Design of a Low-Power Wireless Structural Monitoring System for Collaborative Computational Algorithms

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Agenda

- Research background
- Hardware design of the latest wireless sensing unit prototype
- Software design of the latest wireless SHM system
- Large-scale field validation tests
- Future direction
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Over 580,000 highway bridges in U.S. mandated for biannual evaluations.

Advanced Sensing Technology for Autonomous SHM:
Rapid, accurate, low-cost
From Wire-based Sensing to Wireless Sensing

- **Traditional DAQ System**: wire-based

- **Future Wireless DAQ System**: Wireless SHM prototype system jointly developed by researchers in Stanford University and the University of Michigan

- E. G. Straser, and A. S. Kiremidjian (1998): Installation of wired system can take about 75% of testing time
- M. Celebi (2002): Each sensor channel and data recording system: $2,000; Installation (cabling, labor, etc.) per wired channel: $2,000.
Challenges in Wireless Structural Sensing (1)

- Requirements for long-distance high-speed wireless data acquisition, and extensive local data processing

HIGHER PERFORMANCE

LOWER POWER
Challenges in Wireless Structural Sensing (2)

- **Hardware**
  - Restricted communication range
  - Limited bandwidth
  - Unreliable wireless transmission

- **Software**
  - Difficulty for data synchronization
  - Difficulty for robust communication design
Wireless SHM Unit Prototypes from Stanford and UMich

Dr. E. G. Straser, Prof. A. Kiremidjian (1998)

Dr. J. P. Lynch, Prof. K. H. Law et al. (2002)


Y. Wang, Prof. J. P. Lynch, Prof. K. H. Law (2005)
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Picture of the Prototype with Wireless Modem
Prototype Double-layer Circuitry Board

- Atmega128 Micro-controller
- Sensor Connector
- Connector to Wireless Modem
- Address Latch for the External Memory
- 4 Channel, 16-bit A2D Converter
- 128kB External Memory
- Power Switch
Wireless Sensing Unit Prototype Package

Antenna Length:
5.79" (14.7cm)

Power supply requirement: 5.2V

Container Dimension
4.02" x 2.56" x 1.57"
(10.2cm x 6.5cm x 4.0cm)
Hardware Performance Summary

- Power consumption: 75 – 80mA when active; 0.1mA standby
- Communication range: 90m indoor, 300m outdoor
- 16-bit Analog-To-Digital conversion, 4 A2D channels
- Local data processing
- Point-to-multipoint, and peer-to-peer communication
- Low hardware cost
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Wireless Sensing Network

Prototype system: simple star topology network

Server-side computer
software

Firmware for wireless sensing units
Reliable Beacon Signal Synchronization Protocol

**Central Server**
- Broadcast Beacon signal to all WSUs
- Verify with each WSU if it received the Beacon signal
  - A WSU didn't receive the Beacon signal
    - Inform WSUs* one by one to restart
  - Received beacon signal
    - Wait and Respond to Beacon verification
      - Wait for data collection command from CS
        - Received data collection request and data is ready
          - Transmit data to CS
            - Finish one round of data transmission

**Wireless Sensing Unit**
- Restart and acknowledge with CS**, wait for Beacon signal
  - Y
- Begin sensor data sampling and storage
  - Y
  - Wait and Respond to Beacon verification
  - Y
  - Wait for data collection command from CS
  - Received data collection request and data is ready
    - Y
    - Transmit data to CS
      - Finish one round of data transmission

* WSU: Wireless Sensing Unit
** CS: Central Server

Approximate beginning synchronization precision: 20 micro-Seconds.
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Geumdang Bridge Test, Korea

Abutment

14
13
12
11
10
9
8
7
6
5
4
3
2
1

NORTH

18.7m
46.0m
18.7m
Bridge Traffic Excitation

Wireless Sensor System Output - Location #9 - Geumgang Bridge, December 6, 2004
<table>
<thead>
<tr>
<th>Sensor Property</th>
<th>PCB Piezoelectric (Cable System)</th>
<th>PCB MEMS Capacitive (Wireless System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Range</td>
<td>1 g</td>
<td>3 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>10 V/g</td>
<td>0.7 V/g</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2000 Hz</td>
<td>80 Hz</td>
</tr>
<tr>
<td>RMS Resolution (Noise Floor)</td>
<td>50 µg</td>
<td>0.5 mg</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>200Hz</td>
<td>70Hz</td>
</tr>
</tbody>
</table>
Time History Comparison Between Two Systems

- Difference in sensors and signal conditioning
Comparison of FFT Results

FFT - KAIST DAQ

Wire-based System

FFT - Wireless DAQ

Wireless System

Comparison of FFT Results

Wireless System

Wire-based System

Sensor Location #8

Sensor Location #8

Frequency (Hz)

Magnitude

Frequency (Hz)
Validation Results Summary

- Rapid installation, and low cost
- Communication range: 50 – 60m in box girder
- Networked real-time and non-stopping data collection: up to 24 wireless sensors at 50Hz sampling frequency
- Data is near-synchronized: modal analysis
- Local data processing capability: 4096-pt FFT by wireless sensing unit
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Future Direction

To be improved for current prototype system:

- Sensor signal conditioning
- Greater wireless communication range, higher data rate
- Large-scale data collection from densely allocated sensors
- Local data analysis and damage identification algorithm
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The End

Thank You