Final Report: Special Session on Robotics and Cyber-Physical Systems at the International Conference on Intelligent Robots and Systems

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October 29, 2008

The President's Council of Advisors on Science and Technology (PCAST) August 2007 report identified cyber-physical systems (CPS) as one of the highest priorities for research supporting the USA's global competitiveness. This conclusion is underscored by the European Union's Framework Seven ARTEMIS project (243M Euros) and by Don Winter, Vice President of Engineering and Information Technology of Boeing Phantom Works, in his testimony to the Committee on Science and Technology of the United States House of Representatives on July 31, 2008 (http://democrats.science.house.gov/Media/File/Commdocs/hearings/2008/Full/31july/Winter_Testimony.pdf).

The National Science Foundation (NSF) has developed a new research initiative in CPS that spans the engineering and computer science directorates. Subsequent to the workshop summarized in this report, NSF released the following solicitation: http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf08611. The CPS program officers from the Engineering (ENG) and CISE directorates are:

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To increase awareness of the CPS initiative within the robotics research community and to help the robotics and CPS research communities understand the linkages between robotics and CPS, two special sessions on robotics and CPS were held as part of the IEEE International Conference on Intelligent Robots and Systems (IROS) on September 24, 2008 in Nice France. Participation in the workshop was supported by a grant from NSF.

The web page of the special sessions (http://www.ece.cmu.edu/~webk/IROS_CPS/) contains the accepted position papers and the slides of the presentations. In this report, we give the highlights of the sessions and shed some light on the main questions for discussion.

The two Robotics-CPS special sessions, ran back-to-back from 13:30 to 17:50 with a 20-minute break. Each session began with a 10-minute presentation by NSF Program Director Michael Branicky on NSF's interest in CPS. Branicky's presentation was followed by five presentations and 15-30 minutes of open discussion with the audience. Approximately 50 people attended each session. Attendees were, mostly robotics researchers from the USA, but there was a significant fraction from Europe and Asia as well. See Appendices A and B for the agenda of the sessions and the abstracts of the invited presentations.

To focus the presentations, the speakers were asked to address two main questions:

- *What research in robotics should be generalizable to the broader CPS domain?*
- *What research in CPS could lead to dramatic advances in robotics?*

To encourage discussion between the audience and the speakers and organizers, the following questions were asked of the audience after the speakers' presentations:

- *What is the scope of CPS?*
- *Where are formal methods used in robotics?*
- *What are the analogs to deadlocks and other concurrent programming issues in robotics?*

The following paragraphs contain some partial answers to some of these questions and a few other related thoughts that arose during the sessions.

- *What is the scope of CPS?*
  - The CPS domain is very broad. It includes all physical systems that deeply integrate computing, communication, and control.
  - CPS systems problems arise in many sectors of the economy, including defense, health, energy, transportation, critical infrastructure, and industrial automation.
  - CPS exploit pervasive, networked sensing, computation, and control.
  - CPS will transform how we interact with the physical world just as the Internet transformed how we interact with and communicate information.
  - Robots, modern high-end cars, and "smart bridges" are instances of CPS.
  - A related project in funded by the European Commission is called, "The Internet of Things."
- *Where are formal methods used in robotics?*
  - It was suggested that the robotics research community should embrace such techniques and try to extend them to handle robotics problems. Even if formal methods can be applied only to small parts of robotic systems, the insights should be valuable in the development of more complex systems. An example of what can go wrong when they are not used arose in the Mars PathFinder mission (http://www.ece.cmu.edu/~raj/mars.html).
  - There was skepticism as to how formal methods can be applied to even a simple one-degree-of-freedom haptics device.
  - Formal methods are used in the design of Airbus aircraft, so we should be able to use such methods in complex robotic systems.
- *What are the analogs to deadlocks and other concurrent programming issues in robotics?*
  - In multi-robot systems, the robots are resources for which the various controllers acting throughout the system compete. Existing approaches

