Report from the Workshop on Control of Cyber-Physical Systems

Held at the University of Notre Dame London Centre

October 20-21, 2012

Introduction & Background

This workshop[1] was organized to bring together researchers with interests in the area of control of Cyber-Physical Systems (CPS). Three of the four organizers[2] are from institutions in the United States, with research efforts supported by the CPS program at the National Science Foundation. An objective of the workshop was to highlight these research efforts and to bring some European researchers with programs in related areas together for the dissemination of results and a discussion of the major research challenges in CPS.

Presentations/Abstracts/Descriptions

The workshop was organized into five sessions, which spanned topics from fundamentals (mathematical and computational challenges particular to CPS) to applications with an emphasis on controls challenges. The main emphasis was on control, because the topic is especially important in CPS in that it is at the intersection of the "cyber" and "physical" parts of CPS.

Presentations covered many of the following topics:

Fundamentals: security, model reduction, analysis of CPS based on passivity and symmetry, simulation issues particular to CPS, design based on composability.

Applications: transportation systems (ground and air), energy systems and connections with some classical network theory.

Control challenges in CPS: safety and reliability, fault diagnosis in CPS, topical algebras as a tool for hierarchical control systems, model predictive control, aperiodic control in CPS, tradeoffs between feedforward and feedback and remote and local control actions in CPS, bisimulation theory (equivalence of systems) in CPS, networked embedded systems and control, number

---

[1] The web site for the workshop contains the workshop schedule, links to all presentation abstracts and slides and references from many of the presentations. http://controls.ame.nd.edu/mediawiki/index.php/London_CPS_Workshop

[2] Panos Antsaklis, Electrical Engineering at the University of Notre Dame, Bill Goodwine, Aerospace and Mechanical Engineering at the University of Notre Dame, Vijay Gupta, Electrical Engineering at the University of Notre Dame and Karl Henrik Johansson, School of Electrical Engineering, KTH Royal Institute of Technology.

representation in embedded CPS systems and event-triggered and self-triggered control in CPS.

Cyber-Physical Systems (CPS)

As computers become increasingly faster and communication bandwidth ever-cheaper, computing and communication capabilities will be embedded in all types of objects and structures in the physical environment. In this workshop, we defined **"*Cyber-physical systems (CPS)* are physical, biological and engineered systems whose *operations are monitored, coordinated,* controlled *and integrated by a computing and communication core*."** This definition is similar to that used by the US National Science Foundation: "*Cyber-physical systems (CPS) are engineered systems that are built from and depend upon the synergy of computational and physical components*."

Desired characteristics or descriptive words of well-designed and engineered Cyber-Physical Systems include: coordinated, distributed, connected, heterogeneous, robust and responsive, providing new capability, adaptability, resiliency, safety, security, and usability.

This intimate coupling between the cyber and physical will be manifested across a broad range of length scales, from the nano-world to large-scale wide-area systems of systems. Correspondingly, Cyber-Physical Systems will often have dynamics at a wide range of time-scales, such as at the discrete clock scale for some computational aspects to multi-day or even year-long time scales for system-wide properties and evolution.

Applications with enormous societal impact and economic benefit will be created. Cyber-Physical Systems will transform how we interact with the physical world just like the Internet transformed how we interact with one another. **We should care about CPS because our lives depend on them.**

Technological and Economic Drivers

The decreasing cost of computation, networking, and sensing is the main economic driver behind the development of Cyber-Physical Systems.

In addition to the development of new systems, a variety of social and economic forces will require more efficient use of existing national infrastructures.

Environmental pressures will mandate the rapid introduction of technologies to improve energy efficiency and reduce pollution.

Furthermore, there is a need to make more efficient use of health care systems, ranging from facilities to medical data and information.

Some Applications

Medical care and health

Currently: Pacemakers, infusion pumps, medical delivery devices, connected to the patient for life-critical functions

In the Future: 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 (clothing, jewelry) and benignly implantable devices.

Energy and Utilities

Currently: Centralized generation, Supervisory Control and Data Acquisition (SCADA) Systems for transmission and distribution

In the Future: 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

Transportation and Mobility

Currently: Vehicle-based safety systems, ABS, traction and stability control, powertrain management; precision GPS-enabled agriculture

In the Future: 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

Manufacturing

Currently: Computer controlled machine tools and equipment; robots performing repetitive tasks, fenced off from people

In the Future: 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, design for manufacturabillity, programmable foundries

Materials and other sectors

Currently: Relatively few, highly specialized applications of smart materials– predominantly passive materials and structures.

