Wireless Structural Health Monitoring

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Bridges C+
- Almost four in 10 are 50 years or older.
- 56,007 (9.1%) bridges were structurally deficient.
- Backlog of bridge rehabilitation needs: $123 billion.

Dams D
Levees D
Roads D
...
America's Infrastructure GPA: D+

http://www.infrastructurereportcard.org
Smart Civil Structures

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

Minneapolis Bridge Collapse

Freeway after 1989 San Francisco Earthquake
Structural Health Monitoring

Current Practice

- Bridges: inspected **manually** once every **two years**.
- Costly and time consuming.

**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.
Wireless Structural Health Monitoring

- Detect and localize damages to structures
- Wireless sensor networks monitor at high spatiotemporal 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 with 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
- Perform part of computation on sensor nodes
- Send (smaller) intermediate results to base station
- Complete computation at base station
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) [Messina96]
  - 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 base station.
  - Minimize energy consumption
  - Subject to resource constraints
D Integers

(1) FFT

2D Floats

(2) Power Spectrum

2D Floats

(3) Curve Fitting

D Floats

(3b) Equation Solving

5*P Floats

(3a) Coefficient Extraction

Healthy Model

(4) DLAC

Damaged Location

Data Flow Analysis

DLAC Algorithm

D: # of samples
P: # of natural freq.
(D » P)
Data Flow Analysis

(4) DLAC

Healthy Model

(3a) Coefficient Extraction
100 bytes

(3b) Equation Solving

(2) Power Spectrum
4096 bytes

(1) FFT
8192 bytes

Effective compression ratio of 204:1

20 bytes

Damage Location

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

(3) Curve Fitting

4096 bytes

100 bytes

4096 bytes
Implementation

- **Platform: 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 Evaluation
Energy Consumption Evaluation

- Equation Solving
- Coefficient Extraction
- Power Spectrum
- FFT
- Raw Data Collection

Energy Consumption (mAh)
Memory Consumption Evaluation
What we have learned so far

- 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.

Hierarchical Damage Localization

- The DLAC method employs no collaboration among sensors → limitations in SHM capabilities.
  - For example, cannot detect multiple damages.

- New hierarchical architecture for collaborative localization.
  - Embed processing into a hierarchical architecture
  - Send (smaller!) partial results between layers of hierarchy
  - Multi-level damage localization

- Demonstrate the generality of cyber-physical co-design
Flexibility-based Methods

- Structures flex slightly when a force is applied
- Structural weakening => decreased stiffness
- Flexibility acts as a “signature” of the structure’s health

- Two flexibility-based methods of interest for our work
  - Beam-like structures: Angles-Between-String-and-Horizon flexibility method (ASHFM) [Duan, J. Structural Engineering and Mechanics 09]
  - Truss-like structures: Axial Strain flexibility method (ASFM) [Yan, J. Smart Structures and Systems 09]
Hierarchical Architecture 1

- Sensors form *groups*

- *Group members*
  - collect raw vibration data
  - $\rightarrow$ power spectrum

- *Group leaders*
  - collect and correlate power spectrum from children
  - $\rightarrow$ modal parameters (natural frequencies + mode shapes)
Hierarchical Architecture 2

- **Base station**
  - collects modal parameters from group leaders
  - \(\rightarrow\) structural flexibility
  - compared against “baseline” collected when structure was known to be healthy

- Differences in flexibility \(\rightarrow\) localize damage

![Graph showing changes in ASHF versus element number]
Distributed Data Flow

Group Member
- Sensing
  - 2D ints
  - FFT
  - D floats
  - Power Spectrum

Group Leader
- Cross Spectral Density
  - D matrices
  - Singular Value Decomposition
  - P natural frequencies + mode shapes
  - D floats

Base Station
- Flexibility
  - D: # of samples
  - P: # of natural freq.
  - (D ≫ P)
Enhanced Distributed Data Flow

Group Member
- Sensing
  - 2D ints
  - FFT
  - D floats
  - Power Spectrum
  - D floats
  - Peak Picking

Group Leader
- Cross Spectral Density
- P matrices
- Singular Value Decomposition
- P natural frequencies + mode shapes
- P floats

Base Station
- Flexibility
- D: # of samples
- P: # of natural freq.
  (D \gg P)
Multi-Level Damage Localization

- Only a handful of sensors are needed to detect damage
- As more sensors are added, localization gets more precise
- Save energy by exploiting localized nature of flexibility-based approach
Implementation

- **Hardware:** Imote2 + ITS400 sensor board
  - 13 – 416 MHz PXA271 XScale CPU
  - 32 MB ROM, 32 MB SDRAM
  - CC2420 802.15.4-compliant radio
  - 3-axis accelerometer on sensor board

- **Software platform**
  - TinyOS 1.1 operating system
  - UIUC’s ISHM toolsuite used for sensing, reliable communication, and time sync
Evaluation: Truss

- Simulation of 5.6 m, 14-member steel truss structure at UIUC

- Simulated sensor data generated in MATLAB and injected into live application using “fake” sensor driver
  - Intact data set: no damages
  - Damaged data set: three members reduced on left side of truss, four on right side
Evaluation: Truss

Level 1: nine sensors at uniform points along truss’s length

![Graph showing damage identification on left and right halves of the truss.](image-url)
Evaluation: Truss

- Level 2: move all nine sensors to respective halves (emulate higher density)

![Bar charts showing damage indicator for element numbers 1 to 13. The charts indicate that damage was localized correctly to all seven members.](image-url)

**Damage localized correctly to all seven members**
Evaluation: Truss

- Codesigned architecture reduces communication latency from estimated 87s to 0.21s

- 78.9% of energy attributable to synchronization and sensing

- Compare to theoretical energy supply of 20,250 J (3x 1.5 V, 1250 mAh AAA batteries)

### Group Member

<table>
<thead>
<tr>
<th>Activity</th>
<th>Energy (J)</th>
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<tr>
<td>Synchronization</td>
<td>12.1 J</td>
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<tr>
<td>Sensing</td>
<td>23.0 J</td>
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<td>Computation</td>
<td>9.28 J</td>
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<td>Communication</td>
<td>0.08 J</td>
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### Group Leader

<table>
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<tr>
<th>Activity</th>
<th>Energy (J)</th>
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<tr>
<td>Sensing</td>
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<td>Computation</td>
<td>8.52 J</td>
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<td>Communication</td>
<td>0.76 J</td>
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</table>
Full-Scale Truss
Test Results: Full-Scale Truss

- Two levels of damage localization
  - Level 1: localized damage to bay 9
  - Level 2: localized damage to element 42
Summary

Cyber-physical co-design for wireless structural health monitoring
- Distribute flexibility-based damage localization methods in a hierarchical architecture
- Multi-level search strategy only activates sensors in area of interest; many sensors remain asleep

Localize damage to a simulated truss and a real full-size truss with low energy consumption

Long-term goal: a general cyber-physical co-design approach to integrated sensing and control

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
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]