Structural Health Monitoring of Civil Infrastructure: *from Research to Engineering Practice*

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Director, MUST-SIM: NEES@Illinois
Director, Smart Structures Technology Laboratory (SSTL)
Outline

◊ Background and Motivation
◊ Enabling Wireless Smart Sensor Technology
  □ High-fidelity Hardware
  □ Service-oriented Software Framework
◊ Full-scale Implementations
◊ Future Directions
◊ Conclusions
Why Monitor Infrastructure?

- To detect and localize damage
  - Deteriorating structures
  - Lessons from catastrophic bridge collapses
  - Limits in visual inspection
  - SHM reduce inspection cost, while providing increased public safety
  - Lifetime monitoring of future construction projects

![Corrosion](image1.jpg)

![Fatigue (Bay Bridge in CA, 2009)](image2.jpg)

![Sung-su bridge collapse in Korea (1994)](image3.jpg)

![I-35 bridge collapse in MN (2007)](image4.jpg)

![Capital investment (US DOT 2008)](chart.jpg)

- System expansion (39.9% increase)
- Rehabilitating (75.2% increase)

<table>
<thead>
<tr>
<th>Year</th>
<th>System Expansion</th>
<th>Rehabilitating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>$21.5 billion</td>
<td>$23.0 billion</td>
</tr>
<tr>
<td>2006</td>
<td>$30.1 billion</td>
<td>$40.4 billion</td>
</tr>
</tbody>
</table>

(US DOT 2008)
Why Monitor Infrastructure?

◊ To validate the structural designs and characterize performance (e.g., develop database)
◊ To assist with infrastructure maintenance
◊ To design appropriate retrofit measures
◊ Improve seismic risk assessment
◊ To monitor and control the construction process
◊ To characterize loads in situ
◊ Assess load carrying capacities
◊ To assist with emergency response efforts, including building evacuation and traffic control
Structural Health Monitoring

- Limitation of traditional methods
  - Dense arrays of sensor are required to effectively monitor structures
  - Wired monitoring systems are expensive, with much of the cost derived from cabling and installation
  - Centralized data collection is not challenging for monitoring large civil infrastructure

Bill Emerson Memorial Bridge SHM system: $1.3M for 86 sensors, ~$15k/sensor (Caicedo et al. 2002; Celebi et al. 2004)
Enabling Wireless Smart Sensor Technology

* low cost
* ease of installation
* accurate data
Computers are Faster and Cheaper

- $400,000/MIPS (Cray-I)
- $500/MIPS (i860)
- $1/MIPS

1980 1990 2005
Where Computing is Done

Number Crunching Data Storage

productivity interactive

streaming information to/from physical world

year
Networking Plays an Important Role

1946

The first computer

1965

High performance Computing

1980

Personal Computers

1995

Internet

2010

IoT/WSN

Cyber Physical Systems
Vision of the Future: Internet of Things

◊ Vast networks of sensors, installed in the urban environment, can serve as the eyes and ears of a first line of defense against various vulnerabilities

◊ Different types of sensors can be envisioned, each reporting information that provides insight to the status of critical infrastructure in real-time

◊ **Wireless Smart Sensors** will act as the fundamental building block for such sensor networks
  - Low costs allow for dense deployment as needed
  - Modularity provides inherent flexibility for use in both permanent and temporary applications
**Smart Sensors**

◊ But... what is a *smart sensor*?

◊ First open source hardware and software platforms developed at Berkeley in the late 1990s as part of DARPA’s Smart Dust project (Mica family of smart sensors).
Historic Decade of Smart Sensors

WINS 1 (1999)
SmartDust WeC (1999)
BTnode rev3 (2004)
U3 (2002)
EYES (2003)
Intel Imote (2004)
Prototype by Prof. Lynch (2002)
Imote2 (2006)
## Full-scale Implementations to Bridges (selected)

