales, are dynamic, and can reconfigure to adapt to certain situations. They are also composed of multiple entities including humans. Transportation sectors are migrating toward the use of model-based development that relies on sophisticated tool chains to automate the development process. Because most existing model-based development approaches focus on specific aspects, such as control models or component connection models, there is a need to develop approaches that take multiple system

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[252] Winter. “CPS in Aerospace.”
[253] Poovendran et al. “2008 HCTCPS Workshop Report.”
[254] Feron and Balakrishnan. “CPS and NextGen.”
[255] Poovendran et al. “2008 HCTCPS Workshop Report.”

views into consideration. Issues in CPS environment modeling, such as debugging, are challenging in a simulated environment and become even more difficult as system development progresses to "hardware in the loop" and target platform testing (e.g., flight test and vehicle test tracks).[256]

In the terms of transportation infrastructure, modeling techniques and tools that can capture environmental and physical aspects, with their uncertainties, are needed but not yet developed. Another challenge in CPS environment modeling includes collecting, managing, and mining data, especially because the data sets involved can be massive. Development of model formalisms is necessary at the system level to capture safety specifications of multiple vehicle systems. Traditional fault modeling that captures individual vehicle faults will not be sufficient for an integrated transport system. To compensate, theories for composition of fault models that can capture system-level faults beyond individual vehicles can be used. The complexity of transportation CPS is beyond current real-time theory and practice in reasoning about large-scale mobile network protocols with multiple dynamic inputs. Current rate-based and aperiodic event models must be extended to events whose priorities change based on environment.[257]

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Smart Healthcare

INTRODUCTION

The market for medical devices in the United States is the largest in the world ($83 billion in 2006, approximately half of the global total) and is growing at about 6% per year, approximately double the rate of U.S. gross domestic product (GDP). The industry is comprised of organizations of all sizes, from individuals working out of their homes to global conglomerates (e.g., Siemens) and employed more than 350,000 workers in 2006; however, of the 8,500 U.S. medical device firms, about 80% have fewer than 50 employees.

The medical devices produced by this industry are similarly diverse, ranging from digital measuring devices (temperature, pressure) through prosthetics and implants (such as cochlear or visual) to robot hospital (or home) health care assistants. Products also include surgical and medical instruments; orthopedic, prosthetic, surgical appliances and supplies; dental equipment and supplies; x-ray apparatus and tubes; irradiation apparatus; electrotherapy and electromedical apparatus; ophthalmic and ear equipment; and in-vitro diagnostic substances.

A technological revolution over the past decades has seen new materials (plastics) replace metals and devices and systems based on information technologies (IT) replace analog devices used in diagnosis, monitoring, and treatment. The development of microprocessors and sophisticated networking and miniaturization of circuits has produced an explosion in personal digital assistants and associated new devices, ranging from very small (ingestible digital cameras with real-time video) to very large (e.g., scanning and irradiation equipment and geographically distributed electronic records systems) These new technologies can be interconnected in complex configurations, creating large scale “systems of systems.” The emerging classes of IT-enabled medical devices delineate a very important shift in this domain: essentially passive devices controlled by a human operator with specialized knowledge have been replaced with complex computing systems. These systems have embedded sensors and actuators that monitor and actively control a variety of critical physiological processes and functions. Computing, sensing, modeling, and communications technologies deeply integrated in physical elements allow these new cyber-physical systems (CPS) to achieve new levels of performance with unprecedented functionality.

KEY DRIVERS

additional calculations to produce interpretable answers. It is not uncommon for multiple devices synthesize data, and act on their observations. Rising health care costs, an aging population, and diminishing medical professional resources are driving health-care providers to seek technological innovations to maintain or improve patient care as efficiently as possible. A high cost is usually associated with traditional (hospital, clinic) care settings, particularly for interventions that do not demand the resources of a full-service hospital. This has led to increasing interest in alternatives such as home care, assisted living, and commoditized convenient care settings. Such emerging health care venues have the potential to become major consumers of innovative, commoditized, and cost-effective medical and laboratory technologies.

