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# Cyber-physical systems: challenges & opportunities

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*Boston University*

## Cyber-Physical Systems

Challenges & Opportunities

**Azer Bestavros**

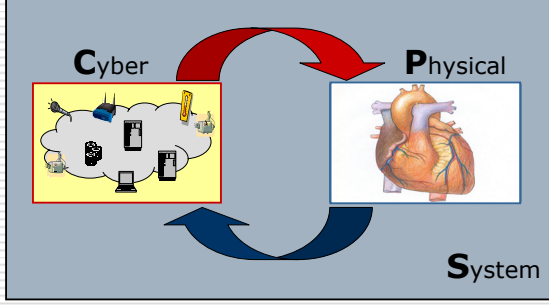
Computer Science Department  
Boston University



<http://www.cs.bu.edu/groups/wing>

Sensor Network Consortium  
May 8, 2008

## Cyber-Physical Systems (CPS)



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## CPS: Major Roadblock

- All our software frameworks abstract out or add uncertainty to spatio-temporal attributes:
  - Programming languages
  - Virtual memory
  - Caches
  - Dynamic dispatch
  - Speculative execution
  - Power management (voltage scaling)
  - Memory management (garbage collection)
  - Just-in-time (JIT) compilation
  - Multitasking (threads and processes)
  - Component technologies (OO design)
  - Networking (TCP)
  - ...

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## CPS: Certification is key

- By definition, CPS = Safety Critical
- System must be certified with respect to a variety of stringent safety constraints
  - Safety constraints
  - Real-time constraints
  - Non-interference constraints
  - Fail-safe constraints
- Not about proofs of concept
- Cost is a secondary concern!

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## The Hospital Dilemma

- Paraphrasing John Rushby, SRI
 

*"The patient on the operating table is the medium through which multiple life-support (respiratory and circulatory) subsystems interact. There are documented cases of deaths and severe injury due to medical device interference."*
- Who is liable? The manufacturers? The hospital? A real stumbling block for innovation!

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## The Boeing Dilemma

- Paraphrasing Edward Lee, UC Berkeley:
 

*"In fly by wire aircraft, it is not the software that is certified but the entire system. If a manufacturer expects to produce a plane for 50 years, it needs a 50-year stockpile of fly-by-wire components that are all made from the same mask set on the same production line. Even a slight improvement require the software to be re-certified."*
- What about outsourcing? How is Airbus doing it?

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## What Could Go Wrong?

- A few potent examples
  - Interference between controllers
    - Interference between multiple life support subsystems
  - Compatibility questions
    - Will upgrading break my system? (regression is hell!)
  - Data plane interactions
    - Could I substitute a Kalman filter with another?
  - Control plane interactions
    - Do firewall security rules compose safely with my network monitoring infrastructure?

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## (Scalable) Compositional Analysis

- **Composition:**  
*The system Z that results from having X interact with Y*
- **Analysis:**  
*Formally derive safety properties of a system W*
- **Analyzing a composition:**  
*Derive properties of Z by analyzing the composition of X and Y*
- **Composing the analysis:**  
*Derive properties of Z by composing the analysis of X and the analysis of Y*

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## Component Property Projections

- Allows us to abstract the system for a particular perspective

- But, for CPS, no one perspective is enough!

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## Need to "Compose" Theories

- Different techniques are better at dealing with different types of properties
  - Thermodynamics: Heat diffusion; energy transfer, ...
  - Control theory: Convergence, stability, dynamics, ...
  - Network calculus: Max/min delays, b/w, loss rates, ...
  - Queuing theory: Average delay, utilization, ...
  - Real-time theory: Schedulability/timing analysis, QoS, ...
  - State-space analysis: Deadlocks, synchronization, ...
  - Game theory: Price of anarchy, mistreatment, ...
  - ... *put your pet theory here*
- Need a seamless way to leverage all such theories and techniques

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## BU Project: snBench

Design/implement an integrated software development and certification environment for CPS applications over a shared CP infrastructure

**The CPS *is* the computer...**

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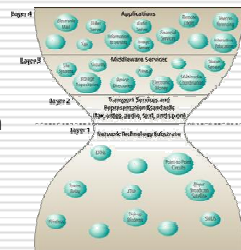
## snBench: Hourglass Model...



- If the Physical World is the Computer, then what is its ISA?