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Purpose</th>
<th>Sensor Platform</th>
<th># of Nodes</th>
<th>Sensor (channels)</th>
<th>Test duration</th>
<th>In-network Processing</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alamosa Canyon (Lynch et al. 2003)</td>
<td>Wireless system proof-of-concept</td>
<td>WiMMS (prototype)</td>
<td>7</td>
<td>Accel. (14)</td>
<td>Short-term</td>
<td>Independent FFT</td>
<td>Modal frequencies</td>
</tr>
<tr>
<td>Ben Franklin (Galbreath et al. 2004)</td>
<td>Demonstration of wireless system with remote programming</td>
<td>Microstrain SG-Link</td>
<td>10</td>
<td>Strain + Temp. (10)</td>
<td>Continuous</td>
<td>None</td>
<td>Streaming real-time strain time histories</td>
</tr>
<tr>
<td>Guemdang (Lynch et al. 2006)</td>
<td>Wireless sensor prototype and embedded computing validation</td>
<td>WiMMS (prototype)</td>
<td>14</td>
<td>Accel. (14)</td>
<td>Short-term</td>
<td>Independent FFT and peak picking</td>
<td>Modal frequencies, ODS</td>
</tr>
<tr>
<td>Golden Gate (Pakzad et al. 2008)</td>
<td>Test wireless sensor network requiring multi-hop communication</td>
<td>MicaZ</td>
<td>64</td>
<td>Accel. (128) Temp. (64)</td>
<td>Medium-term</td>
<td>None</td>
<td>Modal analysis after central data collection</td>
</tr>
<tr>
<td>Gi-Lu (Weng et al. 2008)</td>
<td>Test for health monitoring of cable-stayed bridge</td>
<td>WiMMS (prototype)</td>
<td>12</td>
<td>Accel. (12)</td>
<td>Short-term</td>
<td>None</td>
<td>Modal analysis and cable tension force</td>
</tr>
</tbody>
</table>
Smart Sensor Monitoring of the Golden Gate Bridge (2008)
Smart Sensor Monitoring of the Golden Gate Bridge (2008)

Requires **12 hours** to transmit **80 seconds** of data back to the base station!
## Full-scale Implementations to Bridges (selected)

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</tr>
</thead>
<tbody>
<tr>
<td>Stork</td>
<td>Validation of long-term field test using wireless sensor network</td>
<td>Tmote Sky</td>
<td>6</td>
<td>Accel. (6)</td>
<td>Long-term</td>
<td>None</td>
<td>Cable tension force</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferriby Road</td>
<td>Evaluation of the potential of wireless sensor network</td>
<td>MicaZ</td>
<td>7</td>
<td>Crack (3) Inclin. (3) Temp (7) Humid.(6)</td>
<td>Long-term</td>
<td>None</td>
<td>Crack growth and inclination of deck</td>
</tr>
<tr>
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<tr>
<td>New Carquinez</td>
<td>Wireless system proof-of-concept</td>
<td>Narada/Imote2</td>
<td>30</td>
<td>Accel. (14)</td>
<td>Long-term</td>
<td>SSI Modal Analysis</td>
<td>Mode Shapes</td>
</tr>
<tr>
<td>(Lynch et al. 2010)</td>
<td></td>
<td></td>
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</tbody>
</table>

Despite the fact that smart sensors have been readily available for nearly a decade, full-scale implementations are still limited.
What’s Been Lacking?

◊ Hardware

☐ Platform with computational capacity for high-data rate applications and distributed computing
☐ Sensor hardware that to produce high-fidelity data that is appropriate for SHM

◊ Software

☐ Middleware services to acquire high-fidelity data
☐ Application software to implement distributed SHM
☐ Flexible software that supports network and application scalability

◊ Full-scale implementation considerations

☐ Communication performance evaluation
☐ Autonomous network operation
☐ Power management
☐ Fault tolerance
High-fidelity Hardware
Imote2 with Sensor Boards

From MEMSIC (2010)

<table>
<thead>
<tr>
<th></th>
<th>MicaZ</th>
<th>Telos</th>
<th>iMote2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microprocessor</td>
<td>Atmel Atmega128L</td>
<td>TI MSP430</td>
<td>Intel XScale PXA271</td>
</tr>
<tr>
<td>Clock speed (MHz)</td>
<td>7.373</td>
<td>8</td>
<td>13-412</td>
</tr>
<tr>
<td>Active Power (mW)</td>
<td>24</td>
<td>10</td>
<td>44 @ 13 MHz</td>
</tr>
<tr>
<td>Non-volatile memory (bytes)</td>
<td>128 K (Flash) + 512 K (EEPROM)</td>
<td>48K (Flash)</td>
<td>32 M (Flash)</td>
</tr>
<tr>
<td>Volatile memory (bytes)</td>
<td>4 K</td>
<td>1024K</td>
<td>256 K + 32 M (SDRAM)</td>
</tr>
<tr>
<td>Dimensions (mm) / Weight (g)</td>
<td>58<em>32</em>7 / 18</td>
<td>65<em>31</em>6 / 23</td>
<td>36 <em>48</em>9 / 12</td>
</tr>
</tbody>
</table>

