Future Directions in Cyber-Physical Systems, Robotics, and Autonomy

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1 Introduction

As a preamble to this report, it is useful to define the two technical areas that the report addresses: Cyber Physical Systems (CPS) and Robotics Science and Technology.

Cyber Physical Systems (CPS)[1] are smart networked systems with embedded sensors, processors and actuators that are designed to sense and interact with the physical world (including the human users), and support real-time, guaranteed performance in safety-critical applications where the proverbial "blue screen of death" can have catastrophic consequences. In CPS systems, the joint behavior of the "cyber" and "physical" elements of the system is critical - computing, control, sensing and networking are deeply integrated into every component, and the actions of components and systems must be carefully orchestrated. The National Science Foundation (NSF) has invested over $240M in basic research and education for CPS systems over the last five years, partnering with other federal agencies including the Office of Science and Technology Policy (OSTP), the National Institute of Standards and Technology (NIST), The Department of Transportation (DOT), the National Institutes of Health (NIH), and the National Aeronautics and Space Administration (NASA).

In June 2011, President Obama unveiled the National Robotics Initiative (NRI), with an initial focus on robots that can work with humans to extend and augment human skills. Robotics science and technology, more broadly defined, are leading to a new generation of opportunities across manufacturing, national defense, homeland security, civil infrastructure, healthcare, and education.[2] In 2012, NSF in partnership with OSTP, the U.S Department of Agriculture (USDA), NIH, and NASA

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[1] The Impact of Control Technology, T. Samad and A.M. Annaswamy (eds.), IEEE Control Systems Society, 2011, available at www.ieeecss.org. K. Baheti and H. Gill, Cyber Physical Systems, http://ieeecss.org/sites/ieeecss.org/files/documents/IoCT-Part3-02CyberphysicalSystems.pdf

[2] A Roadmap for US Robotics, May 2009. http://www.us-robotics.us/reports/CCC%20Report.pdf

and launched the National Robotics Initiative (NRI)[3] to invest in this field and establish new avenues for socio-economic development, new industries, commercialization opportunities and creation of new jobs. They issued a joint solicitation[4] committing over $50M to develop the science and technology for robots that can safely co-exist and operate in close proximity to humans. Since this launch, the NRI program has invested over $150M in research and development programs. Now in its fourth year the NRI includes a team of over fifty program managers from nine different funding agencies and many of our best national laboratories including the Army Research Laboratory, the Naval Research Laboratory, and the NASA Johnson Space Center.

The workshop on September 24, 2015 brought together leading educators and researchers with four main goals:

1. to review the impact of NSF investments in CPS and NRI,
2. to identify the current drivers for CPS and NRI in today's rapidly evolving technological landscape,
3. to identify possible synergies between the two programs, and
4. to explore new opportunities in related areas that are currently not being emphasized.

We are at a particularly important point in time in both these fields. According to the McKinsey Global Institute[5], advanced robotics, autonomous vehicles and cyber physical systems (also called the Internet of Things) are 3 of 12 technologies that can "truly disrupt the status quo, alter the way people live and work, and rearrange value pools across industries." There is substantial interest from industry and there has been a significant influx of private funding from industry and venture companies over the past two years. In December 2013, Amazon CEO Jeff Bezos announced plans for Amazon Prime Air, which will deliver small packages weighing less than 5 lbs (which constitute 86% of products shipped by Amazon) using aerial robots in the next five years. Later in the same month, Google acquired robotics companies with expertise in legged robots, low-cost arms, perception, virtual reality, and omni-directional wheels. The Internet of Things (IoT) revolution is being projected to lead to an economic impact in the tens of trillions of dollars and over 75% of business leaders surveyed predicted a direct impact of this technology on their business. DJI, a drone company that is built on research results from both the CPS and robotics communities, raised $75M at a $10B evaluation in May 2015. Indeed over $1B of venture funds have been invested in this area in the last two years.

While there are a number of technology demonstrations in robotics and CPS that suggest that these fields are becoming mature, it is also clear that many of these solutions only work under tightly constrained conditions and, are at best "demos". The recent Defense Advanced Research Projects Agency (DARPA) Robotics Challenge serves to highlight many of the open problems in robotics and

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[3] T. Kalil and S. Kota, Developing the Next Generation of Robots, June 2011. http://www.whitehouse.gov/blog/2011/06/24/developing-next-generation-robots

[4] NSF's National Robotics Initiative Program Solicitation, 2011. http://www.nsf.gov/pubs/2011/nsf11553/nsf11553.htm

[5] J. Manyika, M. Chui, J. Bughin, R. Dobbs, P. Bisson, and A. Marrs. Disruptive technologies: Advances that will that will transform life, business and the global economy, May 2013. http://www.mckinsey.com/insights/business_technology/disruptive_technologies

CPS in addition to underscoring the tremendous potential of this field. It also highlights the central science and technology policy question asked of workshop attendees: What are today's important challenges in robotics and CPS, and what high-impact research initiatives can address these challenges?

2 Background

This section summarizes presentations on the NRI and CPS programs by the key program managers and the discussions that followed these presentations.

2.1 The National Robotics Initiative

The National Robotics Initiative (NRI) is a program coordinated by NSF but with active involvement and support from NSF, NASA, USDA, NIH, the Department of Defense (DOD), the U.S. Department of Energy (DOE)[6] and OSTP. The stated goal of the National Robotics Initiative is "to accelerate the development and use of robots that work beside or cooperatively with people in the United States."

The basic research themes in the NRI solicitation include:

- Sensing and perception
- Design and materials
- Modeling and analysis of co-robots
- Human-robot interaction
- Planning and control

There is also an emphasis on STEM education through robotics, as well as on research to understand long-term social, behavioral, and economic implications of co-robots.

In addition to the basic research focus, the participation of mission-oriented federal agencies brings a broader perspective to the NRI. There are new applied research and development themes as well as multi-faceted collaborative efforts in diverse application sectors including agriculture, defense, medicine and space.

