Wireless Structural Health Monitoring and the Civil Infrastructure Systems: Current State and Future Applications

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Objectives

- Present the current state of wireless structural health monitoring
- Outline challenges
- Present future directions
Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers
- Conclusion
- Future Directions
Outline

- Motivation
- Wireless Monitoring System Design
- Example application
- Current barriers = future opportunities
- Conclusion
Motivation - Why wireless?

- Advances in electronics –
  - sensors,
  - wireless radios – range, bandwidth, reliability
  - power harvesting to extend life
- Low-Cost solution
  - No wires
  - No installation of wires
  - Cheaper sensors
  - Small form factor
- Flexible network architecture – reconfigurable system
- Flexible computational platform – options for computing
  - Local – sensor level – embedded and updatable
  - Centralized
Outline

- Motivation
- Wireless Monitoring System Design
  - Overall System Design
  - Hardware Features
  - Software Features
- Example application
- Current barriers = future opportunities
- Conclusion
Wireless Structural System Components

Control Center
- Manager on site
- Data storage
- Data management and archiving

Decision Support & Emergency Response System

Data Analysis and Post-processing System
- Synchronization
- Signal Processing
- Spectral Analysis
- Feature Extraction & Damage Classification
- Decision making

Data Storage

Sensors & Network

Manager on site

Control Center

Synchronization

Signal Processing

Spectral Analysis

Feature Extraction & Damage Classification

Decision Making

Data Storage
Sensing Unit Design
Sensing Unit Design

Multiple sensors
- Acceleration –
  - Strong motion – 3D
  - Ambient vibrations -3D
- Strain
- Temperature
- Humidity
- ...
Sensing Unit Design - Chronology

- Five Generations of Sensing Unit Design
  - 1996 – Straser, Kiremidjian and Meng
    - Single 2D accelerometer, wireless modem, single supervisory microprocessor
    - proof of concept with field test of 5 units
  - 2000 – Lynch, Law and Kiremidjian
    - Single 2D accelerometer, wireless modem, dual microprocessor, smaller form, lower power consumption
    - Verification with laboratory test followed by subsequent field tests
  - 2002 – Mastroleon and Kiremidjian – multiple sensors
  - 2006 – Wang and Law – multiple sensors, increased wireless transmission range, data streaming with embedded compression algorithms
  - 2007 – current unit
Sensing Unit Design

- **Features of 5th Generation Design**
  - **Sensors**
    - Dual accelerometer – 24 bit A/D converter
      - 3D strong motion – 2/10g, 200Hz sampling rate
      - 3D ambient vibration – 10^{-4}g, 200Hz sampling rate,
    - Strain gages with three resistances
    - Temperature sensor
    - Humidity sensor
  - **Dual microprocessor**
    - Supervisory
    - Computational
  - **802.15.4 radio module – Zig-Bee compliant for wireless sensing**
  - **Local storage – mini SD card**
Sensing units

- Internal view
- Mounted unit

SM300 Sensing Unit
Wireless Communications Network

- Star, mesh and hybrid topologies for wireless communications networks

- Fundamental Building blocks
Damage Detection Algorithms

- **Main approach**
  - Use statistical pattern classification and signal processing methods
  - Use **single sensor** pre- and post- damage measurements
  - Computationally **efficient** - local micro-processing
  - **Independent** of the sensor – can be used with acceleration, strain, etc.
  - **Scalable** with increased sensor density
  - Reduces amount of transmitted data – **power saving**
NEES Multi-Scale Approach

- Single column tests – UNR and UC-Berkeley
- Development of rotation algorithm for wireless sensors (Allen Cheung, Stanford, 2008)
- Direct earthquake damage identification

![Graph showing displacement vs. magnitude of Rinaldi Ground Motion Test]

![Diagram of a cylindrical structure with dimensions and labels, such as 20.0" [508.0 mm], 98.5" [2501.9 mm], 1.00" pitch [25.44 mm], 22 #4 Grade 60 longitudinal bars, and 20.0" [508.0 mm] at the top.]
Layout of Test Bridge and Instrumentation
Decision Support System - Monitoring Mode
### Test Schedule – 4-span Bridge Test at UNR

#### Complete test schedule for shake table tests

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Test Date</th>
<th>Motion Level</th>
<th>Test Type</th>
<th>Motion PGA (g)</th>
<th>Estimated $D_{Ma}$ (in)</th>
<th>Notes</th>
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<td>W/Restrainer2</td>
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<td>1.55</td>
<td>4.90 5.70</td>
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</tr>
</tbody>
</table>

**Baseline Signals**
- Major cracks at base of column & spalling
- Minor cracks at base of column
- Concrete spalling and exposure or rebar
- Rebar buckling/breaking; concrete pouring out of core
Final Test – White Noise

<table>
<thead>
<tr>
<th>Test</th>
<th>Damage Measure</th>
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<tr>
<td>Reno - Setup Day DC1 and DC2</td>
<td>baseline</td>
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</tr>
<tr>
<td>Final Test Day, White Noise Run 51</td>
<td>59.80</td>
</tr>
</tbody>
</table>
NEES Multi-Scale Approach

- Scaled structural system tests – Stanford/SUNY Buffalo
- Development of fragility functions in terms of structural response parameters obtainable from real time measurements – wavelet based fragilities (Hae Young Noh and Dimitrios Lignos, Stanford, 2009)
Decision Support System

- Visual representation of the structure
- Visual representation locations of the wireless system
- Interface to wireless network
- System command and control center
- Display results of monitoring analyses
- Issue alerts
Decision Support System

- Provide support for decision making for follow-on actions
- Enable web services for
  - wide distribution of alerts and other information
  - remote access by operators and other users.
Outline

- Motivation
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- Example application
- Current barriers
- Conclusion
Current Barriers

- Sensors for specific types of damage - e.g.
  - Corrosion
  - Crack
  - Displacement
- Scalable and robust wireless network system
  - Signal loss
  - Communication barriers
  - Sensor durability and continued operation
- Robust and reliable damage diagnosis and prognosis algorithms
- Reliability of long term power supply
Current Barriers (cont’d)

• Limited demonstrations
  • Laboratory
  • Field ***

• No standards or guidelines for development and manufacturing sensing units, sensor networks, etc.

• Existing legacy sensor companies unwilling to invest in new developments

• Unwillingness of profession to take the risk (or invest in proofs of concept)
Outline

• Motivation
• Wireless Monitoring System Design
• Example application
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• Future directions
Conclusion

- Wireless monitoring systems – inevitable part of the future
- Significant applications throughout Asia, very limited elsewhere
- Must combine structural with other monitoring systems, e.g.
  - Building environmental/energy/lighting/security monitoring
  - Bridge, highway, tunnel, pipeline, transmission line, etc. management systems
- Key to success is providing information and not just data
Outline

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Future directions

- Instrument key structures and **demonstrate utility** of such systems
- Have a multi-scale approach – provide different systems – one system does not fit all applications
  - Just an alarm
  - Complete damage diagnosis and decision support for future actions
  - Systems that combine diagnosis, prognosis and repair actions
Future directions

- Develop the means for providing information to designers/builders at various stages of construction/use for future design purposes
- Systems should have different levels of interface sophistication
  - Technical user/decision maker
  - Management level decision maker with limited technical expertise
  - Common citizen