Imote2 and Basic Sensor Board

Imote2: Top and Bottom

Basic Sensor Board
Aliasing

◊ Consider a 48 Hz signal
◊ What if the signal is sampled at 50 Hz?
◊ The resulting measured signal has an apparent frequency of 2 Hz

◊ Cannot have significant energy above the Nyquist frequency \( (f_s/2) \)
◊ Anti-aliasing filters must be used in dynamic measurements to preserve signal integrity
Multifunctional Sensor Boards

**SHM-A and SHM-H Board**
- Accelerometer: ST Microelectronics LIS344ALH
- Light Sensor: TAOS 2561
- Humidity & Temp. Sensor: SHT11
- External Input Connector
- Programmable Filter w/ ADC Quickfilter QF4A512
- Basic Connector

**SHM-DAQ Board**
- **Data Acquisition** using commercial voltage-output sensors
- **Output Voltage:** -5 to 5 V, 0 to 5 V

**Interfaced Voltage**

[Images of sensor boards and components]
High-sensitivity Accelerometer board (SHM-H board)

- **Pseudo-static test:** slender column with lumped mass on top

- 6 Hz sampling rate was used
- Performed well in low-frequency range (< 0.2 Hz)

- Frequency range: 0.14 Hz, 4.42 Hz, 14.57 Hz
Strain monitoring using SHM-S board

Strain sensor board for Imote2 platform
- High-throughput synchronized strain monitoring
- High precision auto-balanced Wheatstone bridge
- Up to 2500 times gain
- 0.3 μ-strain resolution at 20Hz B/W
- Stacked use with SHM-A or SHM-DAQ board
- Both foil-type strain gage and magnetic strain sensor can be used with SHM-S board

SHM-S board: top, stacked on SHM-DAQ and stacked on SHM-A

RemoteCommand SHMSAutoBalance

Tokyo Sokki magnet strain checker
High-precision Strain sensor board (SHM-S board)

- **SHM-S vs. Ni-DAQ (foil type)**

  a) Time history

  b) PSD

  c) Detail (high-level strain)

  d) Detail (low-level strain)
Pressure and D2A Sensor Board

**SHM-D2A Board**
- 16bits, Digital to Analog conversion of 4 channels

 TI-DAC8565

**SHM-P Board**
- Measure wind/air pressure

Stacked with SHM-DAQ Board
Imote2 Sensor Enclosure

- Solar Panel
- External 5dBi Antenna
- Rechargeable Battery
- Antenna Cable
- Acrylic Jig
- Bolt & Spacer
- Uni-directional magnet
Future Hardware Enhancement

- **24-bit DAQ** (TI ADS1274, Delta-sigma type ADC)
  - Delta-sigma noise reshaping technology
  - Low-power consumption suitable for wireless sensor application
  - Support full capabilities of low-noise/high-sensitivity sensors
  - Make it easy to implement/design new external sensor boards

**Diagram:**
- Signal conditioning circuit for -5V to 5V analog input
- 3-pole AA-filter

**Others:**
- Clean power supply
- Low-noise design (separation of digital/analog parts, low-noise components)
- Reclock circuit for restraining f_ECL/f_CLK = 1/2, 1/4...

**Function selection:**
- Low-speed mode (7mW/ch)
- Enable power down mode (while no-use)
- Low-power Crystal (2MHz)
- TDW & dynamic output format (need only DOUT1, memory saving)
Service-oriented Software Framework
Service-Oriented Architecture (SOA)

◊ Previous smart sensor applications:
  □ Significant effort to create very specific applications
  □ Difficult to modify for other applications, even with extensive CS knowledge

◊ Service-Oriented Architecture simplifies SHM software development
  □ Applications are comprised of manageable, modular services that exchange data in a common format
  □ The middleware framework connects the services by providing communication and coordination
Time Synchronization

- Each sensor has its own local clock which drifts over time
- Synchronization errors can be reduced to ~20μs
- Not the whole story...
Synchronized Sensing Service

◊ Uncertainty in start of acquisition

□ Independent processors

Resampling middleware service achieves synchronized sensing
Power Management and Energy Harvesting

Effective Power Management with Autonomous Operation

- SnoozeAlarm:
- ThresholdSentry:
- AutoMonitor:

Energy Harvesting

- Solar panel (or Micro wind turbine) + Rechargeable Battery
- PMIC charger manipulates voltage and current for fast and stable charging.
ISHMP Services Toolsuite

Fault tolerant WSSN
- Skipping of unresponsive nodes
- Data storage in non-volatile memory
- Monitoring of sensor power
- Exclusion of low-power sensor nodes
- Watchdog timer and etc...