In the Future: Sustainable mass production of "smart" fabrics and other "wearables" with applications in many areas; Actively controlled buildings and structures to improve safety by avoiding or mitigating accidents; 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 (hence NIT) functionality with important physical properties (strength, durability, disposability

Buildings and Infrastructure

Smart buildings are currently a subject of research focus, partly in connection with sustainable energy efforts. These research efforts are directed toward developing smart, "net-zero energy" buildings that are actively monitored, controlled and optimized. Such efforts extend to bridges, dams and other civil structures.

National Defense and Security

Future weapons and defense systems are envisioned as increasingly networked with autonomous air, land and sea vehicles, and sensor networks for distributed monitoring and rapid response.

President's Council of Advisors on Science and Technology (PCAST) Report

Leadership Under Challenge: Information Technology R&D in a Competitive World

An Assessment of the Federal Networking and Information Technology R&D Program, August 2007

New Directions in Networking and Information Technology (NIT)

Recommendation: No 1 Funding Priority: NIT Systems Connected with the Physical World

Other CPS Workshops

Workshop on "High Confidence Medical Device Software and Systems (HCMDSS)", June 2 - 3, 2005, Philadelphia, PA.

Workshop on "Aviation Software Systems: Design for Certifiably

“Dependable Systems", October 5-6, 2006, Alexandria, TX.

Workshop on “Cyber-Physical Systems”, October 16-17, 2006, Austin,TX.

Meeting on “Beyond SCADA: Networked Embedded Control for Cyber Physical Systems", November 8-9, 2006, Pittsburgh, PA.

Workshop on “High-Confidence Automotive Cyber-Physical Systems,” April 3-4, 2008, Troy, MI

Workshop on “High-Confidence Transportation Cyber-Physical Systems: Automotive, Aviation & Rail,” Nov 18-20, 2008, Tyson's Corner, VA

Workshop on “Developing Dependable and Secure Automotive Cyber-Physical Systems from Components,” March 17-18, 2011, Troy, MI

CPS Week, 2008 (St. Louis), 2009 (San Francisco), 2010 (Stockholm), 2011(Chicago), 2012 (Beijing), 2013 (Philadelphia)

Series of topical workshops under NSF sponsorship started in 2006.

“Foundations for Innovation in Cyber-Physical Systems,” NIST Workshop, May, 2012.

What is a CPS? Can we recognize a CPS when we see it?

NIT interaction with physical world. But Digital control in chemical processes half a century old. What is new here??

What is different here is the tight integration of the cyber and the physical parts.

The specifications play a central role. When demanding, the cyber and physical should coordinate and orchestrate their actions and reactions to achieve desired goals.

Example from hybrid systems. Train and gate. To minimize time gate is down, stopping cars from crossing, is obtained when the continuous dynamics of the train and the gate are taken into account.

When there is no heat or energy issue or shared resource issues, there is no reason to worry about reducing the clock speed of the digital device when the control algorithm does not need it, do cross layer design, worry about demanding timing issues in implementing the algorithm

So the same system may be regarded as a CPS or not.

CPS Challenges

Control is a major CPS challenge. It is inherent in many, if not most, Cyber-Physical Systems because it exists at the intersection of the cyber and physical components, making use of each and mediating their interaction. Very difficult challenges are posed for control of CPS, however, due to a variety of factors such as very broad time and length scales, the presence of network communication and delays, coordination of many components (with an associated increased risk of component failure as the number of components grows to be very large), model reduction, tractability, etc.

CPS Characteristics

What cyber physical systems have as defining characteristics:
Cyber capability (i.e. networking and computational capability) in every physical component
They are networked at multiple and extreme scales
They are complex at multiple temporal and spatial scales.
They are dynamically reorganizing and reconfiguring
Control loops are closed at each spatial and temporal scale. Maybe human in the loop.
Operation needs to be dependable and certifiable in certain cases
Computation/information processing and physical processes are so tightly integrated that it is not possible to identify whether behavioral attributes are the result of computations (computer programs), physical laws, or both working together.

