The Structural Health Monitoring Process

1. Operational evaluation
2. Data acquisition & networking
   - Sensors
   - Data collection
   - Data management
3. Feature selection & extraction
4. Probabilistic decision making
Presentation Outline

• Introduction
• **Hardware design of wireless sensors:**
  – Commercial and academic units
• **Embedded firmware:**
  – Operation and data interrogation
• **Field applications:**
  – Long-span bridges and buildings
• **Future directions and technology trends**

---

Structural Monitoring Systems

• **Structures can be instrumented with monitoring systems:**
  – Empirical response data to seismic and wind loads
  – Model calibration using response data is a typical application
  – Detection of excessive responses
• **Structural monitoring ≠ structural health monitoring:**
  – Very few structural “health” monitoring systems in practical use
  – Automated processing of data for damage identification

- Tsing Ma Bridge, HK (+300 channels)
- Pacoima Dam, CA (20 channels)
- Turbines contain multiple sensors
Current State of Practice

- **Characteristics of structural monitoring systems:**
  - Centralized architectures with data stored in a signal data repository
  - Sensors are “wired” to a central processing unit using shielded wiring:
    - Dedicated and reliable communication channel
    - Wiring drives installation cost high – few thousand dollars per channel
    - Cost promotes adoption of low sensor densities

Introduction of Wireless Telemetry

- **First proposed by Straser and Kiremidjian in the mid-1990’s:**
  - Eradicate the need for wiring in order to reduce costs
- **Three major innovations associated with wireless sensors:**
  - Indeed a low-cost option which in turn drives sensing density
  - Wireless communications allows for ad-hoc communications
  - Includes computing resources for sensor-based interrogation
Presentation Outline

- Introduction
- **Hardware design of wireless sensors:**
  - Commercial and academic units
- **Embedded firmware:**
  - Operation and data interrogation
- **Field applications:**
  - Long-span bridges and buildings
- **Future directions and technology trends**

Anatomy of a Wireless Sensor

**Sensing Interface**
- Sensor transparency offered by internal ADC:
  - Multi-channel
  - High-resolution
- To sample data, require local clocking
- Synchronization challenging between independent ADCs in the network

**Computational Core**
- Consists of microprocessor & memory
  - Packetize data for modulation on the wireless channel
- Today, the computational core is the wireless sensor’s most important and powerful functional feature:
  - Locally buffer measurement data
  - Empowers sensors to process data

**Wireless Modem**
- Important element in the design as it eliminates wiring
- Requires digital data formats:
  - ADC & microcontroller are required at the node
- Major consumer of power
- Limited bandwidth
### General Wireless Sensor Families

<table>
<thead>
<tr>
<th>Academic wireless sensor prototypes</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UC Berkeley &quot;Mote&quot; wireless sensor family commercialized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Crossbow MoteZ" /></td>
<td><img src="image" alt="Dust Inc Node" /></td>
<td><img src="image" alt="Intel iMote (Gen1)" /></td>
<td><img src="image" alt="MEMSIC iMote2" /></td>
</tr>
<tr>
<td>Other commercial wireless sensors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Microstrain G-Link" /></td>
<td><img src="image" alt="National Instruments" /></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Los Alamos Dynamics** Structural Dynamics and Mechanical Vibration Consultants

### Navigation of WSN Families

- **Commercial wireless sensors:**
  - Ready to run right out of the box
  - Large user base whose collective experience can be leveraged
  - Generic wireless sensing solutions not tailored to any one application:
    - Typically low data resolution (8 to 12-bits)
    - Short communication ranges (50 m)

- **Academic wireless sensor prototypes:**
  - As engineers, can prescribe system functionality desired:
    - High resolution data collection (at least 16-bits)
    - Communication range can be scaled to system dimensions (100’s m)
  - Necessitates understanding of electronics and embedded systems
  - Most typically a slow evolutionary process
  - Stand-alone system difficult to integrate with other WSN families
MEMSIC MoteZ

- **Very popular commercial wireless sensor platform:**
  - Widely used by the academic SHM community
  - Mature-generation platform based on the Berkeley Mote family
    - Based on the Atmel ATmega microcontroller product line
  - Low cost and comes with complete mesh networking capabilities
  - Operating system utilized to operate device is TinyOS (open-source)
    - Difficult operating system to learn and implement properly

