Design of Wireless Sensor Units with Embedded Statistical Time-Series Damage Detection Algorithms for Structural Health Monitoring

Jerome P. Lynch, Arvind Sundararajan, Kincho H. Law, Anne S. Kiremidjian, Ed Carryer
The John A. Blume Earthquake Engineering Center
Department of Civil and Environmental Engineering
Stanford University, Stanford, CA 94305

Structural Health Monitoring Workshop, UCSD
March 7, 2003

Collaborators:
Dr. Hoon Sohn and Dr. Charles Farrar
Los Alamos National Laboratory
Research Motivation

• Need for a *rational* and *economical* structural monitoring
  – Highway bridges – 583,000 bridges in the United States
  • Require federal mandated visual inspections
  – Buildings - 6 stories or with total floor areas over 5,500 m²
    • Recommend 3 accelerometers (2001 California Building Code & 1997 UBC)

• Variety of sensors needed for civil structures
  – Accelerometers, strain gages, anemometers

• High Installation & maintenance costs
  – 25% of total system cost
  – 75% of installation time (cables)
  – $27,000 *per channel*
    (Tsing Ma Bridge, HK)

**Cost Effective Solution:** Hardware + Software
Future Structural Monitoring Systems

- Draw on the available technologies:
  - *Enhance functionality* - local computational power
  - *Lower overall costs* - wireless communication between sensors

- Wireless Modular Monitoring System (WiMMS)
  - Wireless sensing units (*computational power included*)
  - Various communication architectures permissible (*peer-to-peer*)
Initial Development
(Prof. Kiremidjian and Dr. Strasser, 1998)

Validation: Alamosa Canyon Bridge
(with collaboration with Farrar, et.al. of Los Alamos National Lab)
Wireless Sensing Unit

- Prototype designed and fabricated in 2001
- Off the shelf components used
- Two-layer circuit board designed to house all components
- Size is only 4”x4”x1.5”
- Component Cost is about $400

(Jerome Lynch, 2002)
Wireless Sensing Unit - Design

- Three channel interface
  - Single channel 16-bit A/D converter – 10 kHz (maximum)
  - Two 14-bit digital sensor inputs
- Sensor Transparent
  - Traditional structural sensors (accelerometers, strain gages, etc)
  - Environmental sensors (thermal, chemical and biological sensors)
Wireless Sensing Unit - Design

- Dual processor core – optimized for energy efficiency
  - Atmel AVR 8-bit microcontroller – low power (8 mA)
    - Responsible for overall unit operation
  - Motorola 32-bit PowerPC microcontroller – high power (100 mA)
    - Responsible for engineering analyses
    - Regularly kept off / turned on by 8-bit processor for analyses
Wireless Sensing Unit - Design

- **Proxim RangeLAN2 wireless modem**
  - 2.4 GHz unregulated FCC ISM radio band
  - Draws a lot of power – 160 mA active (60 mA in sleep mode)
  - Frequency hopping spread spectrum – highly reliable
  - Open space range – 1000 feet
  - Enclosed range – 500 feet
MEMS Accelerometers

- Micro-electro mechanical system (MEMS)
  - Accurate and sensitive
  - Smaller form factors and lower unit costs
  - Cost advantage - integration of digital circuitry
- In this study, four MEMS Accelerometers considered
  - Capacitive architectures:
    - Analog Devices ADXL210
    - Bosch SMB110
    - Crossbow CXL01LF1 (Low “g” accelerometer)
  - Piezoresistive architectures:
    - High Performance Planar Accelerometer (Partridge et al 2000)
    - Laboratory Validation (ADXL210, SMB110, HPPA)
    - Field Validation (CXL01LF1)
Laboratory Validation Tests

- A 5-DOF aluminum shear model structure

<table>
<thead>
<tr>
<th>Story</th>
<th>Mass (lb)</th>
<th>Stiffness (lb/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>17</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>17.8</td>
<td>180</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>180</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>180</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>180</td>
</tr>
</tbody>
</table>

