NSF *Cyber Physical Systems* (CPS) Program

Past, Present, and Future

Keith Marzullo
NSF CISE CNS

Directorate for Computer &Information Science & Engineering (CISE)
Division of Computer & Network Systems (CNS)

Directorate for Engineering (ENG)

With involvement/cooperation/interest/support from:

Air Force Office of Scientific Research (AFOSR)
Air Force Research Laboratory (AFRL)
Advanced Research Projects Agency-Energy (ARPA-E)
FAA-Joint Planning and Development Office (JPDO)
Food and Drug Administration (FDA)
Department of Transportation (DOT)
National Institutes of Health (NIH)
National Institute of Standards and Technology (NIST)
National Aviation and Space Administration (NASA)
Nuclear Regulatory Commission (NRC)
National Security Agency (NSA)
National Transportation Safety Board (NTSB)
Director, Defense Research and Engineering (DDR&E)

Lead PDs (supported by a cast of thousands)

2011

Helen Gill, CISE/CNS
Richard Voyles, CISE/CNS
Kishan Baheti, ENG/ECCS
Zygmunt Haas, ENG/ECCS

2010

Helen Gill, CISE/CNS
Kishan Baheti, ENG/ECCS
Michael Branicky, CISE/CNS

2009

Helen Gill
Scott Midkiff
(Bruce Krogh, CMU, consultant)

Why was the program created?

National Priorities and Challenges outlined in several reports[1] including: health, wellbeing, and medicine; high-confidence critical infrastructures; safer transportation systems; collaborative intelligence; competitive economy and our manufacturing base; our aging population; ... networked information systems connected to our physical world.

Examples:

Transportation	▪ Faster and safer aircraft ▪ Improved use of airspace ▪ Safer, more efficient cars	
Energy and Industrial Automation	▪ Homes and offices that are more energy efficient and cheaper to operate ▪ Distributed micro-generation for the grid	
Healthcare and Biomedical	▪ Increased use of effective in-home care ▪ More capable devices for diagnosis ▪ New internal and external prosthetics	
Critical Infrastructure	▪ More reliable power grid ▪ Highways that allow denser traffic with increased safety	

[1] *See, for example, PCAST Reports: Leadership Under Challenge: Information Technology R&D in a Competitive World (August 2007) -- http://www.nitrd.gov/Pcast/reports/PCAST-NIT-FINAL.pdf; Federal Plan for Advanced Networking Research and Development (September 2008) -- http://www.nitrd.gov/pubs/ITFAN-FINAL.pdf; Grand Challenges: Science, Engineering, and Societal Advances, Requiring Networking and Information Technology Research and Development (Third Printing - November 2006) -- http://www.nitrd.gov/pubs/200311_grand_challenges.pdf*

Program Evolution: Workshops about CPS

- High-Confidence Medical Device Software and Systems Workshop, June 2005, Philadelphia, PA
- Aviation Software Systems: Design for Certifiably Dependable Systems, Oct. 2006, Alexandria, TX
- Beyond SCADA: Networked Embedded Control for Cyber Physical Systems, Nov. 2006, Pittsburgh, PA
- High-Confidence Software Platforms for Cyber-Physical Systems, Nov. 2006, Alexandria, VA
- Joint Workshop On High-Confidence Medical Devices, Software, and Systems and Medical Device Plug-and-Play Interoperability, June 2007, Boston, MA
- Composable and Systems Technologies for High-Confidence Cyber-Physical Systems, 2007, Arlington, VA
- High-Confidence Automotive Cyber-Physical Systems, April 2008, Troy, MI
- CPS Summit, CPS Week, April 2008, St. Louis, MO
- Robotics and Cyber-Physical Systems Special Session at IROS, Sept. 2008, Nice, FRANCE
- Transportation Cyber-Physical Systems: Automotive, Aviation, and Rail, November 2008, Vienna, VA
- Energy CPS, June 2009, Baltimore, MD
- ...

What are Cyber-Physical Systems?