<table>
<thead>
<tr>
<th>Performance Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution: 10-bit</td>
</tr>
<tr>
<td>Communication: IEEE 802.15.4 (Zigbee)</td>
</tr>
<tr>
<td>Energy Source: 2 AA Batteries</td>
</tr>
<tr>
<td>Power: 20 mA @ 3V</td>
</tr>
<tr>
<td>Range: 20 m</td>
</tr>
<tr>
<td>Data Rate: 250 kps</td>
</tr>
<tr>
<td>Sample Rate: 100 kHz</td>
</tr>
</tbody>
</table>

MEMSIC iMote2

- **State-of-the-art commercial wireless sensor platform:**
  - Jointly developed between Intel and Crossbow
  - Features richer computational capabilities:
    - Based on the Intel XScale microprocessor family (marketed by Marvell)
  - Comes with communication (IEEE 802.15.4) and processor:
    - Sensor interface board is not included
  - Phasing out in 2011 (to be replaced by iMote3 in 2012)

<table>
<thead>
<tr>
<th>Performance Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory: 256kB SRAM, 32MB Flash, 32MB SDRAM</td>
</tr>
<tr>
<td>Processor: XScale PXA271 (with DSP coprocessor)</td>
</tr>
<tr>
<td>Energy Source: 3 AAA Batteries</td>
</tr>
<tr>
<td>Power: 60 mA (@ 3V)</td>
</tr>
<tr>
<td>Range: 30 m</td>
</tr>
<tr>
<td>Data Rate: 250 kps</td>
</tr>
<tr>
<td>Data Collection: No ADC on-board – requires sensor board</td>
</tr>
</tbody>
</table>
Sensor Boards for iMotes

- **Intel standard sensor board available:**
  - Low ADC resolution of 12-bits

- **Illinois SHM-A sensor board:**
  - Custom designed sensor board for high resolution SHM applications
  - 3-axis MEMS accelerometer with 16-bit resolution (via over-sampling)
  - Built-in variable amplification circuitry (Analog Devices 628)

Microstrain G-Link

- **Proprietary commercial wireless sensor platform:**
  - Internal MEMS accelerometers (2 or 10g versions with 10 mg noise floors)
  - IEEE802.15.4 wireless communications on 2.4 GHz
  - Complete wireless system solution offered:
    - Transmitters, receivers, loggers, among other system components
    - Lack of access to embedded software within the wireless sensor node

<table>
<thead>
<tr>
<th>Performance Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory</td>
<td>2 MB</td>
</tr>
<tr>
<td>ADC Resolution</td>
<td>12-bit</td>
</tr>
<tr>
<td>Sample Rate</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Energy Source</td>
<td>Internal Li-ion rechargable battery</td>
</tr>
<tr>
<td>Power</td>
<td>25 mA (@ 3 V)</td>
</tr>
<tr>
<td>Range</td>
<td>70 m</td>
</tr>
<tr>
<td>Data Rate</td>
<td>250 kps</td>
</tr>
<tr>
<td>Sensor</td>
<td>Internal accelerometer (10 mg resolution)</td>
</tr>
</tbody>
</table>

**National Instruments WSN**

- **First data acquisition company to invest in wireless sensors:**
  - Wireless capabilities for the CompactRIO system
  - Stand-alone base-station also possible
  - Programmable wireless sensor nodes via LabVIEW
- **Slowly building diverse module family:**
  - General purpose analog inputs, strain gages and thermocouples

<table>
<thead>
<tr>
<th>Performance Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Memory</td>
</tr>
<tr>
<td>ADC Resolution</td>
</tr>
<tr>
<td>Sample Rate</td>
</tr>
<tr>
<td>Energy Source</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Data Rate</td>
</tr>
<tr>
<td>Sensor</td>
</tr>
</tbody>
</table>

**Los Alamos Dynamics** Structural Dynamics and Mechanical Vibration Consultants

---

**WiMMS Sensor (Stanford)**

- **Designed for structural monitoring explicitly:**
  - 16-bit ADC with 4 channels to which any sensor can be attached
  - 0-5V sensor voltage range
  - Swappable radio to offer a flexible interface to the wireless channel:
    - MaxStream Xcite – 900 MHz with 300 m LOS range
    - MaxStream Xstream – 2.4 GHz with 1 km LOS range