Enhanced operation
- Autonomous resuming of AutoMonitor
- ThresholdSentry for multi-hop communication
- Email notification of structural response and network anomalies
Illinois Structural Health Monitoring Project (ISHMP)

- **ISHMP Service Toolsuite**
  - SHM application
  - Middleware services
  - OS (TinyOS)
  - Hardware (Imote2)

- **Foundation Services**
  - Reliable communication
  - Time synchronization
  - Numerical library (e.g. FFT, SVD, etc.)

- **Network Services**
  - Network data acquisition
  - Decentralized data aggregation (DDA)
  - Multi-hop communication

- **Application Services**
  - Correlation function estimation
  - Eigensystem realization algorithm (ERA)
  - Stochastic subspace identification (SSI)
  - Frequency domain decomposition (FDD)

- **Tools and Utilities**
  - Test applications for Toolkit components
  - Radio and antenna testing

[http://shm.cs.uiuc.edu](http://shm.cs.uiuc.edu)
Full-scale Implementation
US-Korea-Japan Collaborative Project
on SHM Test-bed Using Wireless Smart Sensor Network
(September 2008 – 2012)

US : B.F. Spencer, Jr. & G. Agha (UIUC)
Korea : H.J. Jung & C.B. Yun (KAIST), H.K. Kim (SNU)
J.W. Seo (Hyundai Institute of Const. Tech.)
Japan : Y. Fujino & T. Nagayama (U. of Tokyo)

<table>
<thead>
<tr>
<th>2nd Jindo Bridge</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Cable-stayed bridge</td>
</tr>
<tr>
<td>Spans</td>
<td>70+344+70 = 484m</td>
</tr>
<tr>
<td>Girder</td>
<td>Steel box (12.55m width)</td>
</tr>
<tr>
<td>Design velocity</td>
<td>70 km/hr</td>
</tr>
<tr>
<td>Designed by</td>
<td>Yooshin cooperation (2000, Korea)</td>
</tr>
<tr>
<td>Constructed by</td>
<td>Hyundai construction (2006, Korea)</td>
</tr>
</tbody>
</table>
Deployment in 2009 (70 Nodes)

Cable: 8
Deck: 22
Pylon: 3
Total: 33

Max. 420 channels of sensors
(207 ch. Acceleration & 3 ch. Wind)

Cable: 7
Deck: 26
Pylon: 3
Wind: 1
Total: 37

Sensor location for Pylons & Cables

Note:
1. ( ) values mean node ID
2. z-axis direction of deck sensors

Deck Nodes
Nodes on pylons
Nodes on pylon top (powered by solar cell)
Nodes on cables (powered by solar cell)
Reference Nodes
Amemometer
Deployment in 2010

TeamViewer (for remotely access to basestation)
Deployment in 2010

In total, 669 sensing channels with 113 sensor nodes were deployed

<table>
<thead>
<tr>
<th></th>
<th>SHM-DAQ board (wind)</th>
<th>Sentry node</th>
<th>Temperature node (exposed)</th>
<th>Functionalities</th>
<th>Communication protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 nodes</td>
<td>3 nodes</td>
<td>1 nodes</td>
<td></td>
<td>Single-hop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 nodes</td>
<td>-</td>
<td>RemoteSensing, AutoUtilsCommand, ChargerControl, ThresholdSentry and SnoozeAlarm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 nodes</td>
<td>1 nodes</td>
<td></td>
<td>Single-hop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>1 nodes</td>
<td></td>
<td>Single-hop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>1 nodes</td>
<td></td>
<td>Multi-hop</td>
</tr>
</tbody>
</table>

W: Anemometer (SHM-DAQ)  WT: Wind Turbine power  S: Strain sensor (SHM-S1)
T: Temperature  H: High-sensitivity (SHM-H)  ST: Strain + Temp correction (SHM-S2)
Evaluation

Typhoon Kompasu (2010.09.01)

- Sep. 1, 21:00 (Closest to Jindo)
- Sep. 2, 21:00
- Sep. 2, 15:00
- Sep. 2, 9:00
- Sep. 2, 3:00
- Sep. 3, 21:00
- Sep. 3, 9:00

