Cyber-Physical Co-Design for Wireless Structural Health Monitoring

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Outline

- What are Cyber-Physical Systems (CPS)?
- Case Study: Wireless Structural Health Monitoring
- Reflection on Cyber-Physical Systems
- Other CPS examples
What are Cyber-Physical Systems?

- NSF CPS Program: The tight cojoining of and coordination between computational and physical resources.

- My Definition 1: CPS = Cyber + Physical

- Corollary: non-CPS
  - Cyber only: traditional real-time scheduling theory
  - Physical only: traditional feedback control theory
Definition 2: CPS > Cyber + Physical

- Holistic *co*-design of cyber and physical subsystems

- non-CPS: traditional approach to digital control
  - Control engineers design control algorithms and their sampling rates
  - Embedded engineers design computing systems to meet the timing constraints given by the control engineers
  - Separation of concerns

- CPS: Scheduling-control co-design
  - Integrate task scheduling and control to optimize control performance
  - Break the barrier between physical and cyber components
American Society for Civil Engineers
2009 Report Card for America's Infrastructure

- Bridges C
  - More than 26%, or one in four, of the nation's bridges are either structurally deficient or functionally obsolete.

- Dams D
- Levees D-
- Rail C-
- Roads D-
- ... ...

- America's Infrastructure GPA: D
- Estimated 5 Year Investment Need: $2.2 Trillion
Wireless Smart Civil Structures

- Develop smart structures (with monitoring and control) to prevent...

Minneapolis Bridge Collapse

Freeway after 1989 San Francisco Earthquake
Bridges: inspected *manually* once every *two years*.

Costly and time consuming.

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**Highway 40 Closing for Boone Bridge Inspection**

*Monday August 10, 2009*

If you're heading to St. Charles this weekend, Highway 40 is not your best option. Westbound 40 from Long Road in St. Louis County to Route 94 in St. Charles County will be closed (weather permitting) while work crews inspect the Daniel Boone Bridge across the Missouri River. The road will close at 5:30 a.m. on August 15 and won't reopen until sometime after 9 p.m. on August 16.
Structural Health Monitoring

Wireless Sensor Networks

- Detect and localize damages to structures
- Wireless sensor networks monitor at high temporal and spatial granularities

Key Challenges
- Computationally intensive
- Resource constraints
- Long-term monitoring
Existing (non-CPS) Approach

- Centralized: stream all data to base station for processing.
  - Too energy-consuming for long-term monitoring

- Example: Golden Gate Bridge project [Kim IPSN'07].
  - Nearly 1 day to collect enough data.
  - Lifetime of 10 weeks w/ 4 x 6V lantern battery.

- Separate designs of sensor networks (cyber) and damage detection (physical).
  - Sensor networks focus on data transport.
  - Not concerned with method for damage detection.
Distributed Architecture

Dilemma
- Too much sensor data to stream to the base station
- Damage detection algorithms are too complex to run entirely on sensors

Distributed Architecture
- Performs part of computation on sensor nodes
- Send (smaller) intermediate results to base station
- Base station completes computation
Cyber-Physical Co-design

- Employ damage detection approach amenable for distributed implementation in sensor networks.
- Optimally map damage detection algorithm onto distributed architecture.
Our Solution

- **Physical**: Damage Localization Assurance Criterion (DLAC) [Messina 96]
  - Identify structure’s natural frequencies based on vibration data.
    - “Signature” of structure’s health
  - “Match” natural frequencies to structural models with damages.

- **Cyber**: Optimally partition data flow between sensors and the base station.
  - Minimize energy consumption
  - Subject to resource constraints
D Integers

(1) FFT

2D Floats

(2) Power Spectrum

D Floats

(3) Curve Fitting

P Floats

(3a) Coefficient Extraction

5*P Floats

(3b) Equation Solving

Healthy Model

(4) DLAC

Damaged Location

Data Flow Analysis

DLAC Algorithm
Data Flow Analysis

(1) FFT

8192 bytes

(2) Power Spectrum Curve Fitting

4096 bytes

(3) Curve Fitting

(3a) Coefficient Extraction

100 bytes

(3b) Equation Solving

Healthy Model

14096 bytes

(4) DLAC

20 bytes

Damaged Location

Effective compression ratio of 204:1

D: 2048
P: 5
Integer: 2 bytes
Float: 4 bytes

Washington University in St. Louis
Implementation

- Sensor platform: Intel/Crossbow Imote2 + ITS400 sensor board
  - 13 – 416 MHz XScale CPU
  - 32 MB ROM, 32 MB SDRAM
  - CC2420 802.15.4-compliant radio
  - 3-axis accelerometer on sensor board