<table>
<thead>
<tr>
<th>Performance Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>Form Factor</td>
</tr>
<tr>
<td>Energy Source</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Data Rate</td>
</tr>
<tr>
<td>Sample Rate</td>
</tr>
</tbody>
</table>

**Los Alamos Dynamics** Structural Dynamics and Mechanical Vibration Consultants
Narada (Michigan)

- Redesign of the Stanford WiMMS wireless sensor node:
  - 4-layer printed circuit board design to achieve true 16-bit resolution
  - 2-channel 12-bit DAC interface for actuation control
  - Designed to incorporate IEEE802.15.4 radio (Chipcon 2420):
    - 2.4 GHz radio with a 250 kbps rate and 70 m range
  - Swappable radio to accommodate a radio with power amplification:
    - Power amplifier provides 10 dBm gain to give 700 m range

<table>
<thead>
<tr>
<th>Performance Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>Form Factor</td>
</tr>
<tr>
<td>Energy Source</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Data Rate</td>
</tr>
<tr>
<td>Sample Rate</td>
</tr>
</tbody>
</table>

WiDAQ (Los Alamos)

- WID3 module offers processing and radio capability:
  - Zigbee communications (using a Zigbit transceiver)

- The wireless data acquisition (WiDAQ) module:
  - Designed to integrate with the WID3
  - Offers 4 conventional A/D channels
  - Offers 1 D/A channel for passive and active sensing
Wireless Impedance Device (Los Alamos)

- **Wireless sensor node optimized for impedance-based SHM:**
  - Built around the AD5933 impedance measurement solution:
    - Frequency Range: 1 to 100 kHz
    - Impedance Range: 10W to 10MW
  - 7 piezoelectric sensors per node
  - Low Power (< 60 mW)
  - 8 Mb flash memory for data storage

---

Word of Caution

- **Data sheets can be difficult to read for novice users:**
  - Inability to truly read the datasheet can lead to poor choices

- **Power is a significant limitation of wireless sensors:**
  - The laws of physics are in play – hence, there is no free lunch!
  - Larger communication range mean higher power ($P \propto R^2$)
  - Higher data rates means higher power ($P \propto f$)
  - Faster processors mean higher power ($P \propto f$)
  - More memory means higher power ($P \propto S$)

- **Energy consumed is a function of:**
  - Time the unit is “active” times the active power
  - Time the unit is “sleeping” times the sleep power
  - Usage is ultimately the final determinant of required energy source
Presentation Outline

- Introduction
- Hardware design of wireless sensors:
  - Commercial and academic units
- Embedded firmware:
  - Operation and data interrogation
- Field applications:
  - Long-span bridges and buildings
- Future directions and technology trends

Overview of Firmware

- **Software embedded in wireless sensors is firmware:**
  - Software usually written in a high-level programming language (C)
  - In-line assembly written for speed and low-latency computations
  - Includes operating system, middleware and applications

Application Software

Middleware

Operating System

Hardware/Devices

*Data processing associated with system ID, control and health monitoring*

*Takes care of general node and network operation (e.g., mesh networking), time synchronization, etc.*

*Hides implementation details from upper layers and manages memory*

*Physical hardware running the system including radio and ADC*
Robust Operating System Options

- Real-time operating system (RTOS) will offer:
  - Deterministic timing of embedded system operations (very important)
  - Multitasking kernel design for concurrent thread execution
  - Abstract device details away from user
- Open-source RTOS options for small microcontrollers:
  - FreeRTOS (http://www.freertos.org)
  - uCOS (http://www.micrium.com)
- Commercial RTOS options:
  - Wind River VxWorks
  - Many more

TinyOS

- Berkeley mote family utilizes TinyOS for its operation:
  - Open-source operating system for mesh networked wireless sensors
  - Written in "nesC", a high-level programming extension to standard C
    - Component-based programming abstraction
    - Strong correlation to object-based abstractions
- Two-generations of TinyOS:
  - TinyOS 1.0 is the first mainstream version widely used up to 2008:
    - Core element of the OS is its handling of mesh networking
  - TinyOS 2.0 is a complete redesign to gain speed and efficiency:
    - Not backward compatible with Tiny OS 1.0
- Commercial uses of TinyOS have been limited:
  - Can not achieve a deterministic timing of tasks making it unreliable for embedded system chores requiring precise timing
Middleware

- Middleware begins to customize wireless sensor node for its operation in a network of wireless sensors:
  - Networking topologies (star versus mesh)
  - Timing and synchronization