The first year of funding (FY 12) funded 61 proposals at a total of over $40M/year. Funding continues at a similar level with increased involvement by partner agencies and $153M has been committed to date (FY 12-15) on 150 projects. 81 of these have been funded by partner agencies.

2.2 The Cyber Physical Systems Initiative

The Cyber Physical Systems (CPS) initiative focuses on *deeply integrating computation, communication, and control into physical systems* addressing fundamental questions in:

- Pervasive computation, sensing and control
- Networking at multiple and extreme scales

[6] At the time of the workshop, DOE was expected to formally join the program in FY 16.

- Dynamically reorganizing/reconfiguring systems
- High degrees of automation systems with and without humans in the loop
- Dependable operation with *potential* requirements for high assurance of reliability, safety, security and usability

CPS is central to different industry sectors with many opportunities to spur economic growth. In particular, the burgeoning IoT industry relies on CPS technologies and promises to transform many different sectors. Industry is interested not only in research and development but also in standards and new mechanisms for monetization of the CPS infrastructure. CPS is central to many national priorities including energy, health care and advanced manufacturing.

Since the CPS initiative launch in 2009, over $240M has been invested in CPS research and education, impacting over 350 investigators in 35 different states. Research themes include coordinated control, complex systems, real-time systems, event triggered control, formal verification, medical CPS, energy grid, cyber infrastructure, model-predictive and robust control, machine learning, robotics, time synchronization, security of cyber physical systems, wireless sensing, wearable CPS, safety critical system infrastructure, fault detection and health monitoring, intelligent transportation systems, resilient systems, intrusion detection, and cyber-enabled manufacturing.

Areas that are being currently emphasized include:

- *System Design* including safety, resilience, security and privacy
- *System Verification* including certification, preserving safety but dramatically **reducing** test space, very large & complex systems
- *Real-time Control and Adaptation* – How do we integrate big data in real-time control? How do we achieve real-time in new environments such clouds or network challenged spaces?
- *Manufacturing* – Harnessing CPS research to conceive, design, and manufacture new products at a pace far exceeding what is being achieved today
- *Smart Cities* – What foundational research is needed to achieve effective integration of networked computing systems, physical devices, data sources, and infrastructure to have a major impact on quality of life within the city?
- *Internet of Things* - What are the foundational research elements needed to harness the power of the IoT? How do we go from the IoT to the Internet of Dependable and Controllable Things at enormous scale? What new areas of CPS research emerge from this?

2.3 Summary

While the NRI initiative has primarily addressed the science and technology for *co-robots*, robots that work alongside, or cooperatively with, humans, CPS has addressed fundamental issues for deeply integrating computation, communication, and control into physical systems. In many cases, these systems are safety critical and thus, the focus is on synthesizing provably correct behavior and guaranteeing safety.

There are many differences between the two initiatives. All robots could be considered cyber-physical systems, and thus one might be tempted to draw the conclusion that all robotics research and education is a part of CPS research and education. However, in fact most CPS systems are not robots and most robotics research projects are not of direct relevance to CPS researchers. But both CPS and NRI initiatives have had a significant impact on the new ecosystem that is emerging in modern society. As we rapidly move toward a world in which physical intelligent agents are part of our society, they are both addressing the fundamental science and engineering problems that arise when we try to create intelligent systems that sense and reason about the physical world we live in and interact with and respond to this physical world. There is broad interest in this field beyond NSF across many other federal agencies including OSTP, NASA, DoD, DOE, USDA, DOT, DHS and NIH, and we believe that this workshop report can help lead to coordinated investments across all agencies in both these areas.

3. Drivers, Metrics, and Impact

This section reports on the main findings from the breakout groups on the key drivers[7] and impact for NRI and CPS.

3.1 NRI

3.1.1 Drivers

One of the main drivers of the NRI is improving economic productivity through robotic technology. Robotic technology has had a huge impact in areas where we can now do new things we could not do before – the technology has increased existing human capabilities. Some examples of this include robotic surgery systems, autonomous cars, and "smart" agriculture that increases yields and reduces waste of water and fertilizer.

Robotic capabilities have improved greatly over the past few years, in part due to the expanded NRI effort, and advances in mobility, manipulation and sensing/mapping are making inroads into many markets and products that can benefit from these capabilities. Space has been a prime example domain for robotics, but undersea applications are also growing, ranging from aquaculture, to the repair and maintenance of pipelines/cables.

Another important application area is disaster prevention and recovery. Robots can prevent disasters; two examples of rapidly growing industries are unmanned aerial systems for inspection of critical infrastructure to prevent incidents, and underwater robots for detection of smuggling and terrorist activities around major ports. Robots can save lives and reduce the economic consequences of disasters as seen in over 20 incidents in the USA including robots capping the leak at the BP Deepwater Horizon Oil Spill.

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[7] Many of the drivers identified by each group are common to both programs, and each group addressed drivers at a different level of granularity. However, this report preserves the spirit of the discussion that occurred in each breakout group.

Robotic technology has also had a major impact on our quality of life. Home health care, mobility, wellness and well-being are being positively impacted by assistive robotics, human-robot interaction, advanced prosthetics, and smart sensing, all areas that are central to the NRI. The emergence of "Smart Cities" and Internet of Things (IOT) initiatives led by private industry is supported by new sensing and robotic technologies coupled with advanced networked software, all components of NRI research.

Finally, Robotics can be seen as a tool for not just enhancing but potentially revolutionizing K-12 STEM education, both formal and informal, in order to train a competitive 21st century US workforce, lower the digital divide, and bring more gender and ethnic balance to the STEM workforce. In this context, social robots can boost the confidence and self-esteem of children from all socio-economic backgrounds, potentially even in families that may not appreciate the importance of STEM education, or education of any kind.