- Data collection and processing application written with TinyOS 1.1
  - 243 KB ROM, 71 KB RAM
Evaluation: Truss

- 5.6m steel truss structure at UIUC
- 14 0.4m long bays, on 4 rigid supports
- 11 Imote2s attached to frontal pane

Damage correctly localized to third bay
Energy Consumption

Centralized

Decentralized

Energy consumption (mAh)

Sampling
Computation
Communication

Evaluation
Energy Consumption Evaluation

Washington University in St. Louis
Summary

- Cyber-physical co-design of a distributed SHM system.
  - Reduces energy consumption by 71%
  - Implemented on iMote2 using <1% of its memory
- Effectively localized damage on two physical structures.
- Demonstrated the promise of cyber-physical co-design.

On-going
- Collaborative damage localization
- Wireless bridge control
- Real-time hybrid structural testing
Reflection: Traditional Methodology

- Localize damages on structures using wireless sensors.
- Traditional: separate network and civil engineering
  - Cyber: Wireless network streams all data to a base station
  - Physical: Base station runs damage localization algorithm
- Clean separation of concern, but ineffective
  - Streaming raw data consumes too much energy

CPS Co-Design

1. Design a damage localization method suitable for distributed processing.
2. Model the data flow.
3. Optimally embed the data flow in a sensor network.

- Get hands dirty
  - Understand the data flow of damage localization
- But still employ clean abstraction and methodology
  - Optimal data flow embedding in a network
- Highly effective
  - Reduces energy consumption by 71% [RTSS'08]
So What are Cyber-Physical Systems?

- Definition may not be the important thing
- Neither are applications

- CPS = Embedded Systems?
  - Yes, they refer to the same applications/systems.
  - No, they focus on different methodologies

- Important: CPS co-design methodology
  - Embedded computing works on cyber abstractions.
  - CPS breaks the barrier between cyber and physical design.
Real-Time Wireless Control Networks

- **WirelessHART**
  - Industry standard for wireless process monitoring and control.

- **Real-time transmission scheduling**
  - Map to multiprocessor scheduling
  - Handle conflicts between wireless transmissions
  - General theory for real-time wireless

- **CPS co-design: real-time wireless and control**
  - Holistic design to optimize control

Clinical Monitoring

- First deployment of clinical monitoring system using wireless sensor networks.
- 7-month clinical trial with 46 patients.
- Much higher frequency than current practice
  - 1 reading/min vs. several readings/day.
- Highly reliable network
- Developing early warning system for clinical deterioration
  - Integration with Electronic Medical Records
  - Decision support through machine learning
  - Clinical trial in four hospital wards

Hackmann, Chen, Chipara, Lu, Chen, Kollef, Bailey, Toward a Two-Tier Clinical Warning System for Hospitalized Patients, AMIA’11.
Concluding Remarks

- CPS is about co-design of cyber and physical components
  - will drastically improve embedded systems

- Positive side effects
  - Multidisciplinary research
  - Holistic perspective on systems design
  - Get real: real requirements and challenges
  - Direct impact on society

- Leverage (instead of replacing) traditional approaches to embedded computing
Thanks

- Collaborators: Shirley Dyke (Purdue), Gul Agha & Bill Spencer (UIUC)
- Students: Greg Hackmann, Bo Li, Fei Sun, Weijun Guo

- CPS Project on Wireless Structural Health Monitoring and Control
  - [http://bridge.cse.wustl.edu/](http://bridge.cse.wustl.edu/)
  - More: [http://www.cse.wustl.edu/~lu/](http://www.cse.wustl.edu/~lu/)

- ACM/IEEE International Conference on Cyber-Physical Systems
  - Flagship conference on CPS
  - Part of CPS Week in Beijing, April 2012