Star Topology

Multi-hop (Peer-to-peer) Topology

Star Networks

- Direct data transmission (star topologies) commonly used:
  - Use a lot of energy upfront with high power at transmitter
  - Power in signal inversely proportional to distance
  - Receive as long as signal power is greater than receive sensitivity
  - More energy consumed ……. but offers superior reliability

$$P_r(d) = \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} P_t$$

- Power, $P_r$
- Range, $R$
- Receiver Sensitivity
Mesh Networks

- **Multi-hop transmission can be used as well:**
  - Multiple short range hops give network overall range
  - Multi-hopping requires significant overhead that erodes at speed
  - Theoretically more energy-efficient … but in actuality it may not be:
    - If one hop is 95% reliable, then multi-hop reliability is $0.95^n$
    - 6-hop example below, 75% reliable likely requiring resends!

\[ P_i(d) = \frac{G_i G_e \lambda^2}{(4\pi)^2 x L} P_i \]

<table>
<thead>
<tr>
<th>Power, ( P )</th>
<th>Range, ( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver Sensitivity</td>
<td></td>
</tr>
</tbody>
</table>

Time Synchronization

- **An inherent challenge with wireless sensors is timing:**
  - Clock drift (sensor-specific problem)
  - Time synchronization (network-specific problem)
- **Clock drift is the result of low-cost crystals on the node:**
  - Piezoelectric oscillation in a crystal used to keep track of time
  - Oscillation varies and is a function of environment (e.g., temperature)
  \[ f = f_{nom} \left[ 1 - 0.04 \text{ ppm}(T - T_{nom})^2 \right] \]
  - High quality crystals drift less (lower ppm drift characteristics)
  - Thermally corrected crystals (but these require battery power!)
Network Synchronization

- **Node-to-node synchronization can be resolved:**
  - Many delay sources that are deterministic and stochastic

<table>
<thead>
<tr>
<th>Time</th>
<th>Magnitude</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Send and Receive</td>
<td>0 - 100 ms</td>
<td>1) adeterministic, depends on the processor load</td>
</tr>
<tr>
<td>Access</td>
<td>10 - 500 ms</td>
<td>2) deterministic, depends on the channel contention</td>
</tr>
<tr>
<td>Transmission / Reception</td>
<td>10 - 20 ms</td>
<td>3) deterministic, depends on message length</td>
</tr>
<tr>
<td>Propagation</td>
<td>&lt; 100 ms for distances up to 500 meters</td>
<td>4) deterministic, depends on the distance between sender and receiver</td>
</tr>
<tr>
<td>Interrupt Handling</td>
<td>&lt; 500 ms in most cases, but it can be up to 700 ms</td>
<td>5) deterministic, can be calculated</td>
</tr>
<tr>
<td>Encoding</td>
<td>100 - 2000</td>
<td>6) Deterministic, depends on radio channel and settings</td>
</tr>
<tr>
<td>Byte Alignment</td>
<td>0 - 800</td>
<td>7) Deterministic, can be calculated</td>
</tr>
</tbody>
</table>

Source: Maróti et al. (2004)

Synchronization Strategies

- **Beacon-based synchronization:**
  - Have nodes locally reset their clocks at the same time
  - Ignore the delays inherent to the beacon send-receive process
  - Easy but lower time synchronization accuracies (< 1 ms)

- **Baseline deterministic and stochastic delays:**
  - Packet communication used to baseline network delays
  - Identify deterministic and stochastic delays
  - Correct for delays when resetting the local clocks
  - More overhead due to multiple packets but great accuracy (< 10 us)
  - Flooding time synchronization protocol (FTSP):
    - Maróti et al. (2004) [Vanderbuilt]
Application Software

- **Embedded firmware allows applications to be created:**
  - With data collected and stored, time to process
  - While computing is possible there are many limitations:
    - Time, memory, and energy

  ![Diagram of Application Software, Middleware, Operating System, and Hardware/Devices]
  - **Application Software**
    - Data processing associated with system ID, control and health monitoring
  - **Middleware**
    - Takes care of general node and network operation (e.g., mesh networking), time synchronization, etc.
  - **Operating System**
    - Hides implementation details from upper layers and manages memory
  - **Hardware/Devices**
    - Physical hardware running the system including radio and ADC