Korea

Japan

China

Jindo Bridges

Typhoon center

Jindo Bridge

Birth of Typhoon

Aug. 29, 21:00

SSTL
Evaluation: Wind Monitoring

- **SHM-DAQ + Anemometer**
  - Wind Speed
  - Ch1: wind speed
  - Ch2: wind direction (horizontal)
  - Ch3: wind direction (vertical)
  - Measured Wind Direction
  - Narrow Strait: Increased wind speed - Slight change in direction

- **Anemometer**
  - Jindo-side (at 21:14)
  - Haenam-side (at 21:12)

- **Locations**
  - Jindo
  - Haenam (Inland)
  - Narrow Strait

- **Details**
  - Measured Wind Direction
  - Wind dir. by KMA (Mt. Chun-Cha)
Evaluation: Acceleration Responses

1 (center span)

2

3

PSD (Haenam side deck)

4

5

6

7

10

11 (pylon)

12

13

14 (girder end)
Evaluation: System ID

- NExT & ERA method
- Identified frequency range: 0~3Hz
- 1000 seconds data at 25Hz sampling

Identified natural frequencies (Hz)

<table>
<thead>
<tr>
<th>Mode Name</th>
<th>Wired System (2007)</th>
<th>FE analysis</th>
<th>WSSN (During Kompasu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Haenam</td>
</tr>
<tr>
<td>DV1</td>
<td>0.440</td>
<td>0.442</td>
<td>0.446</td>
</tr>
<tr>
<td>DV2</td>
<td>0.659</td>
<td>0.647</td>
<td>0.645</td>
</tr>
<tr>
<td>DV3</td>
<td>1.050</td>
<td>1.001</td>
<td>1.033</td>
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<tr>
<td>DV4</td>
<td>1.367</td>
<td>1.247</td>
<td>1.356</td>
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<td>DV5</td>
<td>1.587</td>
<td>1.349</td>
<td>1.555</td>
</tr>
<tr>
<td>DV6</td>
<td>1.660</td>
<td>1.460</td>
<td>1.653</td>
</tr>
<tr>
<td>DT1</td>
<td>-</td>
<td>1.789</td>
<td>1.798</td>
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<tr>
<td>DV7</td>
<td>1.856</td>
<td>1.586</td>
<td>1.871</td>
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<tr>
<td>DV8</td>
<td>2.319</td>
<td>2.115</td>
<td>2.259</td>
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<tr>
<td>DV9</td>
<td>2.808</td>
<td>2.561</td>
<td>2.812</td>
</tr>
</tbody>
</table>
Evaluation: Pylon Strain

- Temperature compensation using the half bridge with a dummy gage worked
- Synchronized acceleration & strain sensing at 25Hz
- For pylon, strain measurement was more informative
Evaluation: Girder Strain

- Strain responses under traffic loadings
  - Compressive strain at pylon bearing and tensile strain at midspan
  - Double peaks (?) in the strain measurements at pylon bearing location

![Strain time history (at pylon bearing position)](image)

![Strain time history (at midspan)](image)

Using magnet strain checker with SHM-S
Evaluation: Strain Analysis

Truck loading simulation using FE model

- Girder strain at pylon bearing location
  - 3.1 sec
  - u-strain
  - time(sec)

- Girder strain at midspan
  - 6.0 sec
  - u-strain
  - time(sec)

- (north bound)
  - Truck moving
  - (51m)/(3.1sec)*(3600sec/hr)/(1000m/km)
  - = 59.2 km/hr

- (100m)/(6.0sec)*(3600sec/hr)/(1000m/km)
  - = 60 km/hr

- Double peaks are caused by the double-concaved influence line
- Can be utilized for estimation of vehicle’s speed, moving direction, and weight (Bridge Weigh-in-Motion, BWIM)
Evaluation: Battery Monitor

![Battery Monitor Graphs]

- **Battery Voltage (V)**
- **Charging current (mA)**

*East-side nodes*
Evaluation: Cable Tension and Temperature

Cable tension estimation

Temperature monitoring

[ Cable ID ]

[ Cable tension comparisons ]
Evaluation: Long-term performance of Jindo-side WSSN

Battery voltage (V)

Charging current (mA)

Number of responsive node (out of 31)

Baseline problem

Battery voltage change (Jindo deck)

Charging current change (Jindo deck)

Awaken node (Jindo deck)