They are **not**:

- traditional, embedded/real-time systems
- today's sensor nets

Some hallmark characteristics of CPS:

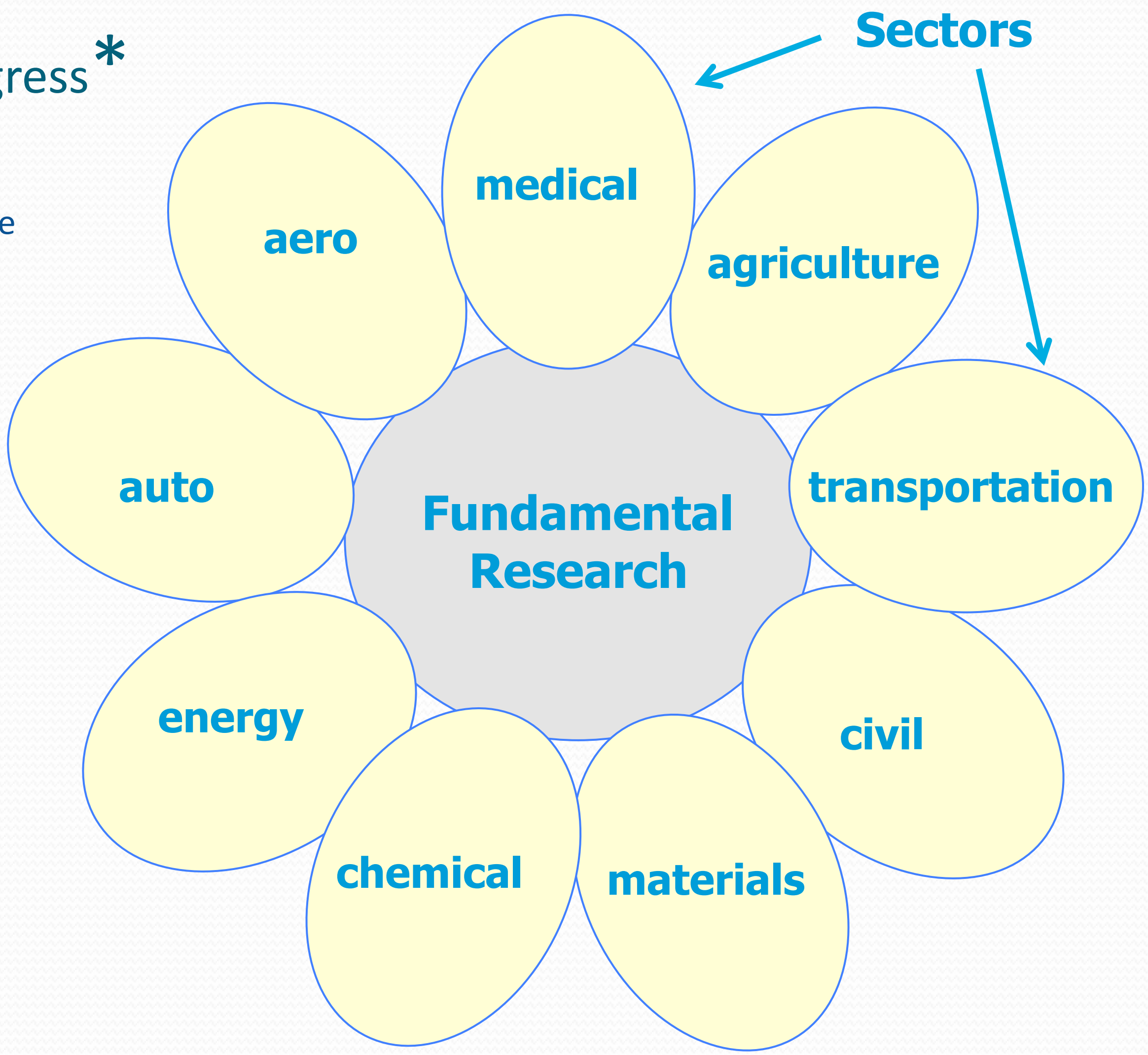
- Cyber capability in physical components
- Networked at multi- and extreme scales
- Complex in many scales
- Dynamically reorganizing/reconfiguring
- High degrees of automation
- Operation must be dependable, and in some cases certified