Local Data Processing at the Node

- **Local data processing capability is a major paradigm shift:**
  - **System scalability**: streaming raw data is not scalable since it would exhaust bandwidth leading to eroded wireless performance
  - **Power reductions**: communication is more power-intensive which is a critical issue for battery powered nodes
  - **Efficient data management**: avoidance of data inundation at the central repository
Unique Computing Platform

- **WSN represent a very unique computing platform:**
  - Small memory and computing footprint at each sensor node
    - But significant memory and data processing ability within the network
  - Can share data between computing nodes via the wireless channel
    - To preserve battery energy and channel quality, minimize channel use

- **Sensor-based versus network-based computing**

Realization-based System Identification

- **Consider simple illustration of embedded computing:**
  - Realization-based subspace system identification
Implementation Details

- **Sensor-level computing:**
  - Parallel MP estimations in each sensor node by $\mu$-MPID algorithm
  - Treating system as a single input-single output (SISO) system

- **Network-level computing:**
  - Model estimation in the server by Ho & Kalman algorithm

Sensor-based Computations

- **$\mu$-Markov parameterization (Van Pelt & Bernstein 1998):**

  - SISO ARMA model

  \[
  y(k) = \sum_{j=1}^{\mu} a_j y(k-j) + \sum_{j=0}^{\mu} b_j u(k-j) = -\sum_{j=1}^{\mu} a_j y(k-j) + b_0 u(0) + \sum_{j=1}^{\mu} b_j u(k-j)
  \]

  $\mu$ times substitutions of time-delayed ARMA model

  \[
  y(k) = -\sum_{j=1}^{\mu} a_j y(k-j+1) + \sum_{j=0}^{\mu} b_j u(k-j) + \sum_{j=1}^{\mu} b_j u(k-j+1)
  \]

  - MP estimation by lease square method:

  \[
  y = \Phi \theta + \epsilon
  \]

  \[
  \hat{\theta} = (\Phi^T \Phi)^{-1} \Phi^T y
  \]

  - Least square solution

  \[
  \hat{\theta} = \begin{bmatrix} \hat{a}_1 \\ \vdots \\ \hat{a}_n \\
  \hat{b}_0 \\ \vdots \\ \hat{b}_1 \\
  \end{bmatrix}
  \]

  - Markov parameters
Server-based Computation

- **Ho & Kalman’s Realization Algorithm (1966):**
  - State-space model realization from MP sequences
  - Origin of realization-based subspace system identification

\[
\begin{align*}
  x(k+1) &= Ax(k) + Bu(k) \\
  y(k) &= Cx(k)
\end{align*}
\]

\[
h(k) = CA^kB
\]

Los Alamos Dynamics

Hill Auditorium

- **Hill Auditorium at University of Michigan:**
  - 42 m x 11 m cantilevered balcony (Mezzanine)
  - 15 Narada wireless nodes to measure mezzanine vibrations
  - 1 Narada used to command modal shaker to vibrate balcony
  - Base station used for ERA implementation and network coordination
**Instrumentation Strategy**

- Control server
- Local coordinator on modal shaker
- Wireless sensor node

**Measured Balcony Response**

- 20.7 kg Modal Shaker
- MEMS Accelerometer
- Acceleration response of balcony

- Chirp (3 to 15 Hz) signal
Modal Results

- In-network processed MP sequences

• Estimated system model
• Modal parameters

\[ A = \Psi \Lambda \Psi^{-1} \]

- Mode 1
  - 5.62Hz
  - (0.998)
- Mode 2
  - 6.05Hz
  - (0.982)
- Mode 3
  - 6.72Hz
  - (0.995)
- Mode 4
  - 7.61Hz
  - (0.933)

Presentation Outline

- Introduction
- Hardware design of wireless sensors:
  - Commercial and academic units
- Embedded firmware:
  - Operation and data interrogation
- Field applications:
  - Long-span bridges and buildings
- Future directions and technology trends
Golden Gate Bridge (2005-2006)

- **Short-term field deployment on the Golden Gate Bridge:**
  - UC Berkeley (Pakzad et al. 2006) deployed 56 MicaZ wireless sensor nodes on the main span and 8 MicaZ on the towers
  - Measure accelerations using ADXL202 and SD1221 accelerometers
  - Pipelining approach to data delivery:
    - Collect at the same time and buffer data
    - After sampling, all stop and send one at a time
    - One sensor sends its data to its neighbor
Los Alamos Dynamics Structural Dynamics and Mechanical Vibration Consultants