3.1.2 Impacts

One of the major impacts of NRI funded research is that it forced many researchers to look beyond their own limited, niche domains and expand their research horizons by collaborating with other researchers to build new systems and applications that involved both humans and robotics (co-robotics). Many of the PIs and students who have been supported by NRI are researchers from various disciplines outside of the traditional core robotics areas. These collaborations have been quite fruitful in creating a much broader and inclusive set of domains for robotics research and applications. Central to this objective is putting researchers into real environments, populated with humans and physical robots.

Another major impact is the open-sourcing of robotics hardware and software. This trend continues to accelerate with positive benefits accruing. Before NRI, it was quite difficult and expensive to build and equip a laboratory focusing on robotics. That cost has been driven down by the emergence of inexpensive and replicable hardware (arms, vehicles, humanoids, sensors etc.) along with open-source libraries devoted to many of the most useful robotic algorithms (planning, control, imaging etc.), all configured to run under the open-source Robotic Operating System (ROS). ROS itself is supported by NRI, and most NRI projects are developing software that can be open-sourced as well. This effect has streamlined and shortened the learning and implementation curves for most robotics researchers while making access simpler for new entrants into the field. Building a complex robotics system, which used to take years, can now be accomplished in months instead. Further, large databases of objects, environments, and physical components have been created and re-used across the community, supporting the trend in large cloud-based computing resources available to all.

A further impact is the benefit that robotics brings to STEM education. Robotics can make STEM courses come alive with engaging physical robots that students can build, program and from which they can learn directly. National Robotics Week, celebrated every April, has blossomed into an effective and far-reaching way to spur students into the robotics and other STEM fields. NRI supported researchers and students are at the front lines of presenting forums, demos and open houses that effectively let the public know about the growth and potential of robotics. STEM education has become a strong national priority. Employers are desperately looking to fill new jobs with qualified STEM graduates. In the robotics sector alone, large industrial organizations such as Apple, Google, Amazon, Uber, Tesla are looking to hire many new robotics engineers, many of whom are coming out of NRI funded programs.

Another impact is that robotics-based STEM training can be more appealing to underrepresented groups such as women, helping to create better gender and socio-economic balance in our country. The appeal of the NRI program has also crossed Federal funding agency boundaries, with participation from NIH, DOD, DOE, USDA and NASA. This helps to further grow the field as robotics enters more and more aspects of our society.

One of the most important metrics for the NRI program is the explosive growth of robotics research across the globe. As interest in robotics increases, there is now a burgeoning and strong community of roboticists. This can be easily measured by:

1. Increased attendance and submissions of papers at the major robotics conferences. At the most recent IROS conference in Hamburg (10/15) there were 2134 contributed paper submissions,45 sessions in 15 parallel tracks, 51 accepted Workshop and Tutorial submissions, 72 accepted Late Breaking Poster papers, 6 plenary and 9 keynote talks, and over 2500 registrants. At ICRA 2015 in Seattle there were over 3000 attendees (an ICRA record). Highlighting the conference were 940 accepted technical papers (out of 2275 submissions) presented over 3 days in 10 parallel tracks, representing authors from over 40 countries. There were also over 1400 attendees (another ICRA record) participating in 42 workshops and tutorials. The conference also highlighted the increasing role of women in robotics, with a General and Program Committee that was entirely female.
2. Development of a wide range of offshoot conferences and workshops focused on robotics topics, as diverse as UAV's, Surgical Robotics, Planning and Control, Humanoids, Disaster and Safety, Ubiquitous robots, and Benchmarking. These are just a few examples from conferences coming up in next few months). Similarly, there are many new academic journals devoted to robotics (e.g. IEEE Robotics and Automation Letters, Soft Robotics, Robots and Biomimetics, Journal of Robotics, Networking and Artificial Life, Journal of Human-Robot Interaction).
3. In academia, evidence of this impact can be seen in (a) increased student enrollment in robotics courses at the undergraduate and graduate levels, (b) new and growing robotics departments, centers, and programs at the undergraduate, master's and doctoral levels, and (c) faculty hiring in robotics has also significantly increased due to the factors above.
4. Private industry is equally interested in robotics. The number of jobs for students continues to grow showing the interest and need for trained roboticists in the industrial sector. Marquee companies like Uber, Google, Amazon, Apple, and Tesla are all looking for graduates trained in robotics, as are the numerous startups that have been created over the last few years. While some of this has been disruptive for academic research (e.g., because of faculty being recruited to start ups), the overall impact on the field has been positive.

5. Open source platforms, databases, code repositories have proliferated. Industrial manufacturers of robots are now almost required to provide an open source ROS interface to their products for them to be successful. GITHUB and ROS repositories now allow new players easy access to developing new robots and capabilities.
6. Hardware has also become less expensive as more companies are building it. This reduced hardware platform cost has also reduced entry barriers for those wanting to do robotics research.

These metrics show that the NRI has been an enabler and catalyst for the growth of robotics as both a scientific discipline and economic force. However, this is only the tip of the iceberg in terms of what the US needs to train and employ a 21st century STEM workforce and to remain competitive internationally..

3.2 CPS

Research in Cyber-Physical Systems (CPS) has been focused on "engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components."[8] Motivated by different application domains such as transportation, healthcare, energy systems and smart infrastructure, the fundamental research in this area has addressed the design, security, verification, safety, dependability, and performance of such complex systems.

3.2.1 Drivers

The main emerging drivers and opportunities for research in CPS can be grouped in four areas.