Today's medical device architectures lack interoperability. The typical device employs proprietary systems and relies on trained professionals to operate the device and interpret system output, which frequently requires to be connected to a patient at one time (e.g., in an operating room), in which case clinicians must monitor all devices independently, Clinicians frequently consult others present to interpret the readings. This is an error prone process and it can be affected by stress, fatigue, and other human factors.

risingWhen we consider medical devices, two fundamental enabling component technologies must be addressed: the **hardware** and the **software**. The hardware mostly consists of specialized embedded systems or, more recently, systems on a chip. Hardware architectures for medical devices include wired and wireless interfaces, facilitating networked communication of patient data. However, ad hoc efforts by professionals and clinicians to aggregate data across devices designed to operate separately can lead to unintended or accidental results. There is a need to manage networks of devices in an automatic and secure manner.

The software development methods follow established approaches in software engineering. Software development in the medical device arena is driven by the growing interest in such capabilities as home health care services (aging populations), delivery of expert medical practice remotely (telemedicine), and online clinical lab analysis. This, however, shows the important role of advanced networking and distributed communication of medical information in the health systems of the future. However, software development methods in the established practices are not adequate for the high-confidence design and manufacture of very complex, interoperable medical device software and systems. The systems include "intelligent" prosthetics that anticipate movements and modify themselves appropriately, minimally invasive surgical devices, implants that process signals and provide output for a neural circuit, and nanotechnology-derived microscopic controllers affecting organs.

Today's verification and validation (V&V) efforts are driven by system-life-cycle development activities that rely primarily on methods of post-hoc inspection and testing; these approaches, although adequate for a thermometer or pressure measuring device, are not appropriate for the diverse and complex interactions between different components in the medical devices of the future. Many of those devices have time constraints and/or constraints that rely on analysis of input signals coming from the patient.

Dealing with such problems represents a challenge for the current and future generations of medical device experts. This is because today's engineering foundations and the set of scientific principles available for designing artifacts interacting with the world are not sufficient for enabling the design, V&V of high-confidence medical device CPS. Innovations in control theoretic modeling, in distributed wireless control algorithms, safety and security, as well as provably correct software development through formal methods appear to be necessary.

CURRENT STATE OF THE TECHNOLOGY

The past 25 years have witnessed the transformation of the designs of medical devices from analog to digital. Analog designs were simple, with simple user interfaces and limited functionality. The primary method of controlling risk to the patient was human intervention. The device was used while the specialist was present, handling the device. Because of established business models these devices tended to last a long time.

Today, innovations in technology and new ways of connecting devices to each other have completely changed the landscape of this field. Microprocessors, actuators, sensors of different kinds and software can all be put together easily in ways that they scale up. For example, some of the more complex devices can have a million lines or more of code.

Most devices contain *embedded systems* that rely on a combination of proprietary, commercial-off-the-shelf (COTS) and custom software or software-of-unknown-pedigree (SOUP) components. While general-purpose computing systems, such as PCs, execute a wide variety of functions and are easily reprogrammed, an embedded system may be thought of as a special-purpose computer system designed to perform dedicated functions. An embedded system is usually subject to resource-limitation constraints as part of a mechanical device and, because they are not intended to be reprogrammable, implemented in read-only memory. Embedded systems are becoming critical in medicine because they increasingly *control* functions of, and communicate with, patients themselves as well as engineered systems.

These systems are highly proprietary and increasingly dependent on software to provide greater levels of device robustness and functionality. Embedded system design allows the real time acquisition and interpretation of signals of various kinds, and for this reason it has enabled current technology. However, the machine becomes dedicated and difficult to integrate into a network where it gives out information while it also receives information of different kinds. With general purpose computers becoming faster and smaller, the market may favor general computing as opposed to specialized. Nevertheless, in today’s environment medical devices continue to rely on competent human intervention as the ultimate risk-control measure.

To better analyze the state of the art, let us consider hardware architectures and software development.

Hardware: Current device architectures are highly proprietary, not interoperable. Embedded systems are, for the most part, open-loop. Closed-loop systems tend to be implantable devices. Examples of such devices include implantable cardioverter defibrillators (ICDs) or cochlear prosthetics. In current devices any network communication is largely for the purpose of diagnostic output. Both complex instruction set computer (CISC) and reduced instruction set computer (RISC) architectures are commonly used. Multicore and system-on-a-chip (SoC) architectures and flexible reconfigurable architectures, such as field programmable gate arrays (FPGAs), are becoming more common in device designs.