Analog Devices ADXL210

Piezoresistive accelerometer

Bosch SMB110
Structural Response Monitoring & FFT

- **Sweep sinusoid** - $A = 0.075''$ with $f = 0.25$-3 Hz over 60 seconds
- **FFT calculated** *(performed on board by the wireless sensing unit)*

**ADXL210 Measured Absolute Acceleration Response**

**SMB110A Measured Absolute Acceleration Response**

**HPPA Measured Absolute Acceleration Response**

**ADXL210 Frequency Response Function (30Hz)**

- $f_1 = 2.96$ Hz
- $f_2 = 8.71$ Hz
- $f_3 = 13.70$ Hz

2.87 Hz

**Bosch SMB110A Frequency Response Function (30Hz)**

- $f_1 = 2.96$ Hz
- $f_2 = 8.71$ Hz
- $f_3 = 13.70$ Hz
Interfacing of Strain Gages

(Micro Measurement)
Field Validation - Alamosa Canyon Bridge

- Constructed in 1937 (7 simply supported spans)
- 6 Steel Girders (W30x116 @ 58” CL) with 6” concrete deck

WiMMS

<table>
<thead>
<tr>
<th>Sensor Property</th>
<th>Crossbow CXL01LF1</th>
<th>Piezotronics PCB336</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Range</td>
<td>0 ± 1 g</td>
<td>0 ± 4 g</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>2 V/g</td>
<td>1 V/g</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>50 Hz</td>
<td>2000 Hz</td>
</tr>
<tr>
<td>RMS Resolution</td>
<td>0.5 mg</td>
<td>60 µg</td>
</tr>
<tr>
<td>Offset at 0g</td>
<td>2.5 V</td>
<td>-</td>
</tr>
<tr>
<td>Anti-aliased Output</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

(Diagram showing girders and sensors)

(Collaboration with Los Alamos Nat. Lab.)
Sensors Mounted to Bridge Girder
Data Acquisition

Wireless Data Acquisition Unit

Dactron Cabled System
Modal Hammer Test

• 12 lb Piezotronics PCB86C50 modal hammer
• Impulse at span center, sensor location S3
• Four modes identified
  – **Hammer - 6.7, 8.2, 11.4, 12 Hz**

![Response of Alamosa Canyon Bridge to Modal Hammer (Los Alamos Lab System)](image1)

![Response of Alamosa Canyon Bridge to Modal Hammer (WIMMS System)](image2)

![FRF of Alamosa Canyon Bridge to Modal Hammer](image3)

(Collaboration with Los Alamos Nat. Lab.)
Dynamic Vehicle Test

- 40 mph truck drives over a 2x4 wood stud
- Acceleration at sensor location S7
- Four modes identified
  - Van - 6.8, 8.1, 11.2, 11.9 Hz
  - Hammer - 6.7, 8.2, 11.4, 12.0 Hz

Response of Alamosa Canyon Bridge to Van Excitation (Los Alamos Lab System)

Response of Alamosa Canyon Bridge to Van Excitation (WiMMS System)

FRF of Alamosa Canyon Bridge to Modal Hammer
Ambient Vibrations from I25

- Ambient excitations from the I25 bridge adjacent to the ACB
- First three modes identified – 6.5, 8.8 and 11.9 Hz
Power Sources

• **Batteries are used as a primary power source for the wireless sensing units**

<table>
<thead>
<tr>
<th>Operational State</th>
<th>Current (mA)</th>
<th>5-AA L91 (Li/FeS₂) Battery Pack (7.5 V)</th>
<th>5-AA E91 (Zn/MnO₂) Battery Pack (7.5 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT90S8515 Circuit and MPC555 Asleep</td>
<td>54</td>
<td>50 hours</td>
<td>30 hours</td>
</tr>
<tr>
<td>AT90S8515 Circuit and MPC555 Active</td>
<td>160</td>
<td>15 hours</td>
<td>5 hours</td>
</tr>
<tr>
<td>RangeLAN2 Asleep</td>
<td>60</td>
<td>40 hours</td>
<td>25 hours</td>
</tr>
<tr>
<td>RangeLAN2 Active</td>
<td>160</td>
<td>15 hours</td>
<td>5 hours</td>
</tr>
</tbody>
</table>