Cyber-Physical Systems deeply integrate **computation, communication, and control** into **physical** systems

CPS exploit pervasive, networked computation, sensing, and control, i.e., "Internet of [**controlled]** things"

Model for Expediting Progress*

- A new underlying discipline
- Abstracting from sectors to more general principles
- Apply these to problems in new sectors
- Build a new CPS community



* Jeannette M. Wing
past Assistant Director, CISE, NSF

What we hope to achieve

- Enable societal acceptance and reliance – CPS people can bet their lives on
- Overcome complex technical challenges – systems that interface the cyber and physical, with predictable behavior and reconfigurable software and hardware
- *Design for certifiably* of dependable control of (complex) systems
- Discover principles for bridging control, communications, real-time systems, safety, security
- Define next generation system architectures and assurance technology including formal methods and computational frameworks for the design and implementation of reliable, robust, safe, scalable, secure, stable, and certifiably dependable systems
- Develop science and technology for building cyber-physical systems: unified foundations, models, and tools
- Advance cyber-enabled discovery and innovation to enhance understanding and management of complex systems
- Integrate CPS research and education – prepare next generation of practitioners

Enable a research community and workforce that will be prepared to address the challenges of next generation systems	Bridge previously separated areas of research to develop a unified systems science for cyber-physical systems	Develop new educational strategies for a 21st century CPS workforce that is conversant in both cyber and physical aspects of systems

The CPS program addresses:

- tight conjoining of and coordination between **computational and physical resources**.
- **future critical needs** that will far exceed those of today in terms of adaptability, autonomy, efficiency, functionality, reliability, safety, and usability.
- research advances that promise to transform our world with systems that respond more quickly, are more precise, work in dangerous or inaccessible environments, provide large-scale, distributed coordination, are highly efficient, augment human capabilities, and enhance societal wellbeing.

Three CPS Themes:

- ***Foundations*** – develop new scientific and engineering principles, algorithms, models, and theories for the analysis and design of cyber-physical systems
- ***Methods and Tools*** – bridge the gaps between approaches to the cyber and physical elements of systems through innovations such as novel support for multiple views, new programming languages, and algorithms for reasoning about and formally verifying properties of complex integrations of cyber and physical resources
- ***Components, Run-time Substrates, and Systems*** – new hardware and software infrastructure and platforms and engineered systems motivated by grand challenge applications

Highly competitive program

Click “awards” near top of NSF.gov page

Search for program element code 7918

There are 59 active awards:

- 21 small, average $495K
- 35 medium, average $907K
- 3 large, average $1.54M

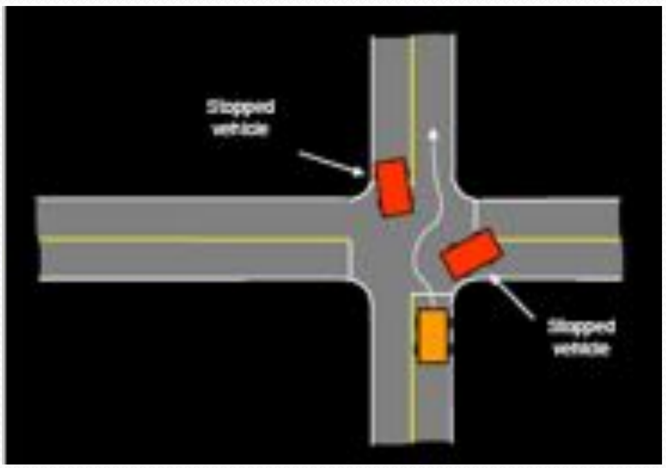
Can generate with a link at the bottom of the CPS program description ➜

... which you can find listed as a *featured program* on the CISE web page.