have exhibited deadlock situations, where individual robots are halted and unable to carry out their portion of a group task.
    - The robotics community should engage to contribute to emerging standards for concurrent programming of real-time systems that interact with the physical world.
- *What research in robotics should be generalizable to the broader CPS domain?*
    - Perception, one of the main areas in which robotics has made significant advances.
    - Distributed real-time control as occurs in swarms, self-organizing, and metamorphic systems.
    - Shared autonomy and human-robot interaction.
    - The use of human models (as in haptic and exoskeleton applications) as part of an overall system model.
    - Complete robotic systems can be elements in a larger CPS system, such as a “macroscope” composed of many mobile sensors among other things.

- *What research in CPS could lead to dramatic advances in robotics?*
    - Provide theories and formalisms that support the rapid design of systems with continuous and discrete dynamics, with distributed sensing and actuation, with time- and event-based computation and control elements, and with synchronous and asynchronous threads.
    - These formalisms should guarantee correctness and stability, and should also give the designer the ability to predict system performance.
    - Formalisms that support the development of components of the system, such that after composition, the performance of the composed system can be predicted.
    - Complexity theory that goes beyond memory space and computing time, considering issues relevant to the physical world. What physical resources should be added? How?

Here are a few other comments that offered food for thought:

- We need a unifying modeling framework for CPS. Partially observable Markov decision processes (POMDPs) and Markov random fields were suggested as possible bases for such frameworks.
- Machine learning techniques are a necessity.
- System performance must be maintained with scaling and the model framework must predict this performance.
- Robotics and CPS are different in that CPS research must focus on the complete system. In robotics it is often reasonable to work on small pieces of the problem. Creating the full system with performance guarantees is what really sets CPS apart from robotics.
- If there were a curriculum for CPS what would it contain? Software design and engineering, math modeling, simulation and prototyping, signal processing…
- The person is the most important complex element in the CPS. In robotics, we often focus on getting the person out of the loop. The CPS should focus only on doing what the person cannot do and then rely on the person to do the rest.

Appendix A: Session Agendas

FIRST ROBOTICS-CPS SESSION (Chair - Jeff Trinkle)
(Rhodes 10, Track 18, 13h30-15h30)

Invited Speakers

"Cyber-Physical Systems Overview," *Michael Branicky, National Science Foundation*

"A Roboticist's Take on CPS," *John Hollerbach, University of Utah*

"Architectures, Abstractions and Algorithms for Networked Cyber Physical Systems," *Vijay Kumar, University of Pennsylvania*

Contributed Position Papers

"Building Planet-Scale Macroscopes using Multitudes of Sensors and Robots," *Gaurav S. Sukhatme, University of Southern California*

"Think Globally, Act Locally," *Geoff Gordon, Carnegie Mellon University*

"Decision Theoretic Execution Strategies for Modularized Problem Solvers," *Kris Hauser, Jean-Claude Latombe, Stanford University*

Panel Discussion

Jeff Trinkle, Moderator

SECOND ROBOTICS-CPS SESSION (Chair - Jeff Trinkle)
(Rhodes 10, Track 18, 15h50-17h50)

Invited Speakers

"Cyber-Physical Systems Overview," *Michael Branicky, National Science Foundation*

"Case Studies in Cyber-Physical Systems: Smart Prosthetic Hands and In-Vivo Platforms for NOTES Surgery," *Peter Allen, Columbia University*

"Robotics as Computation for Interaction with the Physical World," *Daniela Rus, Massachusetts Institute of Technology*

"The Relationship of Quality of Life Technologies to Cyber-Physical Systems," *Takeo Kanade, Carnegie Mellon University*

Contributed Position Papers

"Markov Random Fields Models for Multi-Robot Teams in Cyber-Physical Systems," *Odest Chadwicke Jenkins, Brown University*

"Human-Cyber-Physical Systems for Emergency Response," *A. Ames, R. Murphy, D. Woods, J. Valasek, T. Zourntos, Texas A&M; M. Branlat, The Ohio State University*