1. *Extremely large scale application platforms such as the Internet of Things (IoT) and the Industrial Internet (II):* It is estimated that by 2020, 26 billion smart devices will be installed,[9] which will increase private sector profits 21% and add $14.4 trillion to the global economy by 2023.[10] These extremely large scale systems bring with them many research challenges, all related to the integration of sensing, computation and possibly actuation on physical devices, that are central to CPS systems:
    - Programming abstractions for systems with millions of components
    - Massive amounts of data and the inability to fully model the system will lead to questions of data-driven learning that incorporates safety guarantees and safety analysis that is dependent on learning paradigms
    - Reasoning about the resilience of such systems, their scalability and composability at scale

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[8] NSF's CPS program solicitation, 2015: http://www.nsf.gov/pubs/2015/nsf15541/nsf15541.htm
[9] Gartner. Gartner Says the Internet of Things Installed Base Will Grow to 26 Billion Units By 2020. Dec 2013. http://www.gartner.com/newsroom/id/2636073
[10] J. Bradley, J. Barbier and D. Handler. Embracing the Internet of Everything to Capture Your Share of $14.4 Trillion. Cisco. 2013. http://www.cisco.com/web/about/ac79/docs/innov/IoE_Economy.pdf

- Information from these systems will go through the cloud therefore it is essential to reason about the cloud-to-local interaction where global information affects the local component behavior and vice versa

2. *Broad range of complex systems:* Recent CPS are becoming larger and more complex; for example the Chevy Volt has 10M lines of code, the Boeing 787 has more than 20M lines of code, a pacemaker has 80K lines of code.[11] This increase in complexity and the fact the systems are safety critical make it is clear that the theoretical foundations for the design and verification of CPS must be leveraged to create tools that can be impactful for such applications. This will require:
   - Practical proofs and assurances. Instead of fully verifying a system using formal proof techniques that may not scale, define the notion of assurance, a weaker notion of guarantee
   - Model validation techniques at scale. Typically verification techniques operate on models of the systems that may be high-fidelity but are never exact representations of the system. There is a need for tools that will provide rapid and cost-effective techniques for validating the actual system
   - Definitions of safety and dependability for large scale interconnected CPS
   - Modeling the human interaction as a component of the CPS

3. *Reduce design/verification cycle time and cost:* It is estimated that well over 50% of the development cost of future CPS will be due to software, integration and verification.[12] CPS research is vital for reducing the time and cost associated with designing and deploying new systems. To truly make an impact, CPS research must be developed in partnership with industry and driven by real world application domains such as transportation, healthcare, etc.

4. *Security and privacy challenges in CPS:* With recent remote hacks of CPS such as vehicles[13] and medical devices,[14] emerging challenges for CPS research include security, i.e. ensuring that the CPS cannot be hacked or manipulated by third parties. In addition, with the deployment of large scale systems that can collect large amounts of data about their environment, such as IoT, the notion of privacy and how to ensure it must be investigated. The ability to integrate algorithms for data analysis and control with economic incentive schemes can result in infrastructure systems that can be resilient to a wide range of attacks and faults.

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[11] J. Johnson. The New Industrial Revolution. Wired. October 18 2013. http://insights.wired.com/profiles/blogs/the-new-industrial-revolution#axzz2i1UZFr6B
[12] D. Winter. Cyber Physical Systems- An Aerospace Industry Perspective. Boeing. November 2008. http://www.ee.washington.edu/research/nsl/aar-cps/winterrev4.pdf
[13] For example, the Jeep Cherokee hack http://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/
[14] For example, the insulin pump http://media.blackhat.com/bh-us 11/Radcliffe/BH_US_11_Radcliffe_Hacking_Medical_Devices_WP.pdf

3.2.2 Impact

Impact and metrics for the success of the CPS program and CPS research in general can be divided into three categories; economic, educational and societal impact.

1. *Economic Impact:* The economic impact of CPS can be measured using different metrics such as:
   - Industry adoption, needs and interest as manifested by internal R&D investment, hiring of students trained through the CPS program who continue their research, and industrial partnerships with government and academia
   - Startup companies resulting from CPS funded programs such as Ottomatika,[15] Bluhaptics[16] and MetaMorph[17]
   - Influence on government policy (federal and local), for example Infusion Pump Software Safety Research at FDA,[18] integration of smart communities technology
   - Investments in CPS by other countries, for example the European Union,[19] Singapore, and South Korea

2. Educational and community building: Creating a workforce that is equipped for the emerging challenges of CPS requires training students through courses, both at universities and through MOOCs,[20] and books.[21] For community building, NSF has funded the CPS-VO, a virtual organization for information sharing and collaboration. In terms of the academic community, in 2008 it established CPSWEEK, which brings together several smaller conferences on different aspects of CPS and enabled cross fertilization of these communities. CPS research has also been a major focus at a number of broad conferences including IEEE CDC, ACC, and ACSAC, as well as in many domain-specific conferences such as those focusing on smart grid control and security. One example of the impact is the Smart and Connected Communities thrust from White House which builds on CPS and the integration and deployment of CPS research to impact our lives.

3. Quality of life and sustainability: The long-term impact of CPS can be measured by the large scale deployment of these technologies in different domains. These include healthcare, for example enabling aging in place, developing zero-energy buildings[22] and creating smart communities.

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[15] Carnegie Mellon Spinoff Ottomatika Aquired by Delphi. Carnegie Mellon. August 5 2015. http://engineering.cmu.edu/media/press/2015/08_05_ottomatika.html

[16] Blu Haptics website: http://www.bluhaptics.com/

[17] MetaMorph website: http://www.metamorphsoftware.com/

[18] Infusion Pump Improvement Initiative. FDA. 12 1 2014. http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/GeneralHospitalDevicesandSupplies/InfusionPumps/ucm202501.htm

[19] Cyber-physical systems. European Commission. https://ec.europa.eu/dgs/connect/en/content/cyber-physical-systems-european-ri-strategy

[20] For example, "Cyber-Physical Systems, Berkeley" https://www.edx.org/course/cyber-physical-systems-uc-berkeleyx-eecs149-1x

[21] For example, "Principles of Cyber-Physical Systems" by R. Alur and "Introduction to Embedded Systems - A Cyber-Physical Systems Approach" by E. Lee and S. Seshia

[22] A zero-energy building is building that is so energy efficient, that a renewable energy system can offset all or most of its annual energy consumption.

