Cyber-Physical Systems (CPS)

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)
  - …

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!

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!

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 requires the software to be re-certified."
- What about outsourcing? How is Airbus doing it?
What Could Go Wrong?

- A few potent examples
  - Interference between controllers
  - Compatibility questions
  - Data plane interactions
  - Control plane interactions

What Could Go Wrong?

- A few potent examples
  - Interference between controllers
  - Compatibility questions
  - Data plane interactions
  - Control plane interactions

(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

Component Property Projections

- Allows us to abstract the system for a particular perspective
- But, for CPS, no one perspective is enough!

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

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...
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

snBench: One Hourglass Model / Theory

snBench: Goals

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

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 dispatchable STEPs which are linked
- Load and Execute
  - STEP plans are dispatched and loaded onto the computational core of the CPS infrastructure

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

snBench: Roadmap
CPS: Stakeholders

- 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: 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/

CPS: Challenges

- New cyber-physical systems that:
  - Require novel interaction with human users
  - Demand collaboration across disciplines
  - Engage in non-deterministic environments

From executive summary of CPS Summit Report, April 2008

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
- 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 & EpSOS

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?