Panel Discussion
Jeff Trinkle, Moderator

Appendix B: Invited Speakers, Titles, and Abstracts

Case Studies in Cyber-Physical Systems: Smart Prosthetic Hands and In-Vivo Platforms for NOTES Surgery

Prof. Peter Allen, Columbia University

Abstract
Cyber-Physical systems are emerging as an important component of next-generation computing systems. In this talk, we first describe a new approach to prosthetics that use computational glue to link human neural activity with control of a dexterous robotic hand to perform grasping tasks. This requires an understanding of both how the neural processes operate and how physical grasping is accomplished with hands. Once the physical and computational requirements of these two systems are understood, intelligent algorithms can be developed to link the two systems. In the second part of the talk, we discuss how Cyber-Physical systems can be used in the emerging field of Natural Orifice Translumenal Endoscopic Surgery (NOTES). We present a fully insertable stereoscopic 3D imaging system that can serve as the basis for a full-functioned end-effector platform to do surgery remotely inside the body. These platforms combine computer augmented sensing and control with the surgeon's own expertise to create a new generation of Cyber-Physical surgical systems.

Overview of Cyber-Physical Systems

Prof. Michael Branicky, National Science Foundation

Abstract
The U.S. National Science Foundation is interested in supporting transformative research on the theory and applications of cyber-physical systems (CPS). The term "cyber" refers to the integration of computation, communication, and control. The CPS challenge is motivated by systems in which cyber and physical elements are deeply integrated and networked at all scales. This talk will present the motivation and vision behind CPS research and suggest connections between CPS and robotics.

A Roboticist's Take on Cyber Physical Systems

Prof. John Hollerbach, University of Utah

Abstract
The Cyber Physical Systems initiative is breathtakingly broad in scope and ambition. Rationales for this initiative, that time and the physical world need a stronger representation in computer science, and conversely that computer science concepts need a stronger representation in deployed computer-networked physical systems, are no doubt generally true. The difficulty will be to find meaningful commonalities among diverse applications. To a considerable

extent, robotics has been addressing many issues of importance for Cyber Physical Systems, and this talk will lead a discussion as to what might be the interaction of the robotics community with this initiative.

The Relationship of Quality of Life Technologies to Cyber-Physical Systems

Prof. Takeo Kanade, Carnegie Mellon University

Architectures, Abstractions and Algorithms for Networked Cyber Physical Systems

Prof. Vijay Kumar, University of Pennsylvania

Abstract

Cyber Physical Systems (CPS) require an integrated approach to control, perception and communication which poses many challenges for large-scale networks. Nature offers many proofs of concepts of collective behaviors arising from local interactions between simple organisms. In many cases, these behaviors are robust to noise in sensing and actuation, and resilient to disturbances from the environment. Modeling such systems and developing low dimensional abstractions are critical to understanding nature and to designing networked CPS. We will describe a framework where low-dimensional abstractions for the group can be used to design control systems for individual units with guarantees at the group level. Case studies from biology and robotics will be used as illustrative examples.

Robotics as Computation for Interaction with the Physical World

Prof. Daniela L. Rus, Massachusetts Institute of Technology

Abstract

The recent progress in computation and hardware has given the age of robotics a great leap forward. Computers have evolved from mainframes to desktops, laptops and pervasive computing. Today's computers are connected pervasively and often have perception as a main operation goal. The next logical step in the evolution of computation is the addition of actuation, which will transform the world of personal computers into a world of personal robots. This talk will discuss current opportunities for applying the science of robotics to cyber-physical systems. Many existing cyber-physical systems rely deeply on robotic technology. We will survey recent technical advances in design, control, planning, perception, and networked control that can have a direct impact on physical problems such as creating (1) intelligent transportation systems that minimize congestion, (2) developing model-based sensor networks with predictive powers such as warning for floods, and (3) developing pervasive adaptive sampling and monitoring systems. We will close with some challenges toward achieving highly capable cyber-physical systems.