Software: Current software development methods range from older methods such as **s**tructured programming to object-oriented programming paradigms where objects are instantiated at run-time. Formal methods-based design and analysis that have flourished in computer science are not widely used. To demonstrate that a device will perform as intended the techniques used should be Human resourceintensive. Use of static-analysis tools on implemented code is limited. Development platforms do not facilitate integration of hardware, software, and human factors in design, development, and manufacturing.

BROAD CHALLENGES AND BARRIERS

CPS deployment and integration in healthcare faces general and specific challenges. The general challenges are related to the overall cyber-physical infrastructure: hardware, connectivity, software development and communications. The specific challenges have to do with specialized processes at the intersection of control and sensing, sensor fusion and decision making, security, and the compositionality of CPS.

General Infrastructural Issues

Hardware: Medical device systems are challenging current regulations. The most striking examples are closed-loop systems or systems that are networks of other devices. These devices have different functionalities: they deliver drugs; they monitor physiological characteristics or regulate patient functions, like breathing. Clinicians must collect, analyze and react and make a decision based on this information. In the operating room, for example, one may find many devices providing life-supporting functions and multiple medical professionals interoperating based on information provided by the various devices (and their own observations). Humans are subject to fatigue, miscommunication, information overload, distractions and other factors. These factors can combine to contribute to an undesirable outcome for the patient.

It is rather easy to collect device information using the commercially available digital technology. This information, after appropriately filtered, can be either presented to a clinician or it can be used by the device's computer to autonomously trigger some action. At the easy part of the spectrum this is already happening in the simultaneous display of data from different devices. To monitor patients with heart problems, clinicians simultaneously display data from pulse oximeters, blood pressure devices and EKGs. At the difficult part of the spectrum, we can see devices that use input as a control signal, for example devices that deliver radiation treatment to a tumor in an organ that moves. Such devices can sense the movement and change appropriately the direction of the radiation beam.

However, the way medical devices have been produced over the years has given rise to proprietary devices that are not designed to interoperate with other devices. To make this suboptimal system work, practicioners have introduced "stealth" networks, where information is transferred from device to device using a memory stick, barcodes, a PDA, or even manual transfer through typing. Advanced networking and distributed communication is needed in the cyberphysical architectures of the future medical devices. The information traveling in the network is either electronic health records of patients, or control measurements, or in general computing processes. Realizing architectures of this kind will create cyberphysical medical devices of the next generation, where different component are plagued into the same network.

Multiple cyber-physical devices must interoperate together seamlessly at a very high level of robustness. Interoperability and closed loop systems appear to be the key for success. Computing and networking technologies of the future deployed in medical devices and systems are likely to be interconnected in increasingly complex open systems, with many heterogeneous components. The configuration of devices will be dynamic, determined by a variety of factors, including economic ones as well as medical considerations. Research approaches are needed that can provide assurance for the correctness of the operation of embedded real time systems with networking and control capabilities.

Software: Engineering the complex medical systems envisioned cannot be obtained using current software development practices, because not only we need to know that it is trustworthy software made out of diverse components, but we also need to know whether the system of systems functions as expected. New software engineering techniques are needed that integrate computational and communication designs together with patient models. Software development methods must scale across the device industry’s entire problem.

Technology and Other Challenges

Important next steps in research for laying the foundation for high-confidence cyber-physical medical devices and systems are related in many ways to the research areas needed in other areas, such as manufacturing, transportation, and mobility. They have to do with sensor fusion, with bridging signals and symbols, with intelligent sensorimotor structures for limb prosthetics, with intelligent sensory mechanisms for eye and ear prosthetics, with compositionality, and with control and feedback.

Dr. Watson Synthesizes Medical Information

Almost everyone is familiar with the recent software system called Watson developed by IBM that played the game show *Jeopardy* against humans and won. One could envision a similar system answering medical questions and winning against doctors. Indeed, interoperability and feedback have the potential to turn cyberphysical medical systems and devices to experts, thus emulating the practice of medicine itself. This presents significant challenges because different doctors in diverse specializations tend to think of medical information differently.

Compositionality of Abstractions

Every step of a development process utilizes some level of system abstraction or composition of abstractions. To make progress in the design of cyberphysical medical devices, we need to develop techniques to provide the means for being able to trust abstractions and their interfaces to other abstractions. The industry is in need of a compositional framework that will set the foundations for the structure of any device. Using then formal methods for checking and verification we can give rise to robust means of modeling.