### □ Why an ISA?

- Minimizes cost
- Encourages innovation
- Speeds up adoption
- Scales up education

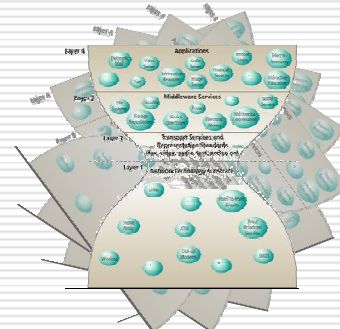


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## ... One Hourglass Model / Theory



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## snBench: Goals



- Write once; run anywhere
- Don't program nodes; program the CPS!
  - Start with building blocks – "Gadgets"
    - Models of the physical domain objects
    - Sensors (cameras, motion sensors, biosensors, ...)
    - Actuators (device controllers, net services, ...)
    - Stock algs (Kalman filter, FFT, edge detect, ...)
  - Glue together with high-level language
    - Conditionals, loops, triggers, functions
  - Pretend the network isn't there
    - "Single CPS System Image"
- Integrate programming and verification

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## snBench: Programming Cycle



- Program
  - Program specified by gluing together building blocks using a high-level language (SNAFU)
- Compile and Certify
  - Program is compiled to produce a plan of execution expressed over a CPS domain abstraction (STEP)
- Map and Link
  - STEP plans are decomposed in smaller dispatch-able STEPs which are linked
- Load and Execute
  - STEP plans are dispatched and loaded onto the computational core of the CPS infrastructure

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## snBench: Certification



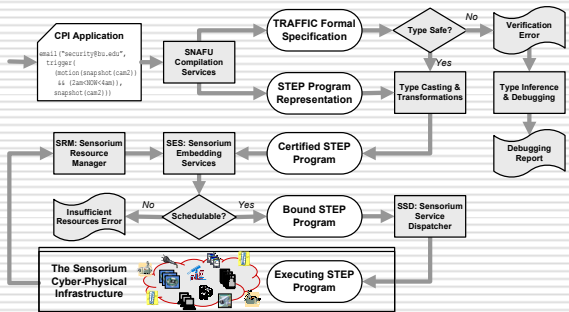
- Annotations used to define behavioral constraints, a.k.a., "types"
- Annotations are distilled into domain-specific formal representation of the interfaces between CPS "gadgets"
- Use type-checking and type inference to mechanically verify safety properties *a priori*

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## snBench: Roadmap



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## snBench: Status



- Used as a platform for projects in SE and AI courses in CS since 2005!
  - Students developed opcodes, GUIs, resource managers, applications, rule-based front-end for medical devices, ...
  - Multimodal sensing and actuation using motes, PTZ-cams, kismet wireless intrusion detection, Garcia robots, ...
- snBench is Alive!
  - Latest code and demos from multiple case studies at <http://csr.bu.edu/snbench/>

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## CPS: Challenges



	New abstraction layers for design	Swamatic foundations for composing models	Composition platforms for heterogeneous systems	Predictability under limited compositionality	Foundation for system integration	Compositional certification	Agile design automation	Open Architectures	Reliable systems from unreliable components	Resiliency to cyber attacks
Aerospace	■	■	■	□	■	■	■	○	■	■
Automotive	■	■	■	□	■	○	■	■	■	■
Defense	■	■	■	□	■	○	■	■	■	■
Energy	■	□	■	■	■	○	○	■	■	■
Biomedical	■	□	■	■	■	■	□	□	■	■

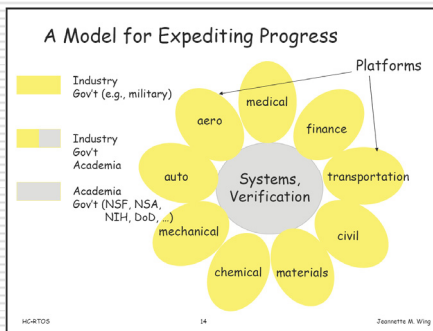
From executive summary of CPS Summit Report, April 2008

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## CPS: Stakeholders



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## CPS: A Global R&D Priority



- Federal Networking and Information Technology R&D *Formative planning workshops by HCSS coordinating group*
- The CSTB and the National Academies *Sufficient Evidence? Building Certifiably Dependable Systems*
- Forthcoming significant R&D funding *NSF started a seeding program in 2007*
- Computing Research Association *A focus area of the Computing Community Consortium*
- Convergence of RT, SN, Emsoft, Hybrid and Control *First CPS Summit with co-located events held in late April*
- Beyond academia and beyond the US *SCADA, Automotive, MD PnP, Aviation, EU ARTEMIS & EPoSS*

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## How Could SNC Members Help?



- CPS research is domain-specific
  - We need domain experts for the modeling and control of physical (mechanical, electromagnetic, biological, chemical, biophysical, biochemical, medical, ...) phenomena
  - We need test-beds and opportunities for student training
- What is your CPS application?

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