Areas that have been funded so far

- Embedded Control
- Model Checking for Discrete/Continuous Systems
- Verification
- Robotics and Prosthetic Devices
- System Integration
- Medical Device Safety and Certification
- Autonomous Vehicles
- Man Machine Interfaces
- Monitoring
- Medical Devices and Robots
- Smart Spaces
- Vehicle Safety
- Structure Monitoring
- Smart Grid Management
- Underwater Systems
- Cooperative Multi-Agent Systems
- Vision and Visualization
- …

Examples of CPS Awards: Aviation and Automotive Systems



CPS: Medium: Autonomous Driving in Mixed-Traffic Urban Environments

Umit A Ozguner, Ashok K Krishnamurthy, Fusun Ozguner, Paolo A Sivilotti, Bruce W Weide (Ohio State U)

http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0931669

The objective of this research is to scale up the capabilities of fully autonomous vehicles so that they are capable of operating in mixed-traffic urban environments. Such environments are realistic large-city driving situations involving many other vehicles, mostly human-driven. The approach is to integrate multidisciplinary advances in software, sensing and control, and modeling to address current weaknesses in autonomous vehicle design.

Figure: An intersection situation from the 2007 DARPA Urban Challenge (a) as originally described, and (b) simplified for consideration in the rules.

Examples of CPS Awards: Health and Medicine

CPS Small: Control of Surgical Robots: Network Layer to Tissue Contact

Blake Hannaford, Howard J Chizeck (U Washington)

http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0930930

This CPS project aims to enable intelligent tele-surgery in which a surgeon, or a distributed team of surgeons, can work on tiny regions in the body with minimal access. The University of Washington will expand an existing open surgical robot test-bed, and create a robust infrastructure for cyber-physical systems with which to extend traditional real-time control and tele-operation concepts by adding three new interfaces to the system: networking, intelligent robotics, and novel non-linear controllers.

The PIs conducted two major field trials to demonstrate the robustness of the RAVEN hardware and software. These included deployment in a tent (top photos)in 100F semi-desert range land outside Simi Valley California (High Altitude Platform, Mobile Robotic Telesurgery (HAPs/MRT)), and deployment in an underwater habitat (bottom photos) 20m below the ocean surface (and at 2 atmospheres of pressure).

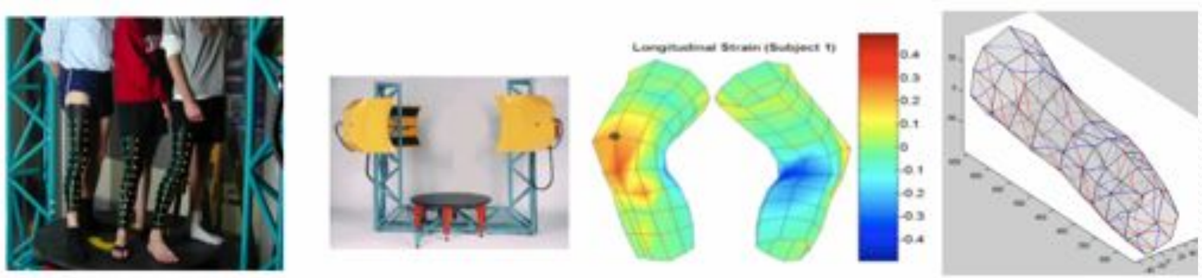
Examples of CPS Awards: Health and Medicine

CPS:Medium: Programmable Second Skin to Re-educate Injured Nervous Systems

Eugene C. Goldfield (Harvard Medical School, Children's Hospital Corp), Rob Wood and Radhika Nagpal (Harvard University), Dava Newman (MIT), Marc Weinberg (Draper), Kenneth Holt and Elliot Saltzman (BU)