• **Duty-cycle usage can substantially extend the battery life for the wireless sensing units**
  – Units are normally kept in sleep mode
  – Returned to an active mode based on a regular schedule
  – Awakened by triggering events (for example - threshold accelerations)

• **Auxiliary power source possible**
Wireless Sensing Unit with PowerPC

- **Motorola PowerPC Microcontroller Core**
  - 32-bit architecture clocked at 40 Mhz
  - Floating point calculations in hardware
  - Sufficient Memory -- 448 Kbytes ROM, 26 Kbytes RAM
Embedded Computational Power

- Energy efficient wireless sensor networks
  - Avoid wireless transmission of raw time histories (in real time)
  - Local execution of embedded engineering analyses
- Current embedded algorithms
  - Statistical AR-ARX time series damage detection
  - Fast-Fourier transform (FFT)
Surface Effect Fast Patrol Boat

Damage Detection

(Courtesy of Farrar and Sohn)
## Auto-Regressive Models Fitted

### AR(10)

<table>
<thead>
<tr>
<th>Coef.</th>
<th>Sensing Unit</th>
<th>MATLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>b₁</td>
<td>1.6650</td>
<td>1.6650</td>
</tr>
<tr>
<td>b₂</td>
<td>1.3009</td>
<td>1.3009</td>
</tr>
<tr>
<td>b₃</td>
<td>0.4752</td>
<td>0.4752</td>
</tr>
<tr>
<td>b₄</td>
<td>0.1171</td>
<td>0.1171</td>
</tr>
<tr>
<td>b₅</td>
<td>0.6756</td>
<td>0.6756</td>
</tr>
<tr>
<td>b₆</td>
<td>1.5212</td>
<td>1.5212</td>
</tr>
<tr>
<td>b₇</td>
<td>1.2646</td>
<td>1.2646</td>
</tr>
<tr>
<td>b₈</td>
<td>0.5989</td>
<td>0.5989</td>
</tr>
<tr>
<td>b₉</td>
<td>0.1498</td>
<td>0.1498</td>
</tr>
<tr>
<td>b₁₀</td>
<td>0.0891</td>
<td>0.0891</td>
</tr>
</tbody>
</table>

### AR(20)

<table>
<thead>
<tr>
<th>Coef.</th>
<th>Sensing Unit</th>
<th>MATLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>b₁</td>
<td>1.5915</td>
<td>1.5915</td>
</tr>
<tr>
<td>b₂</td>
<td>1.2415</td>
<td>1.2415</td>
</tr>
<tr>
<td>b₃</td>
<td>0.5293</td>
<td>0.5293</td>
</tr>
<tr>
<td>b₄</td>
<td>0.0624</td>
<td>0.0624</td>
</tr>
<tr>
<td>b₅</td>
<td>0.2754</td>
<td>0.2754</td>
</tr>
<tr>
<td>b₆</td>
<td>0.8377</td>
<td>0.8377</td>
</tr>
<tr>
<td>b₇</td>
<td>0.5392</td>
<td>0.5392</td>
</tr>
<tr>
<td>b₈</td>
<td>0.1494</td>
<td>0.1494</td>
</tr>
<tr>
<td>b₉</td>
<td>-0.1833</td>
<td>-0.1833</td>
</tr>
<tr>
<td>b₁₀</td>
<td>-0.2473</td>
<td>-0.2473</td>
</tr>
<tr>
<td>b₁₁</td>
<td>-0.4464</td>
<td>-0.4464</td>
</tr>
<tr>
<td>b₁₂</td>
<td>-0.5422</td>
<td>-0.5422</td>
</tr>
<tr>
<td>b₁₃</td>
<td>-0.3261</td>
<td>-0.3261</td>
</tr>
<tr>
<td>b₁₄</td>
<td>-0.1971</td>
<td>-0.1971</td>
</tr>
<tr>
<td>b₁₅</td>
<td>-0.0715</td>
<td>-0.0715</td>
</tr>
<tr>
<td>b₁₆</td>
<td>0.2227</td>
<td>0.2227</td>
</tr>
<tr>
<td>b₁₇</td>
<td>0.1912</td>
<td>0.1912</td>
</tr>
<tr>
<td>b₁₈</td>
<td>0.2397</td>
<td>0.2397</td>
</tr>
<tr>
<td>b₁₉</td>
<td>0.2360</td>
<td>0.2360</td>
</tr>
<tr>
<td>b₂₀</td>
<td>0.0134</td>
<td>0.0134</td>
</tr>
</tbody>
</table>
Data Compression

- **Lossless**: Data compression without loss in data integrity.
- **Lossy**: Data compression with “reasonable” errors in data reconstruction.