4 Synergies between NRI and CPS

The CPS and NRI programs have considerable potential to synergistically benefit one another in many ways. Both programs deal broadly with autonomy for the benefit of society, yet there are key differentiators between the two programs, both in the problems and technologies they address, and the intellectual and philosophical tools used to address them. The CPS program deals with control, autonomy, and safety of distributed systems of sensors and actuators interacting with the physical world, often over large scales. Safety, longevity, and self-sufficiency are commonly emphasized in CPS projects. Traditionally, CPS has emphasized modeling and rigorous theoretical frameworks to investigate the in-depth integration of computational algorithms and physical components. In contrast, NRI projects typically deal directly with advancing the capabilities of a robot---whether it be a multi-link manipulator, a humanoid, or an autonomous vehicle---and stress the robot's interaction with humans. NRI projects emphasize a specific robotics domain (manipulation, mobility, perception, cognition, navigation, etc.) and how a robot can interact with humans in that domain in a co-robot context. CPS projects are more likely to be model based while NRI projects are increasingly focused on data-driven approaches to deal with the complexity of data sets.

However, some of these differences are based on philosophical bent, culture and intellectual approaches, rather than on actual programmatic differences. Of the CPS projects that deal with topics of interest in NRI, many of them address issues of similar character (perception, control, planning, communication and navigation) and even questions related to manipulation and locomotion. Indeed, any robot can be seen as "a collection of sensors and actuators interacting with the physical world" (i.e. a CPS), while many Cyber Physical Systems can be seen as a physically embodied, programmable intelligent system (i.e. a robot) broadly defined. CPS and NRI do not give a strict partition of the research space, but rather represent a difference in the problems of interest, research philosophy and methodology, and intellectual machinery brought to bear upon those problems, in two overlapping, intertwined research spaces. It is these differences in philosophy and intellectual machinery that suggest a significant, though perhaps latent, opportunity for synergy between the two programs. The methods developed under CPS projects can both benefit from, and give benefit to, NRI projects, and visa versa. Below we discuss several specific examples of potential synergies between CPS and NRI projects.

Humans and Safety

Both CPS and NRI are expressly concerned with human safety in autonomous systems, but the way in which the two communities deal with this concern are quite complementary. NRI seeks to emphasize the notion of co-robot, a robot that works together with a human in a symbiotic and complementary way. Safety of the human is implicitly implied in this relationship, however it is expected that safety plays a part in a larger realm of interaction that includes comfortable and natural collaboration between robot and human. Thus communication (both verbal and non-verbal), physical interaction, and intention recognition are all integral to the NRI mission. The system is safe not only if the human is kept from harm, but if the human feels comfortable, natural, and empowered in the interaction with the robot. There is a subtle difference in the CPS conception of safety. A CPS is considered safe if it can be proven to perform, under all conditions, as expected. There need not be a human interacting directly with the system. For example, a bridge instrumented with sensors to sense vibration and actuators to suppress vibration may be deemed safe, even though no human interacts with it directly. Alternatively the human may be modeled as a dynamic component within the CPS, such as human-in-the-loop projects for cyber-physical cars or cyber-physical aircraft. This requires quantifying human reaction times, and timescales of cyber computation vs. human decision making. Then safety is quantified by the verifiability of the system to behave in a pre-specified way despite the presence of the human or by creating a formal model of trust between the robot and the automated system, which can then lead to either a proof or some definition of dependability that can be verified experimentally.

These two complementary approaches present several ripe opportunities for synergistic collaboration. The NRI community stands to benefit from the CPS community's rigorous attention to modeling human behavior mathematically or computationally in its approach to safety. Their development of dynamical models of human behavior and of formal tools to verify and prove the safety of the system under those tools can be adopted by NRI. Conversely, the CPS community stands to benefit from the NRI community's interactive and human-centric approach to safety. Their concerns of cognitive load, user interfaces, haptics, and inferred intentions can benefit CPS. Interesting questions include:

- *How can one synthesize safe human-machine systems?*
- *How can one formally verify safety under realistic human variability and versatility?*
- *What are the best domains of authority in human-machine interaction (who should be in charge of what, when)?*

<u>Models and Uncertainty</u>

Another key area of overlap in CPS and NRI, but one in which the two communities take quite different approaches, is with respect to models, the representation of uncertainty, and the role of learning and adaptation to reduce or mitigate that uncertainty. The CPS community tends to work heavily with mathematical or computational models of the systems they study, and attempts to prove properties of the system through mathematical treatment of those models. Typical tools include differential equations, state machines, hybrid automata, and Markov decision processes treated with stability theory, reachability analyses, formal methods, or dynamic programming. Conversely, the NRI community sometimes adopts all of these tools as well, but is also likely to take a model-free approach. Often, models are derived from experimental data, and the emphasis is not on proving analytical properties of the underlying model, but on verifying that the model itself is a useful description of the behavior of the robotic system. Learning (in the sense of adapting an algorithm based on collected data) is also widely applied in NRI projects. Proof of performance is more commonly put in experimental demonstration and experimental data collection than in mathematical proof (however, there are many exceptions to this trend). In general, CPS publications are more likely to emphasize theory and proofs in their research, while NRI publications are more likely to include experimental results and be based on data-driven algorithms. Of course, there are many exceptions to this. The main reason to point out these differences is that they suggest potential synergies between the two programs. For example, the following questions motivate possible avenues for synergistic research:

- *How can the adaptability of learning systems be combined with the rigor of provable performance?*
- *Can proof-driven and data-driven approaches be applied to a common data set or common hardware platform to compare the performance of each?*
- *How might analytical proof be combined with learning and data-driven methods in a mutually beneficial way, without compromising the standards of rigor of either one? When is experimentation enough - especially considering the need for experimentation in "corner" cases?*