http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0932015

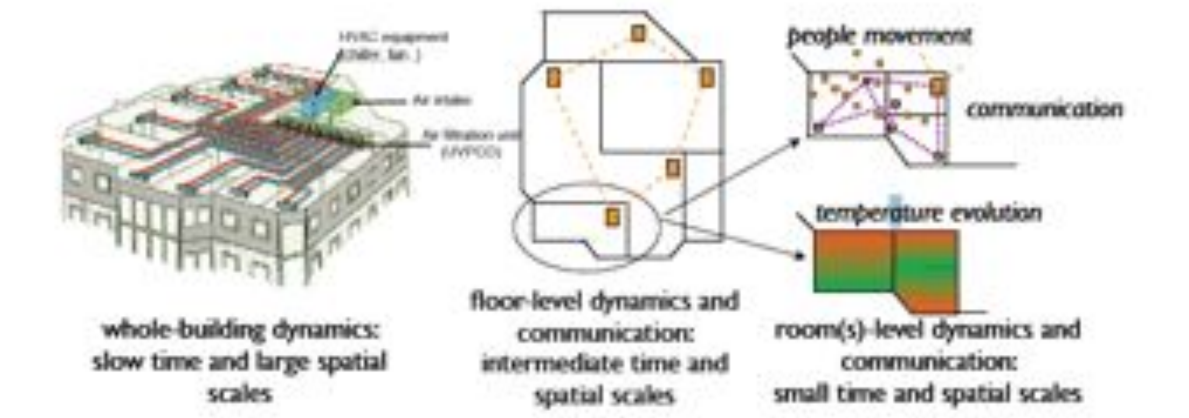
The objective of this research is to create a novel Cyber-Physical System, a self-reconfiguring "second skin orthotic sleeve" consisting of programmable materials. The orthotic sleeve, worn over one or more limbs of brain-injured individuals, may restore brain function by promoting enriched exploration of self-produced limb movements. The approach consists of three steps (1) micro-fabricating sheets with embedded sensors and muscle-like collections of force-producing actuators, (2) conducting longitudinal recordings of kicking by typically developing and preterm brain-injured infants who wear a sensing, but not actuated micro-fabricated second skin, and (3) developing biologically-inspired programming techniques to help determine an algorithm with which the second skin embedded actuators may adaptively assist the ever-changing developmental pattern of infant kicking.



(a) (b) (c) (d)

Figure: (a) Colored markers on subjects' legs serve as fiduciary marks to measure skin strain as the legs are flexed during (b) laser scan data acquisition. (c,) A resulting skin strain field calculation showing up to ±40% longitudinal strains. (d) Sample lines of non-extension.

Examples of CPS Awards: Energy and Environment



Approach to high-performance building system operation with a network of distributed embedded devices for monitoring and control. Multi-scale Markov models and optimal model reduction is used to identify (on-line) clusters of the building whose dynamics are tightly coupled. This is used to decompose the real-time estimation and control problems into smaller sub-problems, and reduce communication requirements.

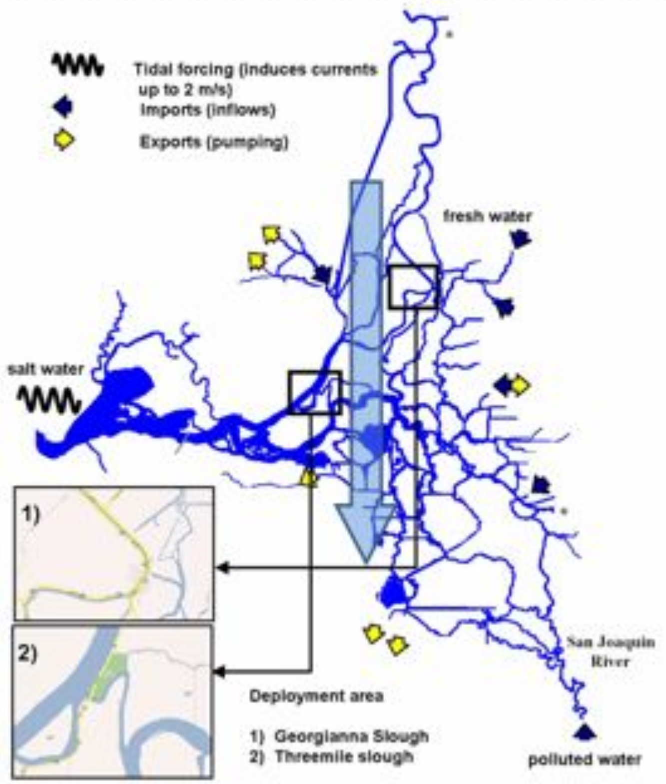
CPS: Medium: Collaborative Research: GOALI: Methods for Network-Enabled Embedded Monitoring and Control for High-Performance Buildings