CPS Issues

There is a set of pervasive underlying problems for CPS not solved by current technologies:

How to build predictable real time, networked CPS at all scales?
How to build and manage high-confidence, secure, dynamically-configured systems?
How to organize and assure interoperability?
How to avoid cascading failure?
How to formulate an evidential (synthetic and analytic) basis for trusted systems? Certified.

Assuming exact knowledge of the components and their interconnections may not be reasonable.

Dynamic change. The physical part may cause the CPS to change. Links disappear. Modules stop operating. These are to be expected when we are interested in the whole life cycle of the system.

If the system was safe, verified to be safe, can we guarantee that it will still be? Can we do something about it? Is it resilient? High autonomy.

If secure originally can we still guarantee that property?

Connections to linear programming, optimization. Simplex and sensitivity analysis.

Approach

Perhaps it is more reasonable to aim for staying in operating regions. Operating envelope.

Flight envelope. The pilot is not allowed to take certain actions that may stall the aircraft (Airbus). Flight envelope.

In DES supervisory control actions are allowed or not allowed to occur and so behavior is restricted

Lyapunov stability implies that the states are bounded-asymptotic stability implies that the state will also go to the origin as time goes to infinity. Restrictions on behavior.

Feedback interconnection of stable systems may not be stable. Switching among stable systems may lead to unstable systems.

Is there any similar, energy like concept where guarantees can be given about properties in, say, feedback configurations?

List of Presentations and Topics

Session 1: Introduction and Welcome

Introduction, presented by Panos Antsaklis (slides)
Alkis Konstantelos presentation (slides)

Session 2: Fundamentals

Xenofon Koutsoukos, *Resilient Cooperative Control of Cyber-Physical Systems* (slides)
Panos Antsaklis, Bill Goodwine and Vijay Gupta, *Passivity and Symmetry in the Control of Cyber-Physical Systems* (slides)
Karl-Erik Årzén, *Simulation of Cyber-Physical Control Systems* (slides)
Stefan Kowalewski, *Architectural Support for Agile Control Design in CPS*
John S. Baras, *Components, Compositionality and Architectures for Networked CPS* (slides)

Session 3: Applications

Carlos Canudas-de-Wit, *CPS in Intelligent Transportation Systems: The Grenoble South Ring Show Case*

Eduardo F. Camacho, *Control of Solar Thermal Plants* (slides)

João Sousa, *Coordination Challenges in Networked Vehicle Systems: Are We Missing Something?* (slides)

Malcolm Smith, Classical Network Synthesis Revisited

Session 4: 2:00-4:00, Panel Discussion

Moderator: Panos Antsaklis

Penelists: Alessandro Astolfi, John S. Baras, Sandra Hirche (slides), Karl Erik Johansson (slides), Alkis Konstantelos, Francoise Lamnabhi-Lagarrigue (slides)

Session 5: Control I

Thomas Parisini and Marios Polycarpou, *Towards Safe and Reliable CPS: A Learning-Based Distributed Fault-Diagnosis Approach*

Joerg Raisch, *Control Hierarchies and Tropical Algebras* (slides)

Jan Maciejowski, *Some New Developments in Model Predictive Control* (slides)

Kostas Kyriakopoulos, *A Framework for Aperiodic Model Predictive Control* (slides)

Antonio Bicchi, *Trading off Feedforward and Feedback, Remote and Local in the Control of Complex Interconnected Plants* (slides)

Session 6: Control II

Arjan van der Schaft, *Bisimulation Theory for Multi-Modal Physical Systems* (slides)

Claudio De Persis, *Coordination Control in a Cyberphysical Environment* (slides)

Marika Di Benedetto, *Analysis and Control of Networked Embedded Systems*

Eric Kerrigan, Number Representations for Embedding Optimization Algorithms in Cyber-Physical Systems (slides)

Maurice Heemels, *Event-Triggered and Self-Triggered Control Design with Guaranteed Performance* (slides)

Recommendations

The presentations, panel discussion and question and answer portions of the workshop highlighted several conclusions regarding research in Cyber-Physical Systems. Cyber-Physical Systems are systems that will be of increasing importance economically and to the quality of life of people throughout the world. Decreased computational expense coupled with increased connectivity will work to make such systems ubiquitous. However, significant engineering challenges must be met for such systems to attain their full potential. Fundamental work in modeling and simulation of Cyber-Physical Systems is still necessary to formulate useful and tractable models for analysis and design. Controls is inherent in such systems because control algorithms make up the intelligence that is at the interface between the cyber and physical parts of CPS.