Role of Hardware, Simulation, and Experimentation

A third realm of potential synergy between CPS and NRI is in the role of hardware, numerical simulation, and experimental verification. Experiments with robotic hardware are fundamental to the NRI community. This is closely tied to the comments above on the integral role that data-driven and model-free or model learning approaches play in robotics. It is also facilitated by the fact that robotic hardware for many applications of interest is readily available, and the applications of interest for NRI projects are often at the human, or laboratory, scale. This is in marked contrast to CPS, in which full demonstrations of hardware are uncommon for several important reasons. First, CPS systems are often large, expensive, inaccessible, or highly distributed. A smart building HVAC system, a smart power distribution grid, or an intelligent automobile traffic routing system cannot be ported into the lab for experimental work, and very few such systems are available for experimentation at full scale. On the other hand it is possible to develop robotic testbeds, even networked robotic systems that will reflect the true challenges of large scale CPS systems. Similarly, simulation tools used by robotics researchers, which generally emphasize sensors, estimators, controllers and planners and are quite sophisticated, can be leveraged to develop better simulators that also incorporate models of computation and communication that can serve the needs of both communities. Again, we can identify the potential for synergies between NRI and CPS in this area, leveraging both the simulation and analysis tools from CPS, and the hardware experimentation tools of NRI. Specific research questions include:

- *How can analysis be used to study scalability to large numbers, large data sets, or long time spans, by bootstrapping from experimental results on smaller samples?*
- *Can common programming languages and simulation environments such as ROS and Gazebo-Player-Stage be developed for the CPS community (as they have been in the NRI community) to facility experimentation and shared community progress? While such common languages and operating environments do exist for CPS, they are domain specific – e.g. BOS (building operating system for smart buildings), and thus efforts to build these environments do not benefit from each other.*

- *Is there a need for NSF-designated shared, large-scale CPS experimental facilities (like an electrical grid, or a building HVAC system) to facilitate experimentation in CPS that can also benefit robotics researchers as they start addressing problems of scale? Similarly, is there a need for open testbeds to enable research and development at scales that are not possible in laboratory settings?*

Developing Synergies

There are many aspects of the CPS culture and intellectual approach that can greatly benefit robotics research. In particular, formal approaches to modeling and analysis developed by the CPS community that capture capability, adaptability, scalability, resiliency, safety, and security can form a basis for robotics components (in hardware and software) that are robust and reliable. For example, CPS work on design verification, as well as real-time safe-critical control, can drive the implementation of modules for a new generation of robots.

Similarly CPS research can greatly benefit from the NRI culture, which has embraced research on data-driven models and learning. Also, NRI has emphasized human-robot, and more broadly human-machine, interaction, and it is important to bring together these techniques with those used in CPS as we design systems that interact with human users.

Developing synergies among the programs will require developing common goals, common infrastructure, and natural points of contact for the communities. There are many opportunities to develop CPS/NRI synergies, some of which have already been outlined above. At a more programmatic level, there are several mechanisms worth considering to develop synergies between these two vibrant communities.

- **Community:** CPS has a federated model of conferences (e.g, CPS Week) in which NRI could be explicitly engaged. NRI can be an active participant and such forums could educate and inform both communities. Conversely, robotics has an independent series of conferences, each of which could host workshops, sessions, and discussion forums to highlight and engage the CPS community. Here the CPS and NRI VOs supported by NSF provide a great platform to further enhance both communities.
- **Testbeds:** NRI-funded researchers may be developing robotic test-beds – for example in agriculture, space, underwater, or manufacturing -- that can also be used to test CPS ideas. For example, many of these systems are built on ROS, but it is well-known that, while ROS-based platforms are versatile and scalable to large systems, they lack guarantees. CPS-based methods could be used to overcome some of these shortcomings while advancing scalability and usability of ROS. Similarly, there are multiple CPS testbeds spanning domains including transportation, unmanned air and ground systems, manufacturing, and energy, and a key question is how we can make these testbeds broadly available across communities.[23]
- **Resources:** Funding mechanisms that promote interactions between CPS and NRI researchers, and a cross-fertilization between their research methodologies can jump-start

[23] NSF Sponsored Workshop on Accessible Remote Testbeds (ART'15), http://art15.gatech.edu/

synergies between the two programs. To this end, the development of common open source platforms and testbeds (that include both software and hardware) would be valuable. This may also be an opportunity to engage existing and emerging industries around both robotics and Internet of Things. In addition, while both NRI and CPS programs have PI meetings for their researchers (a number of whom have both NRI and CPS funded projects), coordination of PI meetings may enable the creation of a common venue including joint poster sessions/demonstrations that could allow greater synergy and networking among the communities.

- **Industry Impact:** It may be advisable to take into account feedback and lessons learned from industry in CPS and NRI to understand what has worked and what has not, and to better articulate key barriers that industry sees itself facing in the future. Such an understanding may also help identify common directions in CPS and NRI where the whole can be bigger than the sum of the parts.

5. New Opportunities

A review of the CPS and NRI programs indicates that there are multiple opportunities where the successes from these programs could be built upon to move the research and technological products of these initiatives forward in new directions. Some of the most important directions are discussed below.

Autonomy

There is a need for increasing the autonomy in complex systems; that is, performing tasks intelligently in complex environments without direct human supervisions. The drivers for autonomy share commonalities with those for CPS and the NRI: safety critical applications and implementations, software infrastructure with guarantees of correctness, and implementations on physical platforms in uncertain environments. The challenge of developing autonomous systems necessitates not only building upon, but going well beyond these results, as we include intelligent decision making, providing feedback loops between the autonomous system and the environment. This will result in unique scientific challenges that extend beyond the scope of the CPS and NRI programs; an increased focus on safety, resilience, methods for handling uncertainty, learning and adaptation. Increasing autonomy will have broad-reaching applications to a variety of domains, including robotics and cyber-physical systems. The next section expands on this opportunity.