Prabir Barooah (U. Florida), Alberto Speranzon (UTRC), Prashant Mehta and Sean Meyn (UIUC), Luca Carloni (Columbia)

http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0931885

The objective of this research is to develop methods for the operation and design of cyber physical systems in general, and energy efficient buildings in particular. The approach is to use an integrated framework: create models of complex systems from data; then design the associated sensing-communication-computation-control system; and finally create distributed estimation and control algorithms, along with execution platforms to implement these algorithms. A special emphasis is placed on adaptation. In particular, buildings and their environments change with time, as does the way in which buildings are used. The system must be designed to detect and respond to such changes. The proposed research brings together ideas from control theory, dynamical systems, stochastic processes, and embedded systems to address design and operation of complex cyber physical systems that were previously thought to be intractable.

Examples of CPS Awards: Energy and Environment



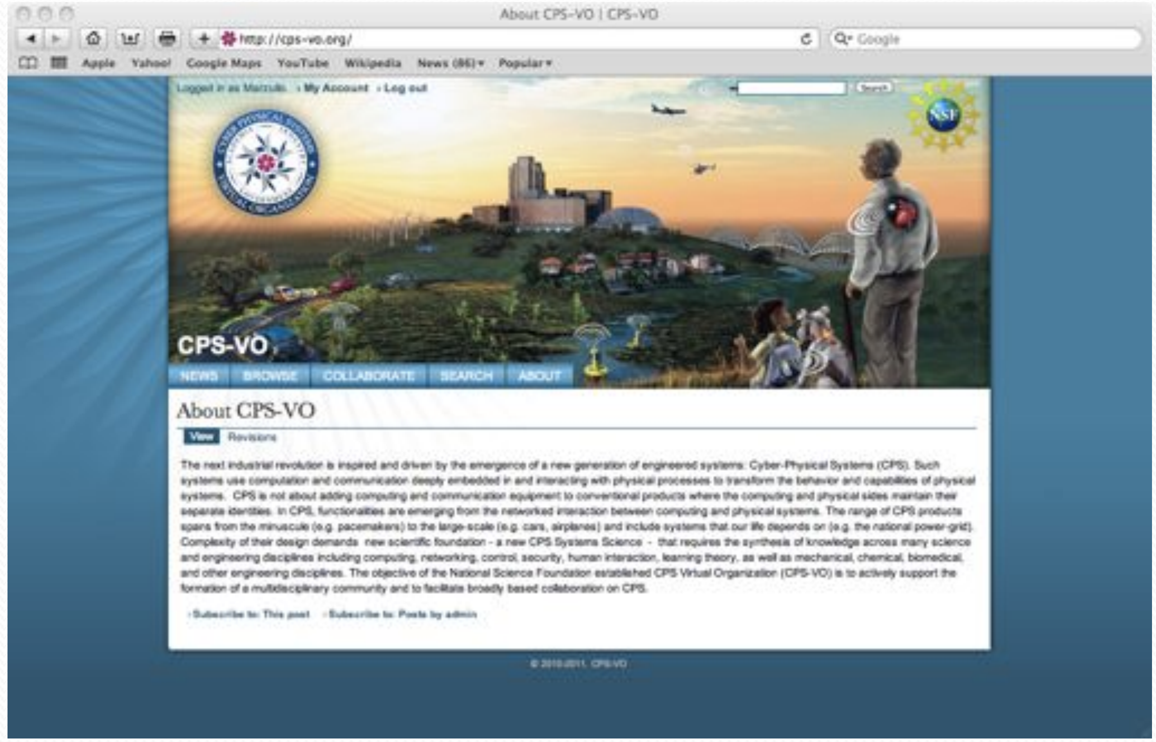
Closing the loop in the Delta: freshwater corridor management using gates operated on a tidal timescale based on Lagrangian/Eulerian sensing.