Security

The study of security for medical devices is at an embryonic stage, simply because most medical devices are not connected to any network. A paradigm shift is underway, with health care patient records changing from paper to electronic media. As this information is used in medical device interoperation, the issue of security becomes important.

Sensor Fusion

Current research explores a variety of sensors that can be implanted or worn (e.g., attached to clothing) or attached to the walls of a room and how information from those sensors can be fused into a useful model of reality that is sufficient to make a decision or execute a specific action. These sensors communicate either wirelessly or through networks woven into fabrics or the environment. The fusion of this sensory information can be used to monitor patient behavior, ranging from gait analysis to the detection of falling, the inability to move or the recognition of gestures. This is a rapidly evolving field of inquiry that exploits monitoring technologies for improving assisted living and home care.

This notion of sensor fusion for monitoring human behavior in a room transfers to the monitoring of particular measurements in the human body. Many tests that today are done "off-line" using a small number of samples sent to a laboratory could give way to online dynamic models obtained from continuous monitoring. An example of this is the treatment of diabetes that has evolved to in-home device based glucose measurement and monitoring for patients with infusion pumps.

Prosthetics: Biomedical Augmentation

Most people are familiar with limb prosthetics, retinal and cochlear implants, and neural and deep brain stimulation implants. Advances in a variety of engineering and scientific disciplines have contributed to a new interest in intelligent prosthetics. The development of new materials and, specifically, "smart skin" provides prosthetic devices with the capability of sensing and providing feedback to the system. These new approaches together with sophisticated control technology point the way to new systems that learn to adapt to the patient, predict the patient's movements and change their characteristics on the basis of the terrain or the environment by being context-aware. There is a variety of challenges for safely and effectively controlling the interaction of the artificial and the biological and they must be addressed

Control and Feedback

Most medical devices are open loop systems. By "open-loop" we refer to systems that lack feedback control; on the other hand, "closed-loop" refers to systems that include feedback control. With cyberphysical medical devices moving towards networked closed loop systems, it becomes important to investigate new concepts in control mechanisms as they relate to sensing. This brings forward the gulf existing between signals and symbols and how control can be achieved not only on the basis of the incoming signal but also on the basis of prior knowledge.

Human-Machine Interaction

The development of cyberphysical medical devices and systems requires new approaches to designing interfaces that satisfy a number of new requirements, such as the sharing of authority, the shared human and device understanding of the current state or agreement on the actions to be taken.

MEASUREMENT PROBLEMS AND IMPEDIMENTS

Verification and validation is driven by system-life-cycle development activities that use inspection and testing. One potential difficulty with this kind of approach is that much of the inspection is a "check-list" activity performed by humans and thus error prone. Worse than that, such techniques cannot be applied to the networked closed loop cyber-physical devices of the future.

The design space is quite complex involving besides the environment, control, communications, timing, computation and other constraints. One way to handle this problem is to create an end to end design together with the verification and validation tools. This will allow information from one tool to be used to increase the effectiveness of other tools in the development cycle.

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Appendix A. Acronyms

3D	three-dimensional
ADS-B	Automatic Dependent Surveillance-Broadcast
AGC	automatic generation control
AMI	advanced metering infrastructure
CAD	computer-aided design
CISC	complex instruction set computer
COTS	commercial-off-the-shelf (COTS)
CPS	cyber-physical systems
DOT	U.S. Department of Transportation
EISA	Energy Independence and Security Act of 2007
FAA	Federal Aviation Administration
FPGA	field programmable gate array
GDP	gross domestic product
GPS	global positioning system
HMI	human machine interface
HVAC	heating, ventilating, and air conditioning
ICD	implantable cardioverter defibrillators
IT	information technology
ITS	intelligent transportation systems
NAS	national airspace system
NextGen	Next Generation Air Transportation System
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NSTC	National Science and Technology Council
NZE	net-zero energy
PBN	performance-based navigation
PCAST	President's Council of Advisors on Science and Technology
RISC	reduced instruction set computer
RNAV	Area Navigation
RNP	Required Navigation Performance
RSF	NREL Research Support Facility
SHM	structural health monitoring
SLOC	source lines of code
SoC	system-on-a-chip

SOUP	software-of-unknown-pedigree
UAV	unmanned aerial vehicle
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
V&V	verification and validation
WSAN4CIP	Wireless Sensor and Actuator Networks for Critical Infrastructure Protection

Appendix B.
Key Stakeholders

Appendix C. Bibliography