Soft Robotics

Most materials used to build traditional robotic or cyber physical systems are hard materials. As a result, the systems are rigid and bulky. The resulting inertia and the inability of systems to absorb impact makes them unsafe and unsuitable for operation in home and even work environments. In contrast, most of the materials seen in nature are soft. Indeed there are many new materials such as liquids, foams, and gels, and biological materials that are now being used to develop the next generation of robotic and cyber physical systems. Novel manufacturing techniques also allow us to use these materials to create products, something that was not previously available. While these systems have the potential to be lightweight, deformable, incorporate embedded sensing and actuation, are able to conform to the environment, and can safely interact with humans, they are also difficult to model and harder to control. New approaches to fabrication, modeling, sensing and control will be needed to realize the full potential of soft robotics. CPS challenges include co-design of not just the discrete and continuous components but also the design of the materials, mechanical and electrical subsystems with the software that will power these devices.

Wearable Embedded Devices

The NRI had, as a large driver, co-robotic systems, *i.e.*, robotic systems that interact synergistically with humans. Yet the focus on humans interacting with robots could lead to new challenges that extend beyond the current NRI program. Similarly, the CPS program includes projects on wearable devices. It is clear that bringing the ideas from NRI and CPS together enables great synergies between the two fields. Of special note is that wearable devices, as a focused area, would require a depth of understanding in soft robotics, including but not limited to novel materials, actuators, control and sensing, nonconventional substrates and a direct connection to biology and bio-inspired models. These devices could be worn by human users, and indeed embedded in human users, and therefore extend well beyond robotics. The importance of this area could be far-reaching in the context of application domains ranging from the medical domain, e.g., rehabilitation, to use by millions of Americans in their daily lives.

Beyond the Industrial Internet

As national initiatives on advanced manufacturing and the materials genome dramatically reduce the cycle time for design and prototyping, and price/performance ratio of sensors and processors continue to fall, we can expect a new generation of inexpensive embedded devices that are capable of autonomous operation — unmanned systems in the air, on the ground and below the ocean surface. The opportunities afforded by this "convergence of the global industrial system with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity" has been called the Industrial Internet.[24] But this is only the tip of a new era of networked and embedded sensors, processors and actuators. We are indeed poised for the next industrial revolution, the swarms of sensors, processors and machines that interact with and humans. This new internet connecting sensors, machines and humans addresses the design of devices that not only compute and sense, but also close the feedback loop and enable actuation in the physical world, thereby directly interfacing with the environment. Making strides in this domain will require advances in autonomy, i.e., complex decisions will need to be made in an autonomous fashion due to the sheer scale of the application domains. Big data will need to meet CPS and robotics. We will need new architectures to distribute and manage local and cloud-based data and computation, new models for accessing the cloud for real-time operation while providing bounds on system performance, new algorithms to distribute computation and learning, and new abstractions for cloud services that are general enough to be used by a large number of applications.

[24] Industrial Internet Now website: http://industrialinternetnow.com/

6. Toward a Science of Autonomy

The NRI and CPS programs have pioneered remarkable advances that are already having an impact on current and future directions in highly active commercial areas such as IoT and robotics. However, as described in the previous section, the advances catalyzed by these programs also enable new opportunities leveraging both CPS and NRI. One area that is of particular interest, and has all the hallmarks of a disruptive technology is *autonomous systems.* By building on the successes of both programs, we can now imagine intelligent, physically-embedded systems that have increased levels of self-sufficiency and decision-making capabilities – that is, systems that have *autonomy*. Such systems would provide a more powerful substrate upon which to develop collaborative systems, but provide new challenges to the current state of the art of formal development and verification methods, as we further articulate below.

What is Autonomy?

Autonomy is a property of a physically embedded system that is able to achieve a range of goals, independent of external human input, while conforming to a set of rules or laws that define or constrain its behavior.[25] Of particular interest is the ability to intelligently reason about uncertainty, in the environment or task, in order to resiliently achieve the goal. Over time, a reduction in the underlying assumptions and environmental constraints necessary to develop and deploy a physically embedded system leads to autonomy.

It is important to realize that autonomy is not automation -- automation is the implementation of a well-defined process that can be *executed according to a fixed set of rules* with little or no human interaction. Automation has been transforming our world since the industrial revolution, but it is much narrower in scope – requiring a *pre-specified* goal and explicit rules of implementation. In fact, these limitations are arguably what permits a formal analysis of the system by virtue of specifying exactly the process and the goal.

As a result, the "Science of Autonomy" is more than simply building "more automated" systems - the *Science of Autonomy encompasses methods, activities, and observations that lead to a full understanding of how techniques generalize across domain, goal, process, and environment, whether the techniques are physical or algorithmic or computational*. For example, there is a spectrum of interaction between humans and unmanned systems – physical interaction, intent recognition and response, and communication. The science of autonomy addresses problems across this spectrum.

Most importantly, the Science of Autonomy is a science of integration. It requires the ability to integrate hardware with software at several levels – sensing and perception, actuation and control, planning and command/execution. It also requires integration across these levels to synthesize

[25] G. Hager, D. Rus, V. Kumar, and H. Christensen. Toward a Science of Autonomy for Physical Systems. Computing Community Consortium June 24 2015 http://cra.org/ccc/wp-content/uploads/sites/2/2015/07/Science-of-Autonomy-June-2015.pdf

perception-action loops, to learn safe behaviors, to enable self-assessment and self-organization. Ultimately, it is the fundamental science on which the engineering of reliable and safe intelligent physical agents can be built.

Some of the basic questions in this "Science of Autonomy" have interesting connections to questions being addressed in the biology, neuroscience and cognitive science communities, as well as in new and emerging areas such as synthetic biology and the interfaces between inorganic and organic elements. This cross-fertilization might lead to new questions such as: What tools from autonomy could be used within these communities? What type of Autonomy is compatible with biological systems?