CPS:Medium:Collaborative Research: Physical Modeling and Software Synthesis for Self-Reconfigurable Sensors in River Environments; Jonathan Sprinkle (U. Arizona), Sonia Martinez (UCSD), Alex Bayen (UC Berkeley)

http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=0930919

This work is addresses a challenging problem: the management of clean water resources. Tidally forced rivers are critical elements in the water supply for millions of Californians. The objective of this research is the transformation from static sensing into mobile, actuated sensing in dynamic environments, with a focus on sensing in tidally forced rivers. The approach is to develop inverse modeling techniques to sense the environment, coordination algorithms to distribute sensors spatially, and software that uses the sensed environmental data to enable these coordination algorithms to adapt to new sensed conditions. This work relies on the concurrent sensing of the environment and actuation of those sensors based on sensed data. Sensing the environment is approached as a two-layer optimization problem. Since mobile sensors in dynamic environments may move even when not actuated, sensor coordination and actuation algorithms must maintain connectivity for the sensors while ensuring those sensors are appropriately located. The algorithms and software developed consider the time scales of the sensed environment, as well as the motion capabilities of the mobile sensors. This closes the loop from sensing of the environment to actuation of the devices that perform that sensing.

CPS-VO Portal



- Principles & Services
  - Community controlled
  - Services for collaborative activities
  - Support for SIGs
  - Industry academy interactions
  - Built on open source framework
  - Home for the community's historical reference materials
  - Calendar of upcoming events
  - Discussion forums and instant messaging
  - Community members list and matchmaking

Check it out!
http://cps-vo.org

- New solicitation just out – a small revision
  - Medium: $300K-$500K per year for 3-4 years
    - Expect 20-30 awards
    - 4th year requires testbed/ prototype development
  - Large: up to $1M per year for up to 5 years
    - Expect no more than one award
    - Requires an exceptional educational and outreach plan
  - Anticipate ~$30M per competition
  - Proposals due March 21, 2011

Cyber-Physical Systems (CPS)

PROGRAM SOLICITATION
NSF 11-516

REPLACES DOCUMENT(S):
NSF 10-515

National Science Foundation
Directorate for Computer & Information Science & Engineering
Directorate for Engineering

Full Proposal Deadline(s) (due by 5 p.m. proposer's local time):

March 21, 2011

January 17, 2012

Third Tuesday in January, Annually Thereafter

IMPORTANT INFORMATION AND REVISION NOTES

A revised version of the *NSF Proposal & Award Policies & Procedures Guide* (PAPPG), NSF 11-1, was issued on October 1, 2010 and is effective for proposals submitted, or due, on or after January 18, 2011. Please be advised that the guidelines contained in NSF 11-1 apply to proposals submitted in response to this funding opportunity. Proposers who opt to submit prior to January 18, 2011, must also follow the guidelines contained in NSF 11-1.

Cost Sharing: The PAPPG has been revised to implement the National Science Board's recommendations regarding cost sharing. Inclusion of voluntary committed cost sharing is prohibited. In order to assess the scope of the project, all organizational resources necessary for the project must be described in the Facilities, Equipment and Other Resources section of the proposal. The description should be narrative in nature and must not include any quantifiable financial information. Mandatory cost sharing will only be required when explicitly authorized by the NSF Director. See the PAPP Guide Part I: *Grant Proposal Guide (GPG)* Chapter II.C.2.g(xi) for further information about the implementation of these recommendations.

Data Management Plan: The PAPPG contains a clarification of NSF's long standing data policy. All proposals must describe plans for data management and sharing of the products of research, or assert the absence of the need for such plans. FastLane will not permit submission of a proposal that is missing a Data Management Plan. The Data Management Plan will be reviewed as part of the intellectual merit or broader impacts of the proposal, or both, as appropriate. Links to data management