### Lossless Data Compression

![Diagram](Image)

**Example: Static Huffman coder**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Compression Ratio(%)</th>
<th>Data MSE</th>
<th>AR MSE(30)</th>
<th>ARX MSE(5,5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lossless</td>
<td>83.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

16 Bit High Speed Boat data histories used in the simulation. Results averaged over three different time histories.
Lossy Compression

- A Daubechies-4 Discrete wavelet transform used
- A Uniform Quantizer: \( x_q = \text{round}(x/q) \)

Input \( x[n] \)
Stream

- \( \star H \)
- 2
- \( \star H \)
- 2
- \( \star G \)
- 2
- \( \star G \)
- 2
- D1[n]
- D2[n]
- A2[n]
## Preliminary Results

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Compression Ratio(%)</th>
<th>Data MSE/mean</th>
<th>AR MSE(30)</th>
<th>ARX MSE(5,5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lossless</td>
<td>83.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Lossy 1*</td>
<td>65.60</td>
<td>10^{-8}</td>
<td>10^{-6}</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>Lossy 2*</td>
<td>58.75</td>
<td>10^{-7}</td>
<td>10^{-4}</td>
<td>10^{-6}</td>
</tr>
</tbody>
</table>

*Lossy 1 and Lossy 2 represent the results at two different levels of Quantization*
Damage Detection and Assessment Methodologies

- **System Level Screening**
  - *Rapid assessment* – determine presence of damage
  - *Statistical pattern recognition techniques*
  - *Embeddable Algorithms*

- **Damage Diagnosis (Detection)**
  - *Damage identification* - locate damage regions
  - *Experimental modal analysis or strain-based measurements*
  - *Statistical model-based system analysis* (Modal vs. Ritz vectors, Ref: Sohn, H., PhD Thesis)
  - *Data synchronization* (Ref: Lei, Kiremidjian, et.al.)

- **Damage Inspection**
  - *Visual or localized experimental methods*

- **Damage Prognosis and Self Diagnostics**
  - *Estimate the performance level and remaining life*
  - *Integrating sensing, self-excitation and control strategies*
Concluding Remarks

• An Overview of Our Research in Structural Health Monitoring
  – Development of a Wireless Modular Monitoring System
  – Investigation of Statistical-Based Damage Detection Techniques

• Structural Health Monitoring is a Multidisciplinary Research Problem
  – Structural mechanics, signal processing, sensing systems, statistical pattern recognition, computer hardware, telecommunications, embedded computing, etc….

• Future Research
  – Multiple sensors per module
  – Integrating monitoring with damage assessment
  – Integrated monitoring network
  – Decentralized sensing, monitoring, control
  – Environmental and other effects

PLENTY OF WORKS TO BE DONE
Acknowledgements

- This research has been partially supported by the Civil and Mechanical Systems Program, National Science Foundation, Grant Numbers CMS-95261-2, CMS-9988909, and CMS 0121842.

- Collaboration with Dr. Charles Farrar and Dr. Hoon Sohn of Los Alamos National Laboratory is appreciated. The experiment at the Alamosa Canyon Bridge was supported by the Los Alamos Laboratory Directed Research and Development (LDRD) fund.

- Collaborative work with Prof. Anne Kiremidjian, Prof. Tom Kenny and Dr. Ed Carryer. Special credits are attributed to Dr. Jerome Lynch, Dr. Hoon Sohn and Mr. Arvind Sundararajan.

- Any opinions, findings, and conclusions or recommendations expressed in this material are those of the presenter and do not necessarily reflect the views of the sponsors.
Thank You
Comments and Suggestions