Drivers and Metrics

The main drivers for autonomy come from:

- Applications: A wide range of applications to impact with better performance, including disaster prevention/recovery, construction, defense, health care, service, transportation, exploration (space, underwater)
- Economics: Economic incentives are common, where human productivity is enhanced by robots performing low-value tasks instead of humans. Examples include automated small lot manufacturing, warehouses, infrastructure inspection, and construction.
- New Environments: Unmanned systems are able to inhabit environments unfriendly or inaccessible to humans due to size, environment, or distance. There are particular opportunities where the scale and/or physics of the environment is challenging, such as in granular or nanorobotics.
- Humans: Importantly, there is a *spectrum of interaction/collaboration between humans and unmanned autonomous systems that is not easily defined* with simple metrics. This spectrum includes: replacing tasks (better than a human), to unattainable tasks (operating in dangerous places), to collaboration (working together in manufacturing or the home). Given a complex set of tasks, a fully autonomous system is rarely built in the first generation; rather the level of interaction changes over time as autonomy matures.

In addition, other metrics can be defined and used for some applications as specific drivers for autonomy. Examples include:

- Ratio of Humans to Unmanned Systems: This is a simple metric for autonomy large scale systems, and has been used, particularly in defense systems. This metric, however, can be overly narrow to simply define a system; some applications may require, or even desire, strong interactions (e.g. working/playing together in the home).
- Communications: Another relatively simple metric for autonomy is (the bit-rate of) communications between humans and unmanned systems, as well as how data/information, including tasks, are consumed/fused/distributed.
- Proliferation: Lower costs of electronics and sensing, public interest, and strong research are driving broad and wide spread development and uses for autonomy. Leveraging this

interest, and working with the community on the "Science of Autonomy" will enable a more impactful payoff in the future.

When considering many of these drivers, a range or spectrum could be considered in the context of the "Science of Autonomy." Examples include human collaboration (low to high) vs economic impact (low to high), or task complexity vs resilience.

Relationship of Autonomy to NRI and CPS

There are challenges not being addressed by the current NRI/CPS programs, suggesting that a separate program in Autonomy will enable a clear and impactful payoff in the future. The following are specific future impacts that would come with a new, special emphasis on Autonomy:

- Clarity and Synergy: The NRI program to date has broadly defined the scope of current projects to emphasize both direct and indirect co-robot research. This is driven by the view that there is a broad spectrum of underlying science required to enable co-robots to realize their potential. However, it is challenging for both researchers and reviewers to know whether a given project is a fit for the current NRI program. Separate programs for Co-robots/Collaboration, and Autonomy would provide clarity to the researchers, proposers, and reviewers, and provide opportunities for synergy between the underlying core methods, and the human-robot research and applications.
- Maturity of Co-Robots and Interaction: Co-robot systems require a particular level of maturity of the underlying autonomy building blocks. Examples include: new sensing and actuation hardware, perception algorithms, distributed communication, verifiable safety and performance, etc. A program on autonomy would provide a place for these technologies to be developed in full, while providing opportunities for integration into direct co-robot research. Importantly, it is clear that separate programs would provide deeper levels of interaction between the CPS and NRI communities, and greater mutual leveraging of results from those communities.
- Cyber Physical Systems: CPS technologies will be essential to developing autonomous systems. Additionally, CPS education and research will also benefit from Autonomy as a new space of investigation that will require increasingly powerful tools to advance and to scale into real applications.
- New opportunities: A key question is what new challenges/opportunities would be enabled with a new program on Autonomy, which are not currently being realized? Examples include: software-only autonomy such as learning controllers or environments from data; self-X systems that are "self-aware"; deep learning methods; scientifically principled methods to solve the recent DARPA Robotics Challenge. Example applications that may not be clearly addressed include swarm delivery systems, unmanned aerial systems for energy harvesting, and applications with no existing methods for validation.

Conclusions

The Cyber Physical Systems (CPS) program and the National Robotics Initiative (NRI) have proven successful in many ways, from individual success stories to changing the overall dialogue towards a better understanding of the role of computation in the physical world, collaborations between human and machine, and, more broadly, leading the community towards the utilization of this understanding in a variety of application domains. The goal of this workshop was to understand the synergies between these two programs, ways in which they complement each other and, importantly, consider the question: are there fundamental and broad-reaching opportunities that expand beyond the CPS and NRI programs?

The workshop generally concluded that CPS research has, as a major driver, been able to make formal guarantees about a system, its software, and its interface with the physical world. The NRI has focused on developing the technologies to put robots into the real world with humans, i.e., co-robotic systems. As such, these two objectives have many synergies: formal analysis of behaviors with complex specifications operating in uncertain environments, and the coupling between computation and the physical world. Yet the different perspectives taken by the CPS and NRI communities indicate open areas where scientific advancement could have important applications to science, technology and education.

Indeed both the CPS and NRI programs have resulted in large gains in our understanding of complex systems---from making formal guarantees, to synthesizing software solutions that meet specifications, to translating these results to robotic systems that interact with the environment and humans in complex ways. The scientific understanding gained through these programs naturally leads to new horizons in (cloud and wearable) robotic systems and autonomy. This results in the following general recommendation:

> *The CPS and NRI programs have been highly successful, and should continue to be supported so as to reach their full potential. Nucleating and sustaining interactions between the two programs is important to both programs. In addition, the advances catalyzed by these programs have brought into focus the need for a new program charged with a deeper investigation and understanding of physically embedded systems incorporating a combination of autonomous systems and robotics.*

As noted above, it is likely that new types of physically embedded systems, e.g., wearable robots or an internet of robots (or cloud robotics) will form a central pillar to autonomy. Conversely, future work in robotics will require the use of autonomy. All of this will be guided by the formal guarantees and interfacing between computation and the physical given by CPS, coupled with the lessons learned on co-robotic systems in the NRI. Therefore, the existing CPS and NRI programs have the potential to lead the way to a new program that will have important ramifications to manufacturing, robotics, increasing interest in science and engineering, and educating the next generation of Americans.

Appendix

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