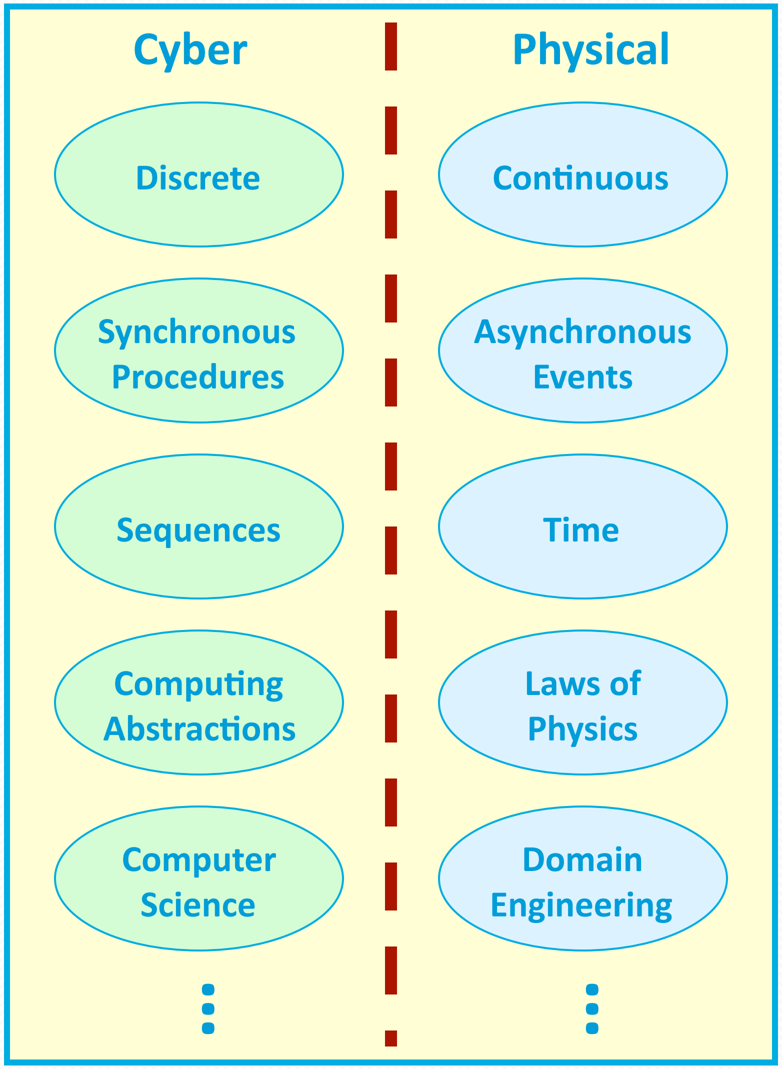
Future of CPS

- CPS is an emerging area:
  New systems science (integrated, design for certifiable dependability)
- So far:
  Many exciting system challenges, preliminary system science, few/no community-based substrates

- VO is very active:
  CPS certification, aviation, medical, CPS security SIGs ready to start

- Emerging:
  Concepts for systems that remain predictable under variations in energy, latency, …; "impedance matching" – e.g.., "slow" control, passivity-based design methods, event-based control; composability of real-time guarantees; increasing interest in analog and broad-based reconfigurable computing.
- Needs:
  Unified science that ties together observation, prediction, and control with topology-varying, networked real-time embedded systems; hybrid distributed systems and new supervisory control concepts; dynamic coordinated RT guarantees; improved abstractions for embedded software/programming; rapprochement between ML and traditional system ID; open source concepts for substrates that scale; innovative resource sharing modalities for CPS (e.g., energy exchange; RT micro-clouds); cyber security concepts that are suitable for CPS.
- Urgent:
  Break silos – computing, communication, dynamics and control, state and behavior representation; certification

CPS Research Gaps



Research Gaps

- Composition
- Design automation
- System integration
- Certification
- Security and privacy
- Education and work force

What will it take?

- *Science and technology* for open, interoperable systems that deeply integrate the cyber and physical and that produce predictable behavior
  - Control theory
  - Networking
  - Real time systems
  - Logics and formal methods for verifying system behavior
  - …

- A *CPS educational strategy* to create the 21st century CPS workforce
  - Discrete mathematics and computer science
    - Automata, logics and formal methods, modeling and verification
    - Systems software, programming languages for CPS
  - Continuous mathematics, physics, chemistry, biology…
    - ODEs, PDEs, fundamental laws of physics, …
  - Hybrid discrete/continuous systems

Discussion