**Golden Gate Bridge (2005-2006)**

- 6V Lantern Battery X 4
- Extreme Rust on C-clamp
- Accelerometer Board and Mote
- Zip tie around antenna
- Bi-directional Patch Antenna
- Duct Tape to Hold Wire

---

**Jindo Bridge (2007-2011)**

- **Jindo cable stay-bridge instrumentation study**
  - UIUC (Spencer), KAIST (Yun), and University of Tokyo (Nagayama)
  - 70 iMote2 nodes with SHM-A boards to measure accelerations
  - Solar cells and mico-wind turbines for power harvesting
Jindo Bridge (2007-2011)

- **Jindo cable stay-bridge instrumentation study:**
  - UIUC (Spencer), KAIST (Yun), and University of Tokyo (Nagayama)
  - 70 iMote2 nodes with SHM-A boards to measure accelerations
  - Solar cells and micro-wind turbines for power harvesting
Stork Bridge (2006 – Present)

• **Stork Bridge (Switzerland) is a permanent installation:**
  – Meyer *et al.* (2001) deploy 7 wireless sensor nodes
  – 6 nodes measure cable vibrations and 1 measures deck vibrations
  – Proprietary wireless sensor node developed at EMPA
New Carquinez Bridge (2009 – Present)

- **New Carquinez Bridge (Vallejo, CA):**
  - Total bridge length is 1056 m (main span of 728 m)
  - Main deck consists of steel orthotropic box girders
  - Hollow concrete tower legs and pre-stressed link beam

- **Permanent monitoring system installed in 2009:**
  - Kurata *et al.* (2010) describes monitoring system design

- **28 wireless sensor nodes collecting 81 channels:**
  - 19 tri-axial accelerometers measuring main deck
  - 3 tri-axial accelerometers measuring vibrations at tower top
  - Wind vane, anemometer and temperature in three locations
  - 3 string potentiometers to measure deck movement relative to tower
Packaged *Narada* Units

- Packaging for long-term deployment on NCB:
  - Water tight enclosure for all electronics
  - Magnetic mounting for quick and easy installations

Installation Details
Installation Details

- Narada node
- Narada server
**Ambient Vibrations**

---

**Comparison to CSMIP Data**

- **California Strong Ground Motion Instrumentation Program:**
  - NCB already has a permanent seismic monitoring system installed
  - Ideal baseline for performance evaluation
  - Past work used CSMIP data for system ID of NCB (e.g., Conte, Betti)
Cyberinfrastructure

- **What do you do with data from hundreds of channels?**
  - Sensor technology has outpaced data management tools
- **Cyberinfrastructure tools offer enormous potential:**
  - Data combined with powerful analytical tools
  - Physics- and statistics-based information discovery

Automated Mode Extraction

- **Owner of bridge (Caltrans) concerned about seismic safety:**
  - Concern is the seismic safety of the bridge during large earthquakes
  - Require high-fidelity models of bridge to simulate seismic behavior
- **Seek modal information for model updating of FEM model:**
  - Modal frequencies and mode shapes used to update ADINA model
Extracted Mode Shapes

- Estimation by Frequency Domain Decomposition (FDD) mode shape estimation algorithm:
  - Distributed implementation proposed by Zimmerman et al. (2009)
  - Excellent agreement with model updated finite element model

Presentation Outline

- Introduction
- Hardware design of wireless sensors:
  - Commercial and academic units
- Embedded firmware:
  - Operation and data interrogation
- Field applications:
  - Long-span bridges and buildings
- Future directions and technology trends
Future Directions

• **Wireless sensors are rapidly maturing:**
  – Early efforts focused on the design of wireless sensor hardware
  – Deployed to various “structures” (bridge, building and turbine)
  – Current efforts more positioned to explore in-network data processing
  – Wireless sensor platforms emerging with greater processing power

• **Integration of actuation capabilities in wireless sensors:**
  – Active sensing with PZT elements (acoustic/ultrasonic inspection):
    • Bridging between global monitoring and NDE methods
  – WSN can be leveraged to reduce the complexity of control systems:
    • Lower cost and greater flexibility in system architectures

• **Strong dependency on batteries:**
  – Other wireless sensing strategies proposed (for example, light-based)
  – Power harvesting – promising field but still in its infancy

References

• **Literature review of the state-of-art:**

• **Case studies:**