Average charging current > 100mA

Responsive rate: 70~85%
Deployment Achievements

- **Hardware**
  - 669 sensors at 113 nodes
  - High-sensitivity accelerometer board
  - Solar panel with rechargeable battery
  - Wind-induced energy harvesting

- **Software**
  - Multi-hop reliable data transfer and printing
  - Fault tolerant operation
  - Remote software updates
  - Better user interface

---

**World’s largest deployment to date of wireless sensors for civil infrastructures monitoring.**

**World’s first long-term deployment.**

- Modal analysis with system synchronization
- Vibration-based tension estimation
- Multi-scale structural health monitoring
  (Modal information + Cable tension force)
- Wind-vibration correlation analysis

- International collaboration for test-bed
- Web-based data repository and sharing
Next Steps
Wind Load and Wind Effects on Xihoumen Bridge

Hui Li, B.F. Spencer, Yan Yu, Jinping Ou
Wind Load and Wind Effects on Xihoumen Bridge

Add 32 wireless pressure modules (P992 connected to SHM-DAQ)

Range: ±250-500Pa
Accuracy: ≤0.5% of full span
Wind Load and Wind Effects on Xihoumen Bridge

Add 12 bidirectional wireless accelerometers in ten sections

Add 10 bidirectional wireless accelerometers
Campaign Monitoring for Management of Railroad Assets
The Future
Cyberinfrastructure for Smart Structures

**Bridges**
- Structure Monitoring
- Hurricane & Earthquake Monitoring
- Traffic Monitoring
- Emergency Response

**Dams**
- Pressure Monitoring
- Leakage Detection
- Deflection Monitoring
- Emergency Response

**Tunnels**
- Deflection Monitoring
- Leakage Detection
- Fire Detection
- Traffic Monitoring
- Emergency Response

**The Other Infrastructure**
- Structure Monitoring
- Hurricane & Earthquake Monitoring
- Load Rating
- Emergency Response

Cloud Services

- WSN applications for structural monitoring
- Repository of structure data and monitoring algorithms
- Repository of models
Objective: 20 KM² urban area in Wuxi
- 4000+ sensor nodes with temperature/humidity and light sensors
- 500+ nodes with CO₂ sensor

Final Goal: 10,000 Nodes, 100 KM²
Goals of APSS Program

- To enhance students' understanding of the cross-disciplinary technological developments on the emerging subjects of smart structure technologies
- To develop the cross-cultural human-network and understanding for the future cooperation in their professional career development.
- 3 weeks program for 6 years among US/Korea/China/Japan/India supported by NSF, NRF, JSPS, & NSFC.

Coordinators
- Korea : C-B. Yun (KAIST)
- US : B.F. Spencer (UIUC)
- Japan : Y. Fujino (U. of Tokyo)
- China : L. Sun (Tongji U.)
1st APSS at KAIST, Korea, 2008
SISTeC-KAIST, July 28 - August 16, 2008
- 50 graduate students attended.
- http://sstl.cee.uiuc.edu/apss

2nd APSS at U. of Illinois, USA, 2009
July 3 – July 25, 2009
- 45 graduate students attended.

3rd APSS at U. of Tokyo, Japan, 2010
July 15 – August 4, 2010
- 40 graduate students attended.

4th APSS at Tongji U., China, 2011
July 28 – August 10, 2011
- 48 graduate students attended.

5th APSS at IIT, India, 2012
July 23-August 11, 2012
- 48 graduate students attended.

6th APSS at KAIST, Korea, 2013
Concluding Remarks
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- This paper discusses recent advances and field validation of a state-of-the-art WSSN framework developed at the University of Illinois at Urbana-Champaign.
- The open source ISHMP Services Toolsuite a wide variety of services and fault-tolerant features.
- Full-scale WSSNs are realized for the purpose of SHM and the evaluation as well as the data analysis show high practicality of wireless SHM systems for civil infrastructure.
- Tremendous potential and a level of maturity of WSSN for SHM has been demonstrated through full-scale deployment on the Jindo Bridge in Korea.
- Education of the next generation of engineers in smart structures technology is of high importance.
Acknowledgement

- NSF Grant CMS 06-00433 (Dr. S.C. Liu, Program Manager)
- Global Research Network Program (NRF-2008-220-D00117) from the National Research Foundation in Korea
- Smart Infra-Structure Technology Center (SISTeC) at KAIST in Korea
- Ministry of Land, Transport and Maritime Affairs in Korea
- Hyundai Construction Co. Ltd